

SPIE



Smart Structures/NDE

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Technical
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Summaries



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6926-01, Session 1

Dynamic characterization and single-frequency cancellation performance of SMASH (SMA actuated stabilizing handgrip)

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The performance of hand-held devices such as surgical tools, optical equipment, manufacturing tools, and small arms weapons is often significantly affected by the human operator's physiologically induced body tremors. Such tremors can prove to be devastating particularly in high-precision operations. While increasing the system inertia can achieve passive stabilization for many devices, it often introduces unwanted weight and bulk which is unsuitable for hand-held systems. A general technology, the SMA Stabilizing Handgrip (SMASH), has been developed to address the tremor problem through the use of active stabilization which does not suffer from these volume and weight penalties. The SMASH is capable of being adapted for a wide variety of hand-held systems, and is applied to the M16 rifle as a case-study. In the SMASH, SMA actuators are employed to produce large forces and displacement without significant size, weight, and packaging consequences. The system is designed to be self-contained, with a power supply, controller electronics, and actuator all packaged within a single handgrip. This paper presents experimental studies in the dynamic domain of a SMASH that satisfies quasi-static force and displacement requirements, which were found to serve as upper bounds throughout the frequency range of interest (0-3 Hz). Studies on the frequency response of the actuator were conducted along with stabilization of simulated jitter over this frequency range. Initial tests on a human subject conclude that the dominant jitter frequency resides at 1 Hz with a displacement of 2 mm peak-peak, and can be estimated with a sinusoid. Efforts were conducted to empirically obtain an operating regime of the SMASH that would most closely cancel this simulated disturbance, and a heating profile was selected to gradually overcome the specific and latent heat of the SMA while retaining smooth operation, which is typically difficult to achieve from the material. With this heating profile, up to 97% RMS cancellation under open loop was obtained. These results demonstrate the success of the SMASH stabilization and demonstrate the potential of the system in reducing human tremor under closed loop control.

6926-03, Session 1

The development of a five-DOF magnetorheological fluid-based telerobotic haptic system

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The performance of telerobotic systems can be greatly improved if some form of kinesthetic feedback is employed. The systems are called "transparent" when the operator controlling the master has the feeling of direct interaction with the remote object without any distortions in forces or geometry caused by the slave. In this study the authors develop haptic systems for telerobotic surgery. The research outlined in this document is subdivided into four parts.

(i) Microstructural Modeling:

A microstructural, kinetic theory-based model of MR fluids has been developed. Microscale constitutive equations relating flow, stress, and particle orientation are produced. These new models for MR fluids are three dimensional and applicable to any flow geometry. The model developed in this study is fully vectorial and relationships between the stress tensor and the applied magnetic field vector are fully exploited.

(ii) Characterization of MR Fluids:

Because of the large range of forces necessary a number of different MR fluids are employed. The rheological properties of these MR fluid samples are characterized using a rheometer and their magnetic properties are obtained using a vibrating sample magnetometer. The resulting shear

stress-shear rate and magnetization-magnetic field graphs of the MR fluid samples are used to determine the optimal MR fluid sample to be used in the design of two haptic systems.

(iii) Actuator Design:

In this stage, MR fluids are used in the design of a novel five degree of freedom (DOF) MR sponge-based haptic system (master) for controlling a telerobotic arm used in telerobotic surgery. The master 5-DOF joystick controls the movement of a 5-DOF slave. A novel multi-axis force sensor is designed by the authors and used at the end effector (EE) of the slave for force feedback control.

(iv) Control, Transparency, and Stability of the System:

The control methodology in this research will be categorized in two sub-sections: motion control of the slave and force feedback control. Two distinct modern control algorithms will be applied to achieve the required performance of the system: state feedback control and model predictive control. Finally, the transparency and stability of the system will be addressed.

6926-04, Session 1

Techniques and considerations for driving piezoelectric actuators at high speed

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Due to their high stiffness, small dimensions and low mass, piezoelectric stack actuators are capable of developing tens of microns displacement over bandwidths of greater than 100 kHz. However, due to their highly capacitive electrical impedance, standard voltage amplifiers are limited in bandwidth to a few kHz (3 kHz for a 1 μ F actuator driven by an amplifier with 50 ohm output impedance). The limiting factors for bandwidth are the high output impedance of high-voltage amplifiers, cable inductance and phase-margin degradation due to load resonance. Maximum power bandwidth is further limited by the current and dissipation limit of driving electronics and the preload force on the actuator.

Two new amplifiers are introduced with the capability to drive large piezoelectric stack actuators from DC up to hundreds of kHz or MHz. By restricting the displacement range at high-frequencies, the amplifiers can be made an order-of-magnitude more efficient than traditional designs. Experimental results are presented for a video-speed scanning probe microscope positioning stage.

6926-05, Session 1

Modeling and simulation of a 2-DOF bidirectional electrothermal microactuator

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MicroElectroMechanical Systems (MEMS) have attracted considerable attention in the last few decades. Microactuators constitute a significant portion of MEMS devices. They can be operated based on various actuation schemes such as piezoelectric, electrostatic, magnetic, pneumatic and electrothermal actuation. Electrothermal actuation is commonly preferred because of its low operation voltage, high repeatability and ease-of-fabrication. However, the majority of the microactuators are restricted to move either horizontally or perpendicularly and thus only have a 1-DOF (degree-of-freedom) motion capability. Hence, there is a need to design microactuators that can perform multidimensional motions for improved dexterity on applications such as for example micromanipulators for biomedical applications.

This paper presents the modeling and simulation of a new 2-DOF electrothermal bidirectional microactuator. The actuator can be moved in four directions along its two axes from its rest position, hence achieving a 2-DOF bidirectional motion. By tailoring the geometrical parameters of the design, the in-plane and out-of-plane motions can be decoupled, resulting in enhanced mobility in both directions. The modeling of this novel microactuator is completed in two steps. First, an electrothermal analysis is performed to determine the temperature distribution along the actuator arms as a function of the input electric potential. The

electrothermal analysis is followed by a thermomechanical analysis which determines the thermal expansion of each individual actuator arms and calculates the deflection at the tip using the principle of virtual work together with Castigliano's theorem. The simulations of the 2-DOF microactuator were performed using ANSYS®. It should be noted that all complex heat transfer mechanisms were taken into account through the simulations. Various simulations were performed for actuators designed with different dimensions and very good agreement with the analytical model was found. It was observed that the deflection at the tip increases non-linearly with increasing input voltages. For instance, it was calculated that for an input voltage of 8 V, deflections of approximately 6 microns and 2 microns can be achieved for the out-of-plane and the in-plane deflection, respectively. The smaller in-plane deflection is due to the less compliant nature of the actuator during the horizontal actuation. In addition, due to the bidirectional motion of the microactuator, the ranges of operation calculated for the vertical and horizontal motion are quite high (i.e. 12 microns and 4 microns respectively), which are comparable with the deflections achieved by state-of-the-art 1-DOF electrothermal actuators. The first prototypes have been fabricated at MEMSCAP using PolyMUMPs® (Polysilicon Multi-user MEMS Process) run 78, demonstrating the compatibility of the actuators with conventional MEMS processing techniques. The experimental verification of the model is underway and the results will be included in the final manuscript. Due to its higher range of operation and ease of fabrication, this novel microactuator foresees a wide variety of applications.

6926-48, Session 1

Finite element analysis of a 3-dimensional acoustic wave correlator response for variable acoustic modes

A. C. Tikka, S. F. Al-Sarawi, D. Abbott, The Univ. of Adelaide (Australia)

Complex signal processing functions can be performed by acoustic wave correlators, with simple structures, through the variation of electrode patterns. Therefore, these devices can be used as wirelessly interrogatable and completely passive devices in hostile environments that can power wireless sensors and actuators in a secure manner.

Manufacturing a correlator to specifically realise a specific configuration is both expensive and time consuming. On the other hand, numerical simulations of Surface Acoustic Wave (SAW) correlator was previously limited to delta function and equivalent circuit models. These models do not replicate the actual behaviour of the device. With the continuous improvement in computing capacity, switching to finite element modelling (FEM) would be more appropriate, where the complete set of partial differential equations is resolved. In this paper a novel way of modelling a 3-Dimensional acoustic wave correlator using finite element analysis is presented. This modelling approach allows the consideration of different code implementation and device structures. In this paper we present simulation results for Barker sequence encoded acoustic wave correlator. The device response for various surface, bulk and leaky modes determined by the excitation frequency will be presented. Moreover, the ways in which the gain of the correlator can be optimised through variation of design parameters will also be outlined.

6926-06, Session 2

Precision displacement control of a piezoelectric flextensional actuator

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Precision position control is a demanding field with many applications including vibration control, machine tooling, and optical alignment to name a few. Smart material actuators are quickly dominating these strenuous applications. Piezoelectric stack actuators, or piezostacks, have been found very suitable as they offer high stiffness, high bandwidth, and nanometer resolution that are tantamount in precision positioning applications. If, however, a larger amount of displacement is required, piezostacks may lack the ability to meet the application needs. A flextensional actuator driven by a piezostack is a viable alternative to the piezostack alone. It possesses the desired qualities of the piezostack but offers increased displacement.

Controlling such a device begins with modeling the open-loop system, or the plant. Several options exist for constructing a dynamic model suitable for control purposes. Of all of the options available, as many have been tried, and some degree of success has been had with each. There are two major avenues that can be traveled to arrive at a dynamic plant model. One is analytical in nature being derived from basic laws of physics. The other is fitting a model to experimental data via a system identification algorithm. With either, the model may be linear or nonlinear. One intention of the research presented here is to address the issue of which modeling technique is best suited to a flextensional actuator and to what degree accounting for or neglecting the nonlinearity affects the model accuracy.

Regarding analytical modeling, IEEE published a set of linear, constitutive relations describing piezoelectric behavior. This set of relations is generally accepted and serves as the basis for most piezoelectric actuator models in use. Since then several models have been put forth that aim to include the piezoelectric nonlinearities in order to compensate for them. With respect to system identification modeling, any model developed will be specific to the particular device at hand as the model is derived from experimental input/output data. After adapting models of the aforementioned types to a piezoelectric, flextensional actuator, the models are compared to determine which best represents the actuator behavior.

After arriving at a sufficient open-loop plant model, a controller is devised based on said model with the intention of commanding the device to track a desired displacement trajectory. The controller must be such that the closed-loop system possesses desired traits (damping, rise time, settling time, etc.). Such traits are typically application specific, so in this case a set of values for these traits are arbitrarily chosen based on what is generally accepted for automatic control systems. As many different control structures exist, this detail is dealt with in the same manner as selecting which open-loop model to use. When the controller is deemed suitable based on simulation, it is taken online with the real actuator to assess the ability of the actual closed-loop, hysteretic system to track a reference displacement signal.

6926-07, Session 2

Advanced control algorithms for a SDOF piezoelectric nano-positioning stage

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Nano-Positioning devices such as translation stages have found applications in ultra-high precision manufacturing, biomedical research, scanning tunneling microscopes, atomic force microscopes, and many other research and development areas. Piezoelectric materials, which produce a strain under the influence of an external electric field, have become elementary components for these nano-positioning devices due to their high-frequency response and almost infinite resolution. Conventionally, translation stages couple a piezoelectric actuator with a linear system controller to achieve sub-nanometer resolution.

Piezoceramics, however, exhibit a complex and strongly non-linear behavior, including hysteresis, rate-dependence, temperature dependence, and creep. The non-linear behavior is amplified with higher electric fields or higher stresses, thus limiting the device operation under conventional linear control to the short stroke and low frequency regime. In order to make efficient use of the actuator, one has to incorporate the non-linear, hysteretic behavior of the actuator into the control algorithm via a model. One method that has been suggested in the literature is known as inverse compensator method, see e.g. [1], [2], which couples a non-linear hysteresis model with a feedback controller. The models used for this approach commonly use rate-independent mathematical descriptions of the hysteresis such as variants of the Preisach model and focus on stability rather than optimality. When operating at higher frequencies, however, the strongly rate-dependent behavior of piezoelectric materials has to be accounted for if the controller is to be presented with an accurate model of the actuator.

The rate-dependent hysteretic behavior is known to be due to domain switching processes in the material. This paper presents a model-based controller capable of compensating for the hysteretic behavior along with the frequency-dependence present in these materials. The controller uses a free energy model, first proposed by Smith and Seelecke [3], which is based on the theory of thermal activation for single crystal piezoceramics. The model couples mechanical stress and electric field and is capable

of representing the rate-dependent kinetics of the switching processes. This piezoelectric actuator model is then coupled with a SDOF model of a Mad City Labs Nano-OP 30 translation stage. The model is validated by experiments conducted on the stage and the results are used for comparison with model simulations. The model also features a convenient mathematical structure, given by a system of ODEs in time, allowing it to be easily integrated into a variety of control schemes.

For feed-forward control, the model is implemented into the optimal control package NUDOCCCS developed by Büskens [4]. The model's ODE system is integrated by an implicit Runge-Kutta scheme (RADAU Ila) using the efficient and robust RADAU5. NUDOCCCS then solves the resulting NLP problem with a sequential quadratic programming method. The optimal control scheme not only compensates for the non-linear and hysteretic material behavior, but also allows optimality criteria like speed of adjustment to be taken into account. Furthermore, a real-time capable version of the optimal controller is developed for the nano-positioning stage designed by Mad City Labs mentioned above. It is based on the parametric sensitivity analysis of nonlinear programming problems originally developed by the authors for shape memory alloys [5]. The real-time controller is ultimately coupled with feedback for improved performance. The efficiency of this type of stage controller will allow it to track arbitrary set point functions at high frequencies and will not be limited to harmonic set points, enabling technologies like, e.g., 3-D force microscopy.

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6926-08, Session 2

Modeling and control of piezoelectric stack actuator using a weighted directed graph

W. S. Galinaitis, Rose-Hulman Institute of Technology

A directed graph is used to model rate independent hysteresis for an actuator with a bounded input $u(t)$ that attains only n distinct levels $\{u_{\min} = u_1 < u_2, \dots, u_{n-1} < u_n = u_{\max}\}$ between a minimum input u_{\min} and maximum input u_{\max} . It is proven that this discrete model fulfills the basic properties of rate independent hysteresis model. It is then shown that a control input u^* exists that minimizes the positioning error induced by hysteresis, and a method for determination of this minimizing control is provided. The veracity of this approach is demonstrated through simulation, and experimentally by controlling a piezoelectric stack actuator in real time.

6926-09, Session 2

Switching sliding mode control for a membrane strip with MFC actuators

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A switching sliding mode controller for the static shape control of a membrane strip is considered. The membrane strip is augmented with two macro fiber composite (MFC) bimorphs. The combined structure is modeled as an Euler-Bernoulli beam under tensile load. The two bimorphs are actuated independently. One bimorph operates in bending, whereas the other bimorph operates in tension. The presence of the later causes the system to be nonlinear, hence the use of the sliding mode technique, and gives rise to a structural singularity. To evade this problem, a switching command is introduced. Hence, the closed loop system utilizes a hybrid

control law, which can cause stability problems. Fortunately, the same Lyapunov function can be used to analyze the stability of the switched system. Consequently, the switching is safe, and asymptotic stability is guaranteed. Simulation results are presented to demonstrate the efficacy of the control law.

6926-11, Session 3

Digital signal processing for an adaptive phase-locked loop controller on a FPGA-based platform

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Piezoelectric transducers are often used as ultrasonic actuators. To gain the highest possible vibration amplitude, most often these actuators are driven in their resonant frequency. Depending on the application these actuators can be grouped roughly in three main categories, weak damped systems, medium damped systems and strong damped systems. Ultrasonic cleaning applications, piezoelectric ultrasonic motors, and powder atomization are some of the various application examples of these categories, respectively.

All these systems have in common that the driving frequency should be - as the definition says - as close as possible to the actual resonance frequency of the system. Furthermore, all these systems do change their resonance frequency during operation. From the control point of view the main difference in these systems is the necessary accuracy of the driving frequency, where in weak damped systems the resonance can be seen as a sharp peak in the admittance diagram, it appears in the strong damped system as smooth round hill. Therefore, a small error in the driving frequency causes a considerable loss in efficiency in the weaker damped systems; a similar error in the driving frequency would nearly not affect the efficiency of the strong damped system. Many common used control algorithms rely on the relationship between the phase zero line crossing and the resonance peak, which can only be used for the weak and medium damped systems. An increasing damping drifts these two frequencies (electrical resonance and phase zero) apart. Further, the increasing damping reduces the phase drop, which causes a loss of the phase zero crossing for high damped systems.

In practice, mostly application-specific driving circuits are used to satisfy the differed needs, which is the best way to optimize resource-utilization for commercial products sold in high numbers. For the use in the laboratory or in products with low quantities a universal systems for driving any kind of resonant piezoelectric actuator is preferred. Therefore, a standalone FPGA-based control platform is developed at the Heinz Nixdorf Institute. This platform allows a high speed data acquisition and data processing for controlling resonant actuators with a driving frequency in the range from 18 kHz to 100 kHz. An FPGA-base solution enables the implementation of application-specific controllers, which can be adjusted for different kinds of piezoelectric transducers, without losing performance, by reconfiguring the FPGA.

The used controller is an adaptive phase-locked loop (APPL) algorithm. While most types of PLL controllers rely on the phase zero crossing for driving the actuator in resonance, the APPL can estimate the mechanical (v/u) phase behavior, which always has a phase zero crossing, to control on it. To measure the amplitude of voltage and current, and the phase between these two signals an FFT algorithm is utilized.

This paper concentrates on the digital signal acquisition, and processing. Further, the implantation of the control algorithm on the FPGA-based platform is described in detail.

6926-12, Session 3

Cooperative behavior of mobile robots as a macro-scale analogous of the quantum harmonic oscillator

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This paper studies a model of cooperative behavior in a multi-robot system that consists of N mobile robots. It is assumed that the robots correspond to diffusing particles, and interact to each other as the theory of Brownian motion predicts. Brownian motion is the analogous of

the quantum harmonic oscillator (Q.H.O.), i.e. of Schrödinger's equation under harmonic (parabolic) potential. However, the analytical or numerical solution of Schrodinger's equation, is computationally intensive, since for different values of the potential $V(x)$ it is required to calculate the modes $\psi_k(x)$ in which the particle's wave-function $\psi(x)$ is decomposed. Moreover, the solution of Schrodinger's equation contains non-easily interpretable terms such as the complex number probability amplitudes which are associated with the modes $\psi_k(x)$, or the path integrals that constitute the particle's trajectory. On the other hand, instead of trying to solve Schrodinger's equation for various types of $V(x)$ one can study the time evolution of the particles through an equivalent diffusion equation, assuming probability density function depending on Q.H.O's ground state, i.e. $\rho_0(x) = |\psi_0(x)|^2$. Each diffusing particle (mobile robot) is subject to the following forces: (i) a spring force (drift) which is the result of the harmonic potential and tries to drive the particle to an equilibrium and (ii) a random force (noise) which is the result of the interaction with neighboring particles (robots or obstacles in the motion plane). This interaction can be in the form of collisions or repulsive forces. It is shown that the diffusive motion of the stochastic particles (kinematic model of the robot) can be described by Langevin's equation which is a stochastic linear differential equation. Following the analysis it is proved that Langevin's equation is a generalization of the conventional gradient algorithms. Therefore the kinematic models of mobile robots which follow conventional gradient algorithms can be considered as a subcase of the kinematic models which are derived from the diffusion analogous of the Q.H.O model. The structure of the paper is as follows: In Section 2, an analysis of the diffusive motion of particles is given and Brownian motion is explained. In Section 3 the background that relates Schrödinger's equation with diffusive motion is analyzed. It is shown that Schrödinger's equation with harmonic potential is equivalent to a stationary diffusion equation with drift. The time-dependent solution of the quantum harmonic oscillator model is obtained through the study of a diffusion process. In section 4, mobile robots self-assembly based on the motion of interacting diffusing particles, is proposed. The position of the mobile robots corresponds to the positions of the particles, while their displacement in a 2D motion plane corresponds to the motion of each particle. The kinematics of the particles is described by Langevin's stochastic differential equation which is shown to be a generalization of conventional gradient algorithms. Moreover, stability analysis is performed to demonstrate that the robots (particles) converge to an equilibrium (attractor). In Section 5, simulation experiments are performed. First, it is demonstrated how the particles (mobile robots) converge to an equilibrium under the drift term that is imposed by a harmonic potential and a random term imposed by the interaction with neighboring particles (robots). Finally, in Section 6, concluding remarks are stated.

6926-13, Session 3

Force control of a shape-memory alloy wire using fuzzy controller

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Shape Memory Alloys (SMAs) are a group of metallic materials that exhibit shape memory effect which occurs through a solid-state temperature and stress dependent shift in their crystalline structure between two different phases. At higher temperatures, the material is in the austenite phase and is relatively hard. As the temperature is lowered, the material changes to the martensite phase which is relatively soft. This unusual characteristic of SMA actuators has a wide variety of applications in control and actuation systems.

Currently, substantial attention is given to micro-grippers that use SMAs in particular SMA wire as a means of actuation. One of the most significant problems to develop such grippers is controlling the force induced in the SMA wire. The hysteresis associated with SMAs makes the development of a mathematical or numerical model as well as designing a tracking controller for SMA materials and actuators a challenging task.

In this paper, an experimental setup including a Nickel-Titanium (NiTi) SMA wire, a load-cell sensor, data acquisition terminal, a power amplifier and computer for recording data is designed and fabricated to measure and control the induced force in an SMA wire. The SMA wire specifications are as 0.1mm diameter, 32cm length, and 37.8 ohm electrical resistance. By Calibration, relation between voltage and force of the load-cell is obtained. When heated, due to transformation from martensite to austenite phase,

the SMA wire tends to be shortened, but because it is clamped at two ends, a tension force is induced in it. By cooling the SMA, it returns to the martensite phase and so the induced force is released.

Using Matlab xPC target toolbox and D/A data acquisition terminal, different pulse inputs are applied to the SMA wire and the response is recorded. The raw signal from the load cell consists of significant noise component. In order to remove the noise, a low pass digital filter is designed to filter the output force signal of the data collected.

Using autoregressive model with exogenous input (ARX) method for system identification of the experimental data, two appropriate transfer functions of the induced force in the SMA wire versus the applied voltage during heating and cooling processes are derived. The model selected for heating and cooling are arx331 (for heating) and arx310 (for cooling).

Afterwards, a conventional PID controller and a self-tuning fuzzy PID controller are designed to control the force in the SMA wire. The self-tuning fuzzy PID control algorithm is implemented by tuning the parameters of the PID controller, thereby integrating fuzzy inference and producing a fuzzy adaptive PID controller, which is used to improve the force control performance.

Finally, the responses of the system with both controllers for different step, multi-step and sine inputs are simulated and compared.

Results show that in the force control of the SMA wire, the self-tuning fuzzy PID controller is more efficient than the conventional PID controller. The results achieved in this study can be used as fundamental and guidelines for force control of a gripper actuated by SMA wires.

6926-14, Session 3

Fuzzy control of flexible structure using piezoelements

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The usage of smart material in vibration suppression of structures is gaining popularity fast. An example of such material is the piezoelectric actuators whose functionality rests on their high compatibility with structures, low weight, rapid reaction, broad bandwidth, and desired force and displacement output. In this paper the vibration suppression of a flexible structure using fuzzy controller with bonded piezoelements was investigated. The system considered in this paper was an aluminum cantilever beam which is fabricated at the Advanced Dynamic and Control Systems lab (ADCSL). On either end of the beam one patch of piezoelectric was attached. One piezoelectric was used as an actuator and the other one as a sensor. The ANSYS software was employed for the FE modeling of the beam. A modal analysis was done on the model and the three first modes with natural frequencies of 7.5388HZ, 45.957HZ, and 125.46HZ were obtained respectively. A harmonic analysis was performed on the smart beam with a frequency range of 0-60 HZ and 0.5 Hz step sizes. A polynomial of order 9 was found as proper fit to frequency response. The accuracy of the model has to be evaluated, thus an experiment was conducted. A chirp signal of 60 volts was applied to the piezoelectric actuator and the first two natural frequencies of the smart beam from experimental, FE model were compared and the error calculated for first and second natural frequencies are .81% and 6% respectively.

A fuzzy control system is then designed and implemented for vibration suppression of the smart beam. This proposed controller has been developed to minimize first and second resonant responses by increasing the damping of the structure. In this manner, it is a resonant fuzzy logic controller (RFLC). For this purpose, the vibration controller is examined for three excitations: impulse, dwell around first natural frequency and dwell around the second natural frequency. The root-mean-square (RMS) output voltage under open-loop, PD-controlled and fuzzy vibration controller were calculated for the three excitations and The results show that the fuzzy controller reduces the magnitude of the first mode under impulse excitation, by 38% compared with the open-loop system. Also it is observed that the fuzzy controller, developed in this research, reduces the displacement due to vibration of an open loop system by 82%. The PD control controller only controls the vibration up to the 75%. A fuzzy controller yields a more significant improvement in displacement reduction over that obtained by PD controller.

6926-15, Session 4

Contact-aided compliant mechanisms for morphing aircraft skin

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While there are numerous concepts for morphing aircraft skins, most of these require many actuators, adding to the structural weight. Recently much attention has been given to sandwich panels with cellular mechanisms as a core for a morphing skin. Because of low in-plane stiffness and relatively high out-of-plane stiffness these structures are advantageous for such morphing applications.

Honeycombs designed for a specific required global strain do not yield the same strain when subjected to aerodynamic loads. A contact mechanism is presented to alleviate stresses so that the required global strain can still be obtained in presence of aerodynamic loads. A 1 lb. aircraft is considered for the initial analysis. The half-span of the wing is divided into number of cells consisting of contact mechanism. The aerodynamic loads are applied and the number of connection points over span direction and chord direction where skin is attached to the underlying morphing mechanism is determined by keeping the maximum out-of-plane deformation below a threshold value. The rectangular portion of the skin between four adjacent connection points defines a skin element. The in-plane and out-of-plane bending moments and shear forces along the edges of a skin element are then found. Kinematic equations are formed relating the geometry of the contact mechanism to the overall span and chord length of the wing. The mechanism is designed so that the maximum stresses are below the allowable stresses with aerodynamic loads. The design is further verified by putting the skin elements into the half-span of the wing and finding the maximum out-of-plane displacement and the reaction forces and moments for the skin element. The above procedure is repeated if necessary.

The mass, maximum stress and global strain are compared to those for honeycomb cells. The maximum stresses in the core are under allowable stresses for contact-aided mechanisms while those for honeycombs are not when subjected to aerodynamic loads. Global strains as high as 100% can be achieved using this approach. Different material models such as linearly elastic, multi-linear elastic and super-elastic are analyzed and their results are compared. The approach used here can readily be extended for larger aircraft.

6926-16, Session 4

Adaptive PI control of a smart projectile fin

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The objective of this paper is to develop an adaptive PI control for the control of the rotation angle of a smart projectile fin. The hollow projectile smart fin is actuated using a cantilevered piezoelectric bimorph that is completely enclosed within the fin. A linear model of the actuator and fin is identified experimentally by exciting the system using a chirp signal. The rotation angle of the fin is controlled by deforming the piezoelectric bimorph which is hinged at the tip of the fin. A linear combination of the fin angle and rate of fin angle is chosen as the controlled output variable and an adaptive control system is designed for the control of the fin angle and disturbance rejection. In the closed loop system, all the signals are bounded and fin angle tracks the desired trajectory. Simulation results are presented along with the experimental validation using the subsonic wind tunnel at the University of Nevada, Las Vegas (UNLV). Both simulation and experimental results show that in the closed-loop system, the fin angle is precisely controlled in spite of uncertainties in the identified model and the aerodynamic moment induced by the wind.

6926-17, Session 4

An application of D-FSMC in speediness track telescope direct drive system

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Speediness track telescope mostly track and observe near spherical object, the characteristic are large inertia, strong wind interferer; it requests high speed and high precision. This paper designs a kind of D-FSMC

(Distance-Fuzzy Sliding Mode Control) for speediness track telescope direct drive system. The track peculiarity of BLDCM used in executive part changes while motor parameter or motor load or input signal changes, traditional PID control method can not fits this motor system very well. The outstanding strongpoint of sliding mode control is that the sliding mode can achieve independent of disturbance and parameter change completely. But a disadvantage --high frequency vibration come forth in switch control as well. So this paper combines sliding mode control and fuzzy control. A SMC output an equivalent control to keep the system statements on the sliding surface; a FC makes a real-time tune to the direction and amplitude of switch control. It uses a method based on distance to form a one dimension fuzzy rule instead of traditional tow dimension fuzzy rule, increases compute speeds. Finally, the D-FSMC softens the control signal, accordingly abates or avoids the vibration of general sliding mode control. The arithmetic is firstly validated in MATLAB. The preliminary simulation result show that the project used in the speediness track telescope direct drive system increases the precision, robust and speediness tracking properties which meet the demand for this system use.

6926-18, Session 5

Adaptive control of hysteresis in smart materials

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Smart materials display coupling of elastomechanics with electromagnetic/thermal influences. Hence these materials have built-in sensing/actuation mechanisms. However, the hysteresis widely existing in smart materials presents a challenge in control of these actuators/sensors. Inverse compensation is a fundamental approach in coping with hysteresis, where one aims to cancel out the hysteresis effect by constructing a right inverse of the hysteresis. The performance of the inverse compensation is susceptible to model uncertainties and to error introduced by inexact inverse algorithm. We develop a mathematical model for describing hysteresis precisely.

On the basis of the hysteresis model, an robust adaptive inverse control approach is presented, for reducing hysteresis. The asymptotic tracking property of the adaptive inverse control algorithm is proved, and the issue of parameters convergence is discussed in terms of the reference trajectory, sufficient conditions under which parameter estimates converge to their true values are derived. Extensive simulations are used to examine the effectiveness of the proposed approach.

6926-19, Session 5

ANFIS-based modeling and inverse control of a thin SMA wire

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The development of modeling and control techniques to compensate effects of unknown hysteresis using parametric and nonparametric models has been studied extensively.

The Preisach model is a well-known approach to model the hysteretic effect. Although being a good generic model, the model parameters are relatively difficult to compute. Several attempts have been made recently to use Neural-Network (NN) based modeling of hysteresis via different network structures. Improving the generalization property of a model for different cases should be solved using appropriate parameters or combining different models. There are also attempts in the literature using different NN structures for modeling the ascending and descending branches of the hysteretic curve to improve the model representing the behavior of hysteresis.

In our work we propose an ANFIS based modeling of the hysteretic effect. By using a hybrid learning procedure ANFIS architectures are powerful tools for many applications, such as identifying nonlinear parameters in a controlled system, predicting chaotic time series and modeling nonlinear functions. Hybrid learning procedure uses both Gradient Descent and Least Squares algorithms. By using a hybrid learning procedure, ANFIS can construct an input-output mapping based on both if-then rules and input-output data pairs.

A test setup has been built to gather data and implement the controller for the SMA wire. The tested wire has 0.001 inch diameter and 5.5 inch

length. The test setup includes a laser displacement sensor, a two disk structure connected with a soft spring to be actuated by SMA wire and a D-Space system to collect sensory data and send control signals.

In the modeling part of our work, we used a Takagi-Sugeno type ANFIS structure. Using only two inputs with 5 membership functions yields remarkable results. For testing the generalization capability of our model we made it predict a hysteresis loop in a different frequency which is not directly included in the input-output data. Results are quite good and the resulting error is $RMSE=0.0043$. Comparisons are made using iterative multiple step prediction.

In the control part, for compensating the hysteretic effect, we used an inverse ANFIS model and used it directly as a controller. After dramatically reducing the hysteretic effect, we implemented a PI control to fine tune the response. This methodology yield quite good results where the maximum tracking error is 0.004 mm for a sinusoidal reference trajectory of 3mm in amplitude. Finally the compensation results in an approximately linear input-output relationship.

6926-20, Session 5

Memory-based hysteresis compensation and nonlinear modeling of galfenol-driven micropositioning actuators

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Galfenol (Fe-Ga) is a relatively new active material which exhibits moderate magnetostriction, and unique metallurgical and mechanical properties including ductility and high strength. However, the presence of large butterfly-like nonlinearity and moderate magnetomechanical hysteresis can complicate its practical implementation in high-performance smart system design. A memory-based hysteresis modeling framework is presented for accurate description of butterfly hysteresis nonlinearity in the response of Galfenol-driven micro-positioning actuators to applied currents. The model is based on three important properties known as targeting turning points, curve alignment and the wiping-out which have been recently established for piezoelectric materials. In short, the hysteresis trajectory targets the closest recorded turning point, aligns to the broken trajectory at this point, and continues its path towards the next set of recorded turning points. Once the direction of input changes, a new turning point is recorded; once a turning point is surpassed, it is no longer useful for the prediction of the response and is thus wiped out.

To describe the nonlinear hysteretic behavior of the actuator, the model initially separates the nonlinearity of the response from the hysteresis loop and approximates it with a piecewise continuously differentiable, monotonically increasing exponential function. The approximate function is then utilized in a nonlinear mapping technique where it is mapped between consequent turning points recorded in the model memory unit. This mapping uses two constant shaping parameters for the ascending and two for the descending trajectories. Curve alignment and targeting the previously recorded turning points are satisfied by the mapping method, while a memory organizer is utilized in the model to wipe-out the surpassed turning points from the memory unit, evacuating it for new turning points. To assess the performance of the proposed model, a Galfenol-driven micro-positioning actuator is utilized for experimental verification. The results indicate that the model is able to precisely predict the response of the actuator for its full-range motion including both major and minor hysteresis loops. The maximum error percentage and the average error between the experiment and the model for a 120 μm stroke are 1.5431% and 0.4364 μm , respectively. With using only 14 coefficients, the proposed framework not only offers a precise model, but also a computationally efficient algorithm to capture the butterfly hysteresis response of Galfenol-driven actuator.

6926-21, Session 5

Nonlinear adaptive control of dynamic systems driven by shape memory alloy (SMA) actuators

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Composite systems with imbedded smart material components are

expected to have attractive health monitoring features such as self-diagnosis, damage avoidance, and even auto-repair. They also have the capability to update their residual life expectation to avoid "high risk" behavior and accidents. Evidently, automatic control theory plays a crucial role in these structural systems. In this work a structure similar to a cantilever beam embedded with a bulk material having "smart" properties is considered.

Embedded distributed sensors in conjunction with embedded distributed actuators are used in the structure to achieve both internal sensing and motion control tasks. The distributed "actuators" whether current, voltage and/or applied magnetic field driven are utilized to control the properties of the structure so as to control or suppress the vibrations. By this, the spillover phenomena associated with a "truncated" model due to neglected modes can be minimized.

It should be noted that such a structural system for use under severe environmental conditions is susceptible to element/component failure during operation, and how to adapt to unexpected faults becomes an interesting and challenging research topic.

This work concerns the development and analysis of nonlinear adaptive based control algorithms for composite structures/systems embedded with Shape Memory Alloy (SMA) actuators, and a mathematical model characterizing the motion of such composite systems is established. By using Lyapunov stability theory, algorithms for vibration damping via controlling the voltage of the SMA actuators are derived. It is shown that with the proposed strategy both the magnitude and frequency of vibrating can be effectively suppressed. The novelty of the proposed approach also lies in the fact that it is fairly easy to model and the computation involved is much less as compared with other strategies. An example is used to verify the validity of the proposed approach.

6926-22, Session 6

Uncertainty representation and propagation in multiscale finite element simulations of local mechanical behavior in damaged metallic structures

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Prediction of scatter on the mechanical behavior of metallic materials due to microstructural heterogeneity is quite important in a variety of scientific and technological applications. This is particularly the case for damaged metallic structures, where degradation mechanisms such as fatigue can be very sensitive to the details of the microstructure and its variability, which is also a contributing factor on the well-known scatter observed in the fatigue response of metallic materials. Two-dimensional (2-D) and Three-dimensional (3D) representations of microstructures of 2xxx Al alloys are created via a combination of dual-scale serial sectioning techniques, with a smaller scale for particles and a larger scale for grains, and available volume reconstruction software. In addition, "artificial" representations of the grains are also built from Electron Backscattering Diffraction (EBSD) measurements of the crystallography and the geometry of the grains in representative cross sections of the samples. These approaches are, in turn, used to define whether or not a length scale can be found for an appropriate Representative Volume Element (RVE) that has statistical and mechanical properties that are comparable to those in larger length scales, via simulations performed using finite element models of the RVE.

The use of finite element models will also allow studying the effects of constitutive behavior, e.g., elastic and plastic anisotropy, progressive damage, in the length scales used to define the RVE and also in the propagation of uncertainty across different length scales via multiscale approaches. In one approach, stochastic homogenization methodologies are used to propagate the uncertainty from the micro- to the meso-scale based on the 2-D and 3-D reconstructions via multiscale Green's functions and stochastic expansions based on the results from the finite element models.

In another approach, the basic characteristics of the RVE will be varied, by introducing changes on either geometry, material properties or both and also by "seeding" defects that represent possible damage mechanisms (microcracks, pores). Then, the finite element engine will be used to

“sample” the different stiffness matrices resulting from the variability in the RVE. Appropriate bounds or limits on these stiffness matrices will be discussed based on the physical mechanisms controlling the mechanical behavior and damage accumulation and on the results from the simulations. In addition, possible probability density function for these matrices will be discussed as well, so that they can be sampled without having to perform full-scale computer simulations.

Methodologies will be discussed for using the sampled matrices for simulations at larger length scales at much lower computational expense, while still representing the variability produced by the heterogeneity of the microstructure. The final version of the paper will describe examples of the microstructure reconstruction procedures for the 2-D and 3-D cases, the dual serial sectioning methodology to sample complex microstructures, i.e., grains and precipitates, the formulation of 2-D RVE's and the sampling of the stiffness matrices for that case with induced defects and microstructural variability.

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6926-23, Session 6

Stochastic crack growth modeling under spectrum loading for health monitoring and prognosis

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Failure prognostics and risk analysis facilitate maintenance scheduling and operation planning of aging aircraft structural components. Decision tools for failure prognostics must have the capability of incorporating the dynamic behavior of material damage under both normal and off-normal operating conditions. This paper models a stochastic measure of fatigue crack damage in ductile alloys under center wing type spectrum load. The center wing type loading spectrum has four to five short span lower load ratio over loads to depict the off-normal operating condition. The non-stationary probability distribution (PDF) function of the damage estimate will be generated by numerically solving stochastic differential equations in the Wiener integral or Ito integral setting. On the other hand, the median crack growth curves representing the damage measure will be found using a hybrid physics and data driven crack growth model.

For statistical variation in data, compact tension (CT) samples with the following nominal dimensions are tested: thickness of 6.31mm, width of 25.4 mm (from the center of the pin hole to the edge of the specimen) and an initial notch length of 6.5 mm. To simulate real flight conditions a typical center wing load spectrum is programmed into the digital controller of the load frame. A total of 32 CT samples subject to the spectrum load will be tested to generate the dataset. From each test, approximately 40 observations will be made leading to approximately 1280 data points. The final paper will present a probabilistic prognosis model for 2024 Al alloy, which is an integral part of our multidisciplinary structural health monitoring framework.

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6926-24, Session 6

Physics-based modeling for time-frequency damage classification

D. Chakraborty, S. O. Soni, J. Wei, N. Kovvali, A. Papandreou-Suppappola, D. Cochran, A. Chattopadhyay, Arizona State Univ.

We use the finite element package ABAQUS to simulate a lug joint sample with different crack lengths and piezoelectric sensor signals. A mesoscale internal state variable damage model defines the progressive damage and is incorporated in the macroscale model. We furthermore plan to use a hybrid method (Boundary element-finite element method) for the purpose of modeling wave reflection and mode conversion of the Lamb wave from the free edges and scattering from the internal defects. The hybrid method

reduces the size of the problem and gives better performance in the analysis of high stress gradient problems.

We describe a damage classification scheme which integrates the physics based modeling with sensing and signal processing. The approach utilizes data computed numerically from the models for learning the parameters of the time-frequency damage classification algorithm. Since the procedure does not require (slow, error-prone, and expensive) collection of data from real experiments but instead relies on efficiently simulated data for training the classifier, this leads to significant savings in design time, complexity and costs. The models capture the essence of the damage wave-physics, and the classifier is naturally more robust to system variability such as sample and sensor variation, the effects of which are often difficult to isolate in experiments. Results are presented from an application to the classification of fatigue-induced material damage in a lug-joint, demonstrating the utility of the proposed approach.

6926-25, Session 6

Sensor fusion and damage classification in composite structures

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The ability to detect and classify damage in complex materials and structures such as composites is crucial both from safety and economical perspectives in aerospace industry. However, many existing techniques dealing with these problems have some practical issues mainly because they fail to consider any uncertainty inherent in the actual material and structural characterization progress. In this context, stochastic approaches have been applied as they aspire to capture the statistical properties characterizing the underlying physical process, accounting for uncertainties and thereby achieving robustness to variance in materials and structural geometry. It also facilitates the integration of both available and unavailable information in a consistent and effective manner.

In this paper we describe a statistical method for the classification of damage in complex structures. Our approach is based on using hidden Markov models (HMMs) to model the time-frequency features extracted from the data. Unlike conventional deterministic methods, the HMM is a stochastic approach which better accounts for the uncertainties encountered in structural damage detection and classification tasks. For the construction of the HMMs, we utilize simulated data generated by finite element (FE) modeling instead of experimentally collected data. Among other things, this is advantageous in situations when enough experimental data is not available for training the classifiers. The model fitting step is followed by a validation step that employs a portion of the experimentally collected data to ensure that the models are matched to the experimental scenario. Once built and verified, the HMMs are integrated efficiently into a Bayesian framework for damage classification.

For each received damage signal, feature extraction is performed using an effective matching pursuit decomposition (MPD) method with Gabor atoms. The HMM defines its underlying states as the number of stationary regions where the associated observation features change very slowly. The inter-state transitions are modeled through a Markov random process, while in-state features are modeled with discrete and continuous observation densities, indicating in this study the use of both discrete and continuous HMMs.

The proposed approach is applied for the classification and localization of delamination in a composite plate. A sensor fusion procedure is also implemented that combines information from all distributed sensors to boost overall classification performance. Results using both discrete and continuous observation density HMMs, together with sensor fusion, are presented and discussed. In addition, due to the dispersive nature of the wave propagation in the composite structure, we plan to study the effect of changing the time-frequency characteristics of the excitation waveform on the classification performance.

6926-26, Session 6

Wave propagation and scattering from damage-induced defects and free edges

S. O. Soni, J. Wei, A. Chattopadhyay, P. Peralta, Arizona State Univ.

Wave Propagation and Scattering from Damage Induced Defects and Free Edges

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When a wave propagates through a damaged medium it gets scattered from internal defects and the free edges. At the free edges, Lamb waves undergo mode transformation upon reflection. It is observed that the reflection of an incident wave becomes close to zero on interaction with other reflected modes over a certain frequency range seen through energy interaction. It increases again beyond this minimum point due to reverse mode conversion.

This paper deals with the study of elastic wave scattering from the free edges and damages present in a complex metallic structure. A mesoscale damage factor is used to define the progressive damage and is incorporated in the macroscale model. A finite element approach is used to model wave reflection and scattering from internal defects and free edges of the complex metallic structure. Further, a hybrid method using boundary element and finite element will be explored to see the improvement in the solutions compared to finite element method alone. The hybrid method works in the following manner: 1) An extended boundary element method will be used to model Lamb wave interaction with the free edges of the metallic specimen and its mode conversion on edge reflection, 2) A finite element approach will be used for lamb wave scattering from the cracks present inside the joint.

Piezoelectrical-mechanical coupling will be used to convert these mechanical displacements due to transient wave propagation into electrical signals. Experiments are carried out on a complex metallic specimen (Lug joint) under fatigue loading. The materials used are Al 2024 and Titanium with PZT sensors and actuators attached on the surface. Sensor readings are taken at different crack lengths. The simulated electrical signals obtained from the model will then be validated against the experimental sensor signal data for different lengths of fatigue crack.

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6926-27, Session 6

Ultrasonic sensing and time-frequency analysis for detecting plastic deformation in an aluminum plate

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We investigate the use of low frequency (10-70 MHz) laser ultrasound for the detection of fatigue damage. While high frequency ultrasonics have been utilized in earlier work, unlike contacting transducers, laser-based techniques allow for simultaneous interrogation of the longitudinal and shear moduli of the fatigued material. The differential attenuation changes with the degree of damage, indicating the presence of plasticity.

In this paper, we extract time-frequency damage features from the ultrasonic data using the matching pursuit decomposition (MPD) algorithm, an algorithm known to be effective for the extraction of specific components of interest in a signal. The features are then processed using a stochastic classification technique known as hidden Markov modeling (HMM). The HMM models the data with a (hidden) Markov random process and inference is performed efficiently in a Bayesian framework. Results are presented for the detection of rolling-induced plastic deformation in a Al-6061 plate.

6926-28, Session 6

Damage detection in bolted joints using hierarchical SVMs

C. K. Coelho, N. Kovvali, A. Papandreou-Suppappola, A. Chattopadhyay, P. Peralta, Arizona State Univ.

Structural health monitoring (SHM) of aerospace components subjected to fatigue loading is an important problem with the current age of a majority of the aircraft in service. This type of automated monitoring is essential especially in hard to access areas. For this reason, damage detection in bolted joints will be the focus of this paper. Bolted joints are used at numerous locations in aerospace systems. In addition to providing alignment and high-pressure gas sealing, aircraft structural joints can operate at high temperatures and may be required to survive very large applied loads resulting from structural failures.

An important characteristic of a bolted joint is that the preload in the bolts varies as a result of changes in the external load (torque) applied to the joint. The magnitude of the preload is also important to prevent slip, separation or fatigue failure of the joint. The required preload is achieved by tightening the nut which creates a strain field between the head and the nut. This strain field can vary with changes in loading environment, causing the bolts to become loose and hasten the growth of fatigue cracks. Experiments are conducted on double lap bolted joints under tension-tension fatigue loading. Preliminary results obtained indicate that crack nucleation and the rate of crack propagation is significantly affected by the torque level in the bolt. Therefore, it is necessary to develop techniques to analyze and detect the initiation and evolution of damage in bolted joints so that appropriate measures can be taken to stop catastrophic failures.

A robust network of piezoelectric (pzt) sensors and actuators will be used to detect the damage due to fatigue. The voltage time history of the sensors will be studied and the damage will be classified using a hierarchical machine learning based approach. This approach is more computationally efficient than most currently used classification schemes that compare a given test signal with every available training set in order to classify the signal. In the hierarchical approach, one or more classifiers are constructed at each level of a category tree and each classifier works as a flat classifier at that level. For example, in a bolted joint the root level of the classifier may decide whether a given sensor signal is healthy or damaged. If the signal indicates damage, the classifier may move into lower level categories that may indicate if the damage is caused by a loose bolt or by a growing crack. The classifier would then reach a final leaf category that could classify the extent of a particular type of damage. In order to do this, the Euclidean distance between damage categories in feature space and their variances will be calculated in order to define appropriate categories and subcategories. Different types of Support Vector Machines (SVMs) algorithms will also be investigated for use at different nodes of the hierarchy.

6926-29, Session 6

Stochastic multiscale model for polycrystal material behavior

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A stochastic model will be described for the coarse scale description of polycrystalline behavior in a manner that simultaneously captures the heterogeneity, the anisotropy, and the specimen variability of polycrystalline material. The model is based on random matrix theory and can be readily implemented into coarse scale computational tools such as ABAQUS.

Specifically, the proposed model develops a probabilistic measure on the elasticity tensor of polycrystalline materials. This probability measure is constructed using the Maximum Entropy principle with suitable constraints that are consistent with gross mechanical behavior of polycrystals. This gross behavior can be either computed via numerical simulations or synthesized through physical experiments. The benefits of the proposed model is that it provides a coarse-scale representation (hence computationally efficient) that is quite faithful to microscale structure and specimen variability. This model is very robust for optimization purposes and for structural health monitoring.

6926-31, Poster Session

Optimization of monitoring parameters of a space tubular structure by using genetic algorithms

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In the last few years both conception and materials have significantly changed in the design of engineering structures. In space structures, for example, metallic components have been intensely replaced by composite and fiber made ones to reduce weight and increase transportation and assembling skills. Impedance-based Structural Health Monitoring is a major concern in this context because different types and categories of damage can affect various areas along the structure. The interpretation of damage signatures is an important challenge to be overcome. As a consequence, erroneous damage identification is quite common. This contribution focuses on damage prediction in a tubular space structure by using a methodology that is able to reduce the possibility of misinterpretation in the monitoring procedure. For this aim, an optimization technique using genetic algorithms is applied to the complete damage signature to determine the best frequency range to be investigated in each problem. Then, a meta-model is built to characterize damage in the structure.

6926-40, Poster Session

A new method to compress a bright object with line property in the high-resolution image

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Pattern recognition technology develops to recognize the object with fast speed. While high resolution imaging device bring us lots of mass data images, sometimes we needn't such mass data to find the object that we are interested in. So to save time, we can compress the original big high resolution image into a small low resolution image and recognize the object in the low resolution image. After we find the object in the small image, we can find the corresponding object in the big image through a certain mapping relation. Image compress technology is very important in the image processing. The most important thing in image compression is to keep the useful information. The general image compress technology contain nearest neighbor extraction, bilinearity extraction, bicubic extraction, etc. the methods present above are designed to adapt the general image and has the satisfaction effect in whole. But in some detail aspects, they will lose many useful information, especially, sometimes they compress a bright line segment to dot-line or others which are far from the real object. This will bring us many difficulties to recognize the real objects, and even we can not recognize them. In this article, we present a new method, i.e. the maximum extraction technology based on the block segmentation, and it solves the problem presented above. At first, we segment the original image to the little segments which have 8i, 8 image elements by sequence. Then we extract the image element with maximum value to represent this block and keep it in a new image that is the new extract image. Because we extract the maximum value of the block, the new extract image looks brighter than the original. To solve the problem, we introduce the grey transform method to depress the brightness of the extract image. Through a lot of experiments, we compare the general three methods with our method, and draw the 3 conclusions. First, our method keeps the bright line property well. Second, the extract image is much more close to the original image than the others. Third, our method will present great use in pattern recognition.

6926-41, Poster Session

Hybrid control and acquisition system for remote control systems for environmental monitoring

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In this paper we describe the architecture and the performances of a hybrid modular acquisition and control system prototype for environmental monitoring and geophysics. The system, an improvement of a VME-UDP/IP based system, is based on a dual-channel 18-bit low noise ADC and a 16-bit DAC module at 1 MHz. The module can be configured as stand-alone or mounted on a motherboard as mezzanine. Both the modules and the motherboard can send/receive the configuration and the acquired/correction data for control through a standard EPP parallel port to a standard PC for the real-time computation. The tests have demonstrated that a distributed control systems based on this architecture exhibit a delay time of less than 25 us on a single channel, that is a sustained sampling frequency of more than 40 kHz. The system is now under extensive test in the remote controls of seismic sensors (to simulate a geophysics networks of sensors) of a large baseline suspended Michelson interferometer.

6926-42, Poster Session

Research of the control strategy of large aperture telescope based on fuzzy direct torque

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Direct torque control (DTC) of permanent magnet synchronous motor applies in telescope direct drive system; it can effectively enhance the larger torque and control precision of large aperture telescope. flux linkage error and torque ripple are caused by variable stator resistance and traditional hysteresis controller at low speed. Since it based on analyzing low-speed performance of direct torque control system, fuzzy controller has been introduced to deal with those problems. It appropriately divides stator resistance, torque error and flux linkage angle into different intervals so as to accurately select voltage vector. Those two kind of fuzzy control algorithm which were stator flux linkage and the torque fuzzy control were comprehensively utilized, so as to causes stator flux linkage path approximate circular, and reduce machine harmonic components and torque ripple, and improve motor steady-state, as well as guarantee torque stable and rapid. In order to simplify fuzzy rule, it carries on the mapping the stator flux linkage angle, reduce control computing time, and accelerate speed of response compared with the traditional direct torque control. The simulation result indicates that fuzzy direct torque control strategy build according to permanent magnetism synchronous motor itself characteristic will available reduced torque and flux linkage ripple, and it has more superior suppression performance to the motor parameter perturbation or/and exterior disturbance.

6926-45, Poster Session

Study of multirobot hybrid control architecture and task allocation

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Multi-robot cooperation is one of hotspots in artificial intelligence and robotics research currently. The research content of multi-robot cooperation consisted of group control structure, modeling and planning, communication and negotiation, perception and learning. Among them, the group control structure is the kernel part in multi-robot system, and the cooperation mechanism of multi-robot system can be reflected by using it. The group control structure decides operation mechanisms of task decomposition, distribution, planning, decision-making in the multi-robot systems and implementation process, it also decides the role of each robot in system. The group control structure affects the efficiency of multi-robot cooperation: high or low. Besides, the group control structure also has acclimatization ability of self organization to the environment. The predecessors had done a lot of work in the field, but most are concentrated in Small-scale multi-robot systems. To solve the problem of task allocation in Medium-scale even Large-scale multi-robot system, hybrid control architecture based on the centralized control structure and the distributed control architecture was been proposed to apply to accomplish multi-robot cooperation in task level. Contract Net Protocol was been used for task allocation. A pyramid-like structure has formed by the entire system with comparison and selection layer to layer. When robot found having no ability to completing the task received, it usually has the task decomposed, and then assigns the tasks to its subordinates

under the action of Contract Net Protocol. The process of task allocation will not end until every decomposed task has been accepted by individual robot. When every single task has been completed by individual robot, the multi-robot system may have completed the whole task. The simulation platform of Multi-robot cooperation movement is player/stage, which is free software in the Player Project of USC (University of Southern California) Robotics Research Lab and enables research in robot and sensor systems. The simulation of multi-robot tracking experiments which red robot followed the blue one, and formation experiments which three robots went to a team showed that the algorithm is effective. In the process of task planning, the granularity size of task decomposition has a direct impact on the efficiency of planning. The size of task decomposition too small, it made the task planning more complex, and it also increased the communication cost of task allocation; and if the size of task decomposition too large, the success rate of task allocation reduced. Therefore the choice of granularity size in task decomposition is a problem which needs full attention in task distribution. In the simulation experiment, to notarize the function of algorithm easily, the communication between each robot in system was presumed having a high reliability. But wireless communications of robots is a very complex issue in research of multi-robot system. Robots in system need to enhance the capabilities of communication. This is the next research needed to enhance the content, NS2 will be introduced to achieve communication of robots in the simulation of multi-robot system.

6926-46, Poster Session

Vibration suppression of beam by using magnet-coil

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Coil inductor has been used widely as an electromagnet, because of the high magnetic field resulting from the voltage applied to the coil. In this study the coils were used in vibration suppression as an actuator. The control system consists of a coil attached in aluminum beam and a permanent magnet set at its bottom. This actuation method is easy to be incorporated into the system and allows significant forces to be applied without contacting with the structure. Three types of coils (cylindrical type, square type, Circular sheet type) were employed in vibration suppression of cantilever beam. The positive position feedback (PPF) controller was applied to the magnet-coil actuator to suppress the first mode of vibration. Experimental results showed that the cylindrical type and square type coil made good vibration suppression efficiency under PPF controller than their eddy current damper. However, there was minimal difference for the circular sheet type coil if compared with its eddy current damper.

6926-47, Poster Session

Application of multisensor information fusion to the self-localization of mobile robot

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Self-localization of mobile robot is a crucial problem for the navigation of mobile robot. The navigation task is difficult due to a number of complex problems. Some issues that complicate navigation are limits on computational power, the difficulties involved in using information provided by the environment, and so on. The intension of this paper is to introduce our research on mobile robot localization in the indoor environment with uncertainty information. While navigating, a robot often uses odometry sensors to estimate its position. These sensors count the number of revolutions that the wheels make while driving and turning. The readings can be used to help estimating the displacement over the floor to give an indication of the location of the robot. However, due to wheel slippage or other small noise sources, the odometer readings may give inaccurate results. Moreover, odometer readings are only based on the number of wheel revolutions and there is no way for the robot to see from these readings alone how accurate they are. The error in where the robot thinks it is will increase. Therefore, simply assuming that the odometer readings are correct can result in incorrect position estimates. The information that robots obtain using their sensors needs to be combined to determine what is going on in the environment. Different sensors on a robot can

give different information about the environment. Different sensors can also give inconsistent or incorrect sensor readings. Sensor fusion is the problem of combining data from different sensors into one unified view of the environment. In order to meet the requirement of accurate localization, a self-location algorithm based on multi-sensor information fusion is proposed. The information that robots obtain using their sensors needs to be combined to determine what is going on in the environment. Different sensors on a robot can give different information about the environment. Sensor fusion is the problem of combining data from different sensors into one unified view of the environment. This algorithm may update continuously position states and estimate the next position according to the motion of robot. Then it can correct estimate value and obtain factual position states in the light of factual inspection sensors information. This paper not only introduces the robot's speed and position controller, but also analyzes various infections on different sensors. First, by analyzing kinematics architecture of mobile robot with two driving wheels, the kinematics model was made based on rigid constrains; the measurement model of odometry and sonar sensors were built based on the theory of sensors. Second, the data provided by odometry and sonar sensors were fused together by means of an extended Kalman filter (EKF) technique. Finally, the position of robot is reset by matched environment feature, so the position estimation of robot was given accurately. Simulation result showed that the proposed algorithm eliminated the cumulative errors of odometry obviously, and improves the localization precision efficiently.

6926-30, Session 7

Optimization of location and number of sensors for structural health monitoring using genetic algorithm

G. S. Naorem, M. G. Joshi, Research and Development Establishment (Engineering) (India)

Damage classification for a structural health monitoring (SHM) scheme is achieved in an Artificial Neural Network (ANN) environment using predefined number of static strain sensors located at a priori identified locations of the structure. It is seen that the error in damage classification by such technique depends on quality of strain pattern for the given types of damages the SHM scheme is devised to monitor. It therefore requires an optimum number and location of the strain sensors to minimize the error of damage classification in a statistical sense. A stochastic objective function based on weighted sum of mean error and information entropy of error associated in the classification of structural damage by ANN is formulated. A real coded elitist genetic algorithm (GA) is developed and devised with simple uniform crossover functions and mutation functions to optimize the location as well as the number of sensors using the stochastic objective function. Results of the method applied to SHM of a cantilever beam structure shows an order of magnitude reduction in the mean and standard deviation of damage classification error with lesser number of sensors.

6926-32, Session 7

Optimal design of active, passive, and hybrid sandwich structures

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In order to optimize the control of the dynamic response of laminated anisotropic flexible structures, a finite element model has been developed for the analysis of sandwich laminated plates with a viscoelastic core and laminated anisotropic and piezoelectric face layers. The finite element model is formulated using a mixed layerwise approach, by considering a higher order shear deformation theory (HSDT) to represent the displacement field of the viscoelastic core and a first order shear deformation theory (FSDT) for the displacement field of adjacent anisotropic layers and/or sensor and actuator piezoelectric laminas/patches. The model is based on a quadrangular 8 noded plate/shell element. The complex modulus approach is used to describing the viscoelastic material behaviour, and the dynamic problem is solved in the frequency domain, using viscoelastic frequency dependent material data for the core. Active control is applied using proportional displacement and negative velocity control

laws, assuming collocated sensor/actuator piezoelectric patches. The model has been validated and used with success in the maximization of structural modal loss factors, using an algorithms of non-linear mathematical programming (FAIPA[1]) or/and a Genetic Algorithm (GAs) in order to attenuate the vibration of passive, active and hybrid damping of sandwich plates and shells.

Reference

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6926-33, Session 8

Thermal modeling of thermally isolated microplates

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As the size and requirements of power usage of micro electro-optical devices decrease, the thermal effects become more important and an accurate prediction of these effects is required in order to predict their performance in the design stage. Thermal modeling of micro devices implies an adequate simplification of the thermal system so that the involved heat transfer equations are solvable. Heat transfer equations can usually be directly applied to simple geometries, such as for example a slab, a cylinder, or a spherical shell. However, as the device geometry becomes more complex, a simplified analysis of the system is not possible and finite element methods need to be used. For instance, when designing micromirrors, the thermal modeling is critical since the temperature profile at a given bias voltage needs to be predicted accurately to avoid undesired thermal stress, malfunction or melting of the device. The thermal effect that infrared (IR) radiation has in an un-cooled micro bolometer is another example of the importance of the use of an adequate thermal model. In this case, the detection mechanism is based on the absorption of the IR radiation by the thin film detector element, or IR sensitive plate. The IR absorption results in a change in temperature of the detector element. The change in temperature is read out by electrical biasing the detector element. If the bolometer plate is perfectly thermally isolated from the substrate, the plate temperature will increase rapidly with only a small amount of incoming IR radiation, resulting in a higher sensitivity. However, increasing the sensitivity results in an increase of the thermal isolation which at the same time reduces the sensing speed of the microbolometer. The thermal isolation between the plate and the substrate is measured by the thermal conductance. Therefore, to fabricate a microbolometer which has the desired speed and sensitivity, the thermal conductance needs to be determined accurately during the design stage.

In this paper, a new model based on the analytical solution of the heat conduction equation is provided for a microdevice shape which is common to both micromirrors and un-cooled microbolometers. The device consists of an isolated plate connected to the substrate by two arms. In this case, the thermal model cannot be easily solved due to the abrupt change in cross section as the heat flows from the plate to the arms. The proposed model approximates the plate and arm structure as a composite region and solves the heat equation analytically. Unlike conventional models, the proposed model depends on the analytical solution of the heat equation. The model also considers the spreading resistance as well as the heat generation on the arms. By using this new model, the thermal conductance of a microbolometer and a tip-tilt micromirror are calculated and compared to experimental results obtained for devices fabricated using PolyMUPMS® runs 73 and 78. The model and experiments are also compared to finite element simulations showing that the proposed model is reliable and has the potential to be applied to a wide range of microdevices and geometries.

6926-34, Session 8

Finite-element-simulations of polycrystalline shape-memory alloys

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Shape memory alloys can be adequately modeled using the thermodynamics-based model by Mueller, Achenbach and Seelecke. The

performance of this approach has already been demonstrated for single crystals under uniaxial loading [1].

The model is extended to polycrystalline materials and programmed for a commercial FEM package (ABAQUS) in order to more closely resemble real-world materials. To this end, the method of parameterization [2] is implemented. Thus, a polycrystal deformation can equivalently be represented by subsequent phase changes of an individual crystal exposed to varying energy barriers, hence reducing the computational effort tremendously. Measured stress-strain curves of uniaxially stretched polycrystals can be reconstructed in FEM using this approach.

In the sequel, we further investigate typical benchmark tests in mechanics where individual fibers of the material are treated as acting independently which permits the loading be considered uniaxial. A prime example is the horizontal cantilever fully restrained at one end and loaded by a vertical point force at its free end.

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6926-35, Session 8

Nonlinear solutions for circular membranes and thin plates

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Circular membranes and thin plates are used extensively in pressure sensors, loudspeakers, earphones, microphones, gas flow meters, radio and radar antennae, optical telescopes, solar powers, propulsions, and civil structures. Plate theories are useful for designs and analyses. An aspect ratio is defined as the characteristic length of a plate in a plane divided by a plate thickness. Based on different aspect ratios, plates can be classified into three categories: membranes, thin plates, and thick plates. The plates with aspect ratios greater than or equal to 80 through 100 are referred to as membranes. The plates with aspect ratios between 8 through 10 and 80 through 100 are classified as thin plates. The plates with aspect ratios less than or equal to 8 through 10 are named as thick plates. The characteristic length can be evaluated by the hydrostatic diameter. In this way, the characteristic lengths for circles and squares are the diameter and the edge length, respectively. The existing nonlinear models for circular membranes and thin plates are reviewed. It is desirable to have analytical or semi-analytical models for the nonlinear deflections, strains, and stresses of membranes because of their maneuverable and insightful forms.

Although the membrane definition implies that the bending resistant vanishes as the aspect ratio of a plate is greater than about 80 through 100 in general, the more accurate way is to calculate it specifically. The new models for pre-stretched and post-heated circular membranes under a uniform pressure, including bending rigidity, by both the Ritz method and the Galerkin method have been derived. As a result, the two models converge into one model. Without a pre-tension and post-heating, deflections of the current membrane model falls in between those by the Hencky's model and the Abram's model. All models used in the comparison show that the deflection slightly decreases as the Poisson's ratio increases. With a pretension, the deflections of the current model is slightly less than those of the Abram's model.

Although solutions for clamped circular thin plates by the Ritz method and the Galerkin method have been established, they are briefly discussed. The clamped circular thin plate model is simply extended to include a pretension and post-heating. When Poisson's ratio is 0.3 the stretching factor is 0.483 instead of 0.488 cited in many journal publications. The more accurate result is 0.471 as the higher order polynomial derived from the bi-harmonic compatibility partial differential equation is used.

For circular membranes and thin plates, both the Ritz method and the Galerkin method give the same answer if the same forms for both the radial and axial displacements are respectively used. In general, however, the Galerkin method has an edge to solve this type of nonlinear coupled partial differential equations since they can be used to linearly or iteratively determine the forms of both radial and axial displacements. The newly

developed membrane and thin plate models have also been checked by the computer software MATLAB.

6926-36, Session 8

Simulation of surface effects in energy dissipation of ultra-high-frequency(UHF) nanocantilevers

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Devices composed of nanoelectromechanical systems (NEMS) possess distinguished properties which make them quite suitable for a variety of applications including ultra-high-frequency (UHF) resonators. However, most GHz resonators have low quality factor Q even though it has been well above 10^3 – 10^5 for very-high-frequency (VHF) microresonators. Recent experiments have shown that the measured quality factor in many devices decreased in a linear manner as the surface-to-volume ratio was increased. This suggests that surface losses play a significant role in determining the quality factor.

The motivation for our investigation of single crystal silicon nanoresonator arises from both its technological importance and its extraordinary surface effects. Since most nanoresonator are typically free standing samples vibrating predominantly either in flexure or torsion, in the present study, ultrathin Si cantilevers will be characterized based on under-damped flexural oscillations. However, to employ any conventional experimental method to characterize the mechanical properties of ultra-small one dimensional nanostructures is such a great challenge. That's why the less expensive and more versatile numerical simulation tools, e.g. molecular dynamics (MD) method, become one of our options to provide an insight to nanomaterial-related phenomena. First-principles calculations are also widely employed because of their high accuracy, but MD simulations can handle much larger systems and can be used to study both the static and dynamic properties of nanomaterials.

In the present study, the mechanical properties of Si nanocantilevers are investigated using the classical MD simulations, in which the empirical Stillinger-Weber (SW) many-body potential is employed for interatomic interactions, and Newton's equations of motion are calculated with a time step of 0.38 fs (femosecond) in a Gear's predictor-corrector algorithm. The intrinsic dissipations of nanocantilever are calculated through analyzing the damped amplitude of the mechanical oscillation. The results show that for nanocantilevers with surface area-volume ratio no larger than 1.0 (1/nm), the displacement amplitudes are in good agreement with the curve fitting of their exponential decays, which means that the values of dissipation can be determined from data fitting. For nanocantilevers with surface area-volume ratio larger than 1.0 (1/nm), the decay of displacement amplitude does not exhibit the exponential trend as expected. Thus, the dissipation values cannot be extracted from the displacement plots. The dominant effect of surfaces in the nanocantilevers dissipation is also illustrated by considering the proportion of surface energy in total energy, which can be obtained from the mean potential energy measured in different geometries of nanocantilevers. Our data show that the intrinsic dissipation increases with increasing surface area-volume ratio of the nanocantilever when its surfaces possess 10%~20% of its total energy.

6926-37, Session 8

Modeling of lossy piezoelectric polymers in SPICE

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Rearranging the mathematical relations of piezoelectric polymers working in thickness mode and comparing them with the standard telegraphist's equations yields the analogy between acoustic transmission and electrical transmission line. The mechanical loss due to the viscoelastic property of the polymers is represented by a lossy electrical transmission line. A complex elastic constant is used for getting the parameters of the electrical transmission line. Due to analogy, frequency dependent G term represents the mechanical loss, instead of R term. The conversion from mechanical domain to electrical, i.e the from the transmission line to the electrical side, is done by an equivalent transformer which has been implemented

by using controlled voltage source in SPICE. The transformation ratio of this transformer and hence the gain of the controlled sources depends on the piezoelectric constant. The electromechanical loss is taken in account by using a complex value of piezoelectric constant. On the electrical side, the polymer is represented by its static capacitance. To incorporate the dielectric losses, the static polymer capacitance is made lossy and is implemented in SPICE with a controlled source whose gain depends on the complex value of dielectric constant.

The mathematical relations given in the IEEE standard on piezoelectricity can not be used to find constants of piezoelectric polymers like PVDF, as they have figure of merit of 2-2.5. Thus, the complex elastic, piezoelectric and dielectric constants were derived from the impedance measurements (done by HP 4285A LCR meter) of PVDF-TrFE samples by using piezoelectric resonance analysis program. Using these complex constants in the SPICE model, the simulated impedance and phase are obtained and then compared with the impedance measurements done by HP 4285A LCR meter). The simulated impedance and phase are found to be in good agreement. An interesting result from the simulation study of the losses independently (considering one of the three at a time/ combination of two at a time/all three altogether) shows that contribution to total losses, by transmission line loss due to the viscoelastic property, is significantly higher than that by dielectric loss and piezoelectric loss.

6926-38, Session 9

Roles of substrate and film properties upon remnant polarisation of ferroelectric thin film memory

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The performance of ferroelectric random access memory devices (FERAM) relies on the remnant polarisation. For high performance, the remnant polarisation of a ferroelectric thin film memory capacitor is desired to be high. However, it has always been recognized that the remnant polarisation of a ferroelectric thin film is about a third to a half of its bulk value. A theoretical work is carried out in this study to explore the roles played by substrate and ferroelectric properties in altering the remnant polarisation. A constitutive law based on the crystal plasticity theory and the finite element method are used to model the ferroelectric switching behavior of a memory capacitor. In particular, it has been found that factors such as crystallographic orientation and initial volume fractions of different ferroelectric variants that are dependent on the type of substrate and film deposition method, can significantly alter the remnant polarisation. An explanation on why such dependencies can hold is provided. Through this study explanations are sought on how to increase the remnant polarisation of a thin film memory capacitor.

6926-39, Session 9

New silicone dielectric elastomers with a high-dielectric constant

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Abstract: Dielectric elastomers (DEs) are a type of EAPs with unique electrical and mechanical properties. The excellent figures of merit possessed by dielectric elastomers make them the most performing properties: high actuation strains and stresses, fast response times, high efficiency, stability, reliability and materials which can be applied in many domains: bio-mimetic, aerospace, mechanics, medicals, etc. However, the price for achieving these high-level capabilities is represented by the high driving electric fields (generally >100 V/ m). For a definite polymer thickness, such field level can be achieved by applying high voltages, but it may be disadvantageous in many applications. The DEs may also be under risk of breakdown if higher actuation strains and stresses are needed. The electromechanical responsive ability of DEs is proportional to the relative dielectric constant of the materials. For this reason, to reduce the driving electric fields, polymers with high dielectric constant are necessary. In this paper, we present a kind of electroactive polymer composites based on silicone Dielectric elastomers with a high dielectric constant. novel highly DEs could be realized by means of a composite approach. By filling an ordinary elastomer (e.g. silicone) with a component

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functional ceramic filler having a greater dielectric permittivity, it is possible to obtain a resulting composite showing the fruitful combination of the matrix's advantageous elasticity and the filler's high permittivity. Here we add the ferroelectric relaxor ceramics (mainly $\text{Pb}(\text{Ta}_{0.5}\text{Sc}_{0.5})\text{O}_3$) which has high dielectric constant (>3000) to the conventional silicone Dielectric elastomers, to get the dielectric elastomer which can exhibit high elastic energy densities induced by an electric field of about 15 V/ m . The electrostatic deformation response of dielectric elastomer material have a relationship with the fabrication process of the materials. We study the principles of the electrostatic deformation response from the microstructure of the dielectric elastomers. Result shows that the tropism of the polymers molecular chains has an effect on the dielectric capability. Tests of the physical and chemical properties (elastic modulus (1.0Mpa), dielectric permittivity (90) and some dynamic properties) of the dielectric elastomers are conducted, which verify our supposes and offer the experimental data supporting further researches. We also study on the electrostatic deformation response of the silicone dielectric elastomers. Prestraining process is a key factor during the whole process. We use this dielectric elastomer as deformation drivers, and confirm the deformative rate (39-53%) and the response time (2-3ms), offering basic parameters (the optimum prestrained ratio, etc) for further design of dielectric elastomer artificial muscle drives. Finally, we discuss some applications the silicone dielectric elastomer. Based on the silicone elastomer we have made, two kinds of new actuators are also fabricated: one is circular actuator, which thickness strains up to 40-50% and area strains up to 90-110% when subjected to the strengthened electric field. Comparing to most of other smart materials, it's performances is quite advantageous to the industrial designs. Another is rolled actuator, which produces high force and stroke in a relatively compact package. Both of these actuators have great applications in the many industry areas

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6927-01, Session 1

High-performance with a 'soft' skeleton: the shark cartilage composite (Keynote Presentation)

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Sharks have changed little over 300 million years, suggesting that their skeleton is well adapted to the rigors of a high performance lifestyle. Though fossil sharks had bone, the skeleton of modern animals is not bone, but rather a composite of mineralized and unmineralized cartilage. At a gross level this composite is a mosaic of mineralized tiles, that are often tied together with collagen fibers, surrounding a soft core. We have approached the problem of understanding the behavior of this skeletal material by a combination of imaging and performance testing. We have imaged the radio-opaque material at nanometer scales using a synchrotron CT scan. This data has revealed the complex connections between tiles. At larger scales (micron & millimeter) we have imaged the mineralized and unmineralized phases using conventional CT and histology. We then measured the material properties at fine scale and coarser scales using nanoindentation and conventional material testing and combined these data with models generated with a rapid prototyper to understand the response of this material to load.

The shark skeleton is not supplied with blood vessels so, like most manufactured materials, it cannot heal over the course of the animals lifetime. Since the skeleton experiences between 10^9 and 10^{11} load cycles we would expect substantial fatigue degradation, however this does not appear to be a problem for these animals. Our emerging understanding of the sharks skeleton suggests that it is a stiff material that is well damped to resist fatigue damage. This may be a general characteristic of high modulus tiles over a visco-elastic core material.

6927-02, Session 1

Humanlike robots as platforms for electroactive polymers (EAP)

Y. Bar-Cohen, Jet Propulsion Lab.

Inspired by science fiction, making human-like robots is increasingly becoming an engineering reality thanks to recent surges in technology advances. These robots have originated from the desire to reproduce the human appearance, functions and intelligence and they may become our household appliance or even companion. For this purpose, biologically inspired technologies are increasingly becoming common tools to support the development of such robots. Potentially, electroactive polymer (EAP) materials as artificial muscles are offering important actuation capability for making such machines lifelike. There are many technical issues in making such robots including the need for more effective EAP materials as actuators. As opposed to other human made machines and devices, this technology raises various questions and concerns that need to be addressed. These include the need to prevent accidents, deliberate harm, or their use in crimes. In this paper the state-of-the-art and the challenges will be reviewed.

6927-03, Session 1

Designing components using smartMOVE™ EPAM technology

M. A. Rosenthal, A. Zarrabi, P. Gise, J. Heim, Artificial Muscle, Inc.

Designing components using SmartMOVE™ EPAM technology requires an understanding of the basic operation principles and the necessary design tools for integration into actuator, sensor and energy generation applications. Artificial Muscle, Inc. is collaborating with OEMs to develop customized solutions for their applications using smartMOVE. SmartMOVE is an advanced and elegant way to actuate almost any kind of movement using dielectric elastomer electroactive polymers. Integration of this technology offers the unique capability to create highly precise and customized motion for devices and systems that require motion actuation. Applications of SmartMOVE include optical positioners for

auto-focus, image stabilization, and zoom as well as pumps, valves, and linear actuators for medical, consumer and industrial applications. This paper will present design guidelines for selecting a smartMOVE actuator design to match the stroke, force, power, size, speed, environmental and reliability requirements for a range of applications. Power supply and controller design and selection will also be introduced. An overview of some of the most versatile configuration options will be presented with performance comparisons. A case example will include the selection, optimization, and performance overview of a smartMOVE actuator for the cell phone camera auto-focus application.

6927-04, Session 1

Elastomeric contractile actuators for hand rehabilitation splints

F. Carpi, A. Mannini, D. De Rossi, Univ. di Pisa (Italy)

The significant electromechanical performances typically shown by dielectric elastomer actuators make this polymer technology particularly attractive for possible active orthoses for rehabilitation. Folded contractile actuators made of dielectric elastomers were recently described as a simple configuration, suitable to easily implement linear contractile devices. This paper describes an application of folded actuators for so-called hand splints: they consist of orthotic systems for hand rehabilitation. The dynamic versions of the state-of-the-art splints typically include elastic bands, which exert a passive elastic resistance to voluntary elongations of one or more fingers. In order to provide such splints with the possibility of electrically modulating the compliance of the resistive elements, the substitution of the passive elastic bands with the contractile actuators is here described. The electrical activation of the actuators is used to vary the compliance of the system; this enables modulations of the force that acts as an antagonist to voluntary finger movements, according to programmable rehabilitation exercises. The paper reports results obtained from the first prototype implementations of such a type of system.

6927-05, Session 2

Fiber spinning and ink-jet printing: advances in conducting polymer device fabrication

G. G. Wallace, J. Foroughi, C. Mire, M. in het Panhuis, G. M. Spinks, Univ. of Wollongong (Australia)

Who would have thought that the ancient arts of spinning and printing would revolutionise how we fabricate novel devices based on conducting polymers. With recent advances in the design and composites containing them the fabrication of enhanced performance devices is now possible. We have recently developed protocols that enable polyaniline or polypyrrole solutions/dispersions with appropriate rheological and surface tension characteristics for wet spinning or ink jet printing to be produced. The electrochemical and physical properties of fibers or printed structures have been evaluated. Their use in a range of electrochemical configurations including artificial muscle structures has been evaluated.

6927-06, Session 2

Enhancement of the electromechanical transduction properties of a silicone elastomer by blending with a conjugated polymer

F. Carpi, G. Gallone, F. Galantini, D. De Rossi, Univ. di Pisa (Italy)

The need for high driving electric fields currently limits the diffusion of dielectric elastomer actuation in some areas of potential application, especially in the case of biomedical disciplines. A reduction of the driving fields may be achieved with new elastomers offering intrinsically superior electromechanical properties. So far, most of attempts in this direction have been focused on composites between elastomer matrixes and high-permittivity ceramic fillers, yielding to limited results. In this work, the

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electromechanical response of a silicone rubber (poly-dimethyl-siloxane) was improved by blending, rather than loading, the elastomer with a highly polarizable conjugated polymer (undoped poly-hexyl-thiophene). The resulting material was characterized by dielectric spectroscopy, SEM microscopy, tensile mechanical analysis and electromechanical transduction tests. Very low percentages (1-6 wt%) of poly-hexyl-thiophene yielded both an increase of the dielectric permittivity and an unexpected reduction of the tensile elastic modulus. Both these factors contributed to a remarkable increase of the electromechanical response, which reached a maximum at 1 wt% content of conjugated polymer. This approach may lead to the development of new types of improved dielectric elastomers for actuation.

6927-07, Session 2

Carbon nanotube yarns: sensors, actuators, and current carriers

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Carbon nanotubes have attracted extensive attention in the past few years because of their appealing mechanical and electronic properties. Yarns made through spinning multiwall carbon nanotubes (MWNTs) have been reported. Here we report the application of these yarns as electrochemical actuators, force sensors and microwires.

When extra charge is stored in the yarns, they actuate by a change in length. This is thought to be because of electrostatic as well as quantum chemical effects in the nanotube backbones. We report strains up to 0.7 % this way. At the same time, the charged yarns can respond to a change in the applied tension by generating a change in current or the potential difference corresponding to the applied tension force. As current carriers, the yarns offer a conductivity of ~ 300 S/m, which increases linearly with temperature. We report a current capacity of more than 108 A/m², which is comparable to those of metal wires. However, these nanotube yarns have a low density (0.8 g/cm³) which is an order of magnitude less dense than metallic wires. The MWNT yarns are mechanically strong with tensile strengths reaching 700 MPa. These properties together make them a candidate for many applications as fast sensors and actuators as well as light-weight current carriers.

6927-08, Session 2

Characterization and modeling of conjugated polymer sensors

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Conjugated polymers as mechanical sensors have received relatively little attention despite their potential applications in biomedical devices, bio/micromanipulation, and biomimetic robotics. In this paper the properties and dynamic behaviors of conjugated polymer sensors are experimentally characterized. A theory for the sensing mechanism is proposed, based upon which a sensing model is developed. The model is further validated in experiments using both step and dynamic mechanical stimuli.

A trilayer conjugated polymer is considered in this work, where two polypyrrole (PPy) layers sandwich an amorphous polyvinylidene fluoride (PVDF) layer. The PVDF layer stores electrolyte (e.g., TBA.PF6 in propylene carbonate), which enables the material to perform actuation and sensing in air. Due to the relative sizes with respect to PPy pores, anions can move in and out of PPy while cations cannot. In the proposed sensing theory it is postulated that, through its influence on the pore structure, mechanical deformation correlates directly to the concentration of anions at the PPy/PVDF interface. This provides one boundary condition for the anion diffusion dynamics in PPy. The partial differential equation governing the diffusion dynamics is solved in its Laplace domain, by assuming zero-ion-flux at the PPy/air interface as the second boundary condition. Consequently, the resulting open-circuit voltage is obtained. This leads to an explicit, transfer-function model for the sensing dynamics that relates the open-circuit voltage to the mechanical input.

Experiments are conducted to validate the proposed model. Step

displacements of different magnitudes are applied to the tip of a trilayer conjugated polymer. Sinusoidal displacements of 0.4 Hz to 20 Hz are also applied through a custom-built apparatus. Experimental measurement of the open-circuit voltage matches well the model prediction. This work provides the first step towards fundamental understanding of mechanical sensing mechanisms of conjugated polymers.

6927-09, Session 4

Advances in the modeling and performance of ionomeric polymer transducers (IPMCs)

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Recently the field of ionomeric polymer transducers, or IPMCs, has been advanced by improved modeling methods and improvements in the fabrication processes for the material. In this presentation we will detail a combined transport and constitutive model that enables the accurate prediction of actuator performance in both the time domain and the frequency domain. The model highlights the need for nonlinear constitutive parameters in the relationship between charge transport and mechanical response, particularly at low actuation frequencies. This model will be used to study a relatively new class of ionic liquid-based ionomeric polymer transducers. These transducers utilize air-stable ionic liquids as the diluent and provide much improved stability in air compared to actuators that utilize water as the means to increase ionic conductivity. We will detail recent morphological studies that correlate polymer composition and transducer performance. An important result from this analysis is that the ionic conductivity, and actuator performance, exhibit a percolation behavior as a function of ionic liquid uptake. The percolation behavior of the transport network is studied and found to yield an invariance with respect to the critical uptake of ionic liquid.

6927-10, Session 4

IPMC paints

K. J. Kim, I. Park, Univ. of Nevada/Reno

The concept of making "IPMC paint" is new and is carried out by spraying IPMC-making constituents directly onto the surface of a structure. The advantage of this type of IPMC sensor/actuator is that it can be sprayed directly onto any complex structures and cured at an ambient temperature. Similar to piezoelectric paints, it is a thick-film technology. It is not prone to accidental damage and is easy to apply. In our experiments, the drying induced the recasted film to the mechanical structures was obtained. We present the preliminary results to produce good quality IPMC paints applied to the mechanical structures.

6927-11, Session 4

Microdeposition method: a novel fabrication method for ionic polymer metallic composites

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Ionic Polymer Metallic Composites (IPMCs) are used as actuators and sensors due to their ability to produce large strains and moderate stress for small voltages, and for their electrical response to strain. Previous studies have shown a direct correlation between the physical architecture of the IPMC and its ability to deform or sense strain. There are two main methods to fabricate an IPMC, the first through a chemical reduction process, called the impregnation reduction method; and the second using a mechanical assembly technique, called the Direct Assembly Process (DAP). The impregnation reduction method is a chemical reduction process in which dendritic formations of a metal are formed on either side of the polymer to form electrodes. The process allows for very little control on electrode thickness and dispersion. To overcome this limitation, the DAP was developed. The DAP allows for control of the chemical composition, however is plagued by the method of deposition it uses to assemble the IPMC. The method of deposition currently used in DAP produces IPMCs with varying electrode thickness, thus impacting the actuation and sensing properties. The new Micro Deposition Method (MDM) solves these short

comings, and allows for repeatable, high resolution fabrication down to the micron scale.

In this paper we will discuss our new fabrication system, the procedure to fabricate a micro IPMC, and nanoscale characterization of fabricated IPMCs using the new technique. The MDM uses the latest in micro scale fluidic deposition technology to disperse individual droplets ranging from 100 picoliters to a few nanoliters in a very controlled fashion, allowing for the construction of a uniform electrode layer. The MDM can create a single actuator or sensor in any two dimensional shape in any desired pattern down to 60 microns with high accuracy and repeatability. This allows for an increase in the mechanical sensitivity and compliance to compete with other actuators and sensors in engineering applications. The fabricated actuators and sensors are imaged using scanning electron microscopy to demonstrate the repeatability of the prototyping technique. The material properties of the different layers in the fabricated IPMC are characterized using X-ray photoelectron spectroscopy, and nuclear magnetic resonance spectroscopy thus demonstrating nanometer scale dimension control in the thickness. Each sample is actuated and its response quantified through percent strain and blocked force. The sample is fixed as a cantilever and its sensitivity characterized as a function of voltage output per unit strain, thus demonstrating the abilities and potential of the new micro deposition method for IPMC fabrication.

6927-12, Session 4

Bimetallically electroded ionic polymer-metal composite(s)

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Ionic Polymer Metal-Composites (IPMCs) with the bimetallic Pt-Pd electrode deposited by an electroless chemical reduction method onto a polymer membrane were investigated. Perfluorinated ion-exchange membranes were soaked in a Pt-Pd complex solution with various compositions. Reduction processes were carried out in an aqueous sodium borohydride solution. The surface compositions of Pt and Pd were compared by energy dispersive X-ray spectroscopy (EDS). The particle sizes were determined by X-ray diffraction (XRD) and surface morphologies of electrodes also were analyzed by scanning electron microscopy (SEM). The performance characteristics including electrochemistry and actuation responses of IPMCs for controlled Pt/Pd compositions were assessed and compared with those of monometallic Pt and Pd electrodes fabricated under similar conditions. Seemingly, an IPMC with the optimal composition of Pt and Pd had not only improved surface morphology but also significantly enhanced the actuation capability.

6927-13, Session 4

A new force field for molecular dynamics studies of Li- and Na-Nafion

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Li- and Na-Nafion® are among the most commonly used polymer electrolytes in Ionomeric Polymer-Metal Composites (IPMCs). Despite a vast range of experimental studies on Nafion®, however, many uncertainties still remain concerning its structure and dynamics. In this context, Molecular Dynamics (MD) simulation and molecular modeling are able to make a particularly useful contribution at the atomic level.

The problem has previously been that Nafion® and related perfluorinated polymer membrane materials are highly complex - requiring equally complex force-field descriptions. However, significant efforts in recent years has led to that the first meaningful MD studies are now beginning to appear for Nafion®-like systems, e.g. [1-3], thereby, opening the door for a more sophisticated atomic-level understanding of the functionality of these materials.

In previous work [4], we have showed the importance of generating an optimized Force Field for Li+ and Na+ interactions with the Nafion® sulphonate groups in order to model IPMCs on the atomic level. In this work, we present the generation of such a Force Field using quantum chemistry calculations (B3LYP/6-311+G(d,p); BSSE corrected by Counterpoise method). We are also presenting MD studies of the Li- and

Na-Nafion® systems using this new Force Field, and comparing our results in term of coordination and ion diffusion with experimental data.

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6927-14, Session 4

A comprehensive dynamic actuation model for ionic polymer-metal composites

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Ionic polymer-metal composite (IPMC) is a kind of ionic electro-active polymer (EAP) which consists of a thin polyelectrolyte membrane and a type of noble metal chemically plated on both sides of the membrane. The IPMC can undergo a fast and large bending motion when a low electric potential is applied to its electrodes. Conversely, the IPMC will generate a measurable electric potential when it is subjected to an imposed deformation. Many first principle models have been proposed on the basis of charge movement and ion interactions. These models have provided important insights into the working mechanism of the IPMC material in various aspects. However, most of these first principle models are focused on the IPMC behaviors under static or alternative electric potentials. Reports on the actuation mechanism of the IPMC material under arbitrary dynamic electric potentials are very limited. As in most of the proposed applications of the IPMC material, various forms of dynamic electric potentials are expected to be used, it is significant to explore the actuation mechanism of the IPMC material under arbitrary dynamic potentials.

In this paper, a comprehensive model is presented to account for the actuation mechanism of the IPMC material under arbitrary dynamic electric potentials. The charge motion within the polyelectrolyte membrane under a dynamic electric potential is first investigated. Based on the Nernst-Planck equation, the Poisson's equation, the Darcy's law and the mass conservation equation, the charge redistribution function is obtained analytically. Subsequently, the dynamic ion-ion interactions within the polyelectrolyte membrane clusters are studied. By analyzing the volumetric changes of the membrane clusters due to the electric field induced stresses and the elastic stresses in the backbones of the membrane, the bending strain and stress are determined. Finally, the bending moment expression due to the applied electric potential is obtained. By using the bending moment expression, the deformation of an IPMC sample under both static and dynamic electric potential can be calculated. An illustrative example is presented. Comparison with the experimental results shows that the proposed model is reasonably good in accuracy. The proposed model is useful for further understanding and modeling of the dynamic actuation mechanism of the IPMC material.

6927-15, Session 4

A distributed model of IPMC

A. Punning, M. Kruusmaa, M. Anton, U. Johanson, A. Aabloo, Tartu Ülikool (Estonia)

This work presents a novel model of an IPMC. IPMC is modeled as a distributed RC transmission line. Unlike other electromechanical models of an IPMC, the distributed nature of this model permits predicting the non-uniform bending of the material. Instead of modeling the deflection of the tip of a cantilevered IPMC actuator or sensor without taking an interest in the shape of the device between the tip and the input contacts, this model describes the uneven changing flexion of the device in the time domain.

The main results of this work are:

- a) a methodology of characterization of ionic polymer actuators and sensors;

- b) a principle of a distributed model of ionic polymer actuators and sensors;
- c) an implementation of some possible causes of nonlinearities to the distributed model;
- d) two “smart” applications utilizing the distributed model, the self-sensing actuator and an S-actuator.

Actually the distributed model of IPMC introduced in this work uses and elaborates several models discussed in the introduction. It uses the model of Kanno et al., and extends it as an RC distributed transmission line. The electromechanical coupling between the electric current and flexure change is adapted from the model of Bao et al., and accommodated to a distributed model.

We expound the different modifications of the distributed model of IPMC. We also describe the simplest model, without any nonlinearities. This is an exceptional case, where a step input to an IPMC-based actuator is solvable in a closed form. All other modifications of the model are approximated by a lumped RC ladder and modelled with a Matlab Simulink model using the SimPowerSystems toolbox. This toolbox makes it possible to simulate the electrical circuits, using the Kirchhoff's circuit laws. We introduce the nonlinearities caused by the changing resistance of the electrodes and the water electrolysis respectively. We explain the distributed model of an IPMC sensor, functioning in the opposite way, when compared to the model of an actuator.

6927-17, Session 5

A scalable dynamic model for ionic polymer-metal composite actuators

Z. Chen, X. Tan, Michigan State Univ.

Ionic polymer-metal composites (IPMCs) have built-in sensing and actuation capabilities which make them attractive in many biomedical and biological applications. In this paper a physics-based but control-oriented dynamic model is proposed for IPMC actuators. The modeling work starts from the governing partial differential equation (PDE) that describes the charge redistribution dynamics under external electrical field, electrostatic interactions, ionic diffusion, and ionic migration along the thickness direction. It is further extended by incorporating the effect of distributed surface resistance. The electrical impedance model is obtained by deriving the exact solution to the governing PDE in the Laplace domain. By assuming a linear electromechanical coupling, an actuation model which relates bending displacement to voltage input is derived. The model is represented as an infinite-dimensional transfer function, which is amenable to model reduction and real-time control design while capturing fundamental physics. It thus bridges the traditional gap between the physics-based perspective and the system-theoretic perspective on modeling of IPMC materials. The model is expressed in terms of fundamental material parameters and dimensions of the IPMC, and is therefore geometrically scalable. The latter has been further confirmed in experiments.

6927-18, Session 5

A correlation between extensional displacement and architecture of ionic polymer transducers

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Ionic polymer transducers (IPT), sometimes referred to as artificial muscles, are known to generate a large bending strain and a moderate stress at low applied voltages (<5V). Bending actuators have limited engineering applications due to the low forcing capabilities and the need for complicated external devices to convert the bending action into rotating or linear motion desired in most devices. Recently Akle and Leo (2006) reported extensional actuation in ionic polymer transducers. In this study, extensional IPTs are characterized as a function of transducer architecture. The electrode thickness is varied from 10 μm up to 40 μm and the RuO₂ to Nafion composition varied from 30% up to 50%. Initial observation showed a strong correlation between transducer morphology and the strain and strain rate. Strains up to the order of 2% are observed with air stable ionic liquid based transducers. A correlation between the

strain and charge buildup in the polymer is also characterized. The different transducers are characterized with constant current, slow and fast linear sweeps, and steps of $\pm 1\text{V}$ and $\pm 2\text{V}$. In order to increase the force in these extensional IPTs, a stiff membrane replaced the soft Nafion/EMI-TF film that is traditionally placed between the two electrodes. In this study, glass mesh and porous aluminum oxide films populated with EMI-TF ionic liquids are placed between the electrodes to perform as ion conductors and electric insulators. Initial results demonstrate that transducers with either the glass mesh or aluminum oxide has faster strain rates and larger forcing output compared to that with Nafion membranes. Furthermore the ionomer in both the electrode and the membrane is replaced with a branched BPS. These transducers are characterized and a correlation between degree of branching and actuation performance is discussed.

6927-19, Session 5

Frequency response of anisotropic ionic polymer metal composites (IPMC) transducers

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The emergence of soft polymer actuators brings a great deal of excitement in the robotics and biomedical engineering community because of the possibilities to easily mimic the motion of living organisms and ability to manipulate living tissue without damaging it. Difficulties arise, however, when the particular application requires softness in one direction to be combined with a certain degree of rigidity in another direction. Examples of such applications are the previously developed undulatory swimming robot and a three link soft manipulator developed in our group. We have designed and manufactured anisotropic ionic polymer metal composites (IPMC) as a way to overcome this difficulty at driving frequencies around 1 Hz. In the present paper we extend our findings by investigating the frequency response of anisotropic IPMCs covering a wider frequency range.

6927-20, Session 5

An investigation on effect of IPMC thickness in actuation performance

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Introduction

Ionic polymer membranes, Nafion for instance exhibiting ionic conductivity and ion selectivity can be developed into electromechanical actuators. Ionic polymer metal composites (IPMC) [1], for instance, have been under investigation primarily because they have light weight and can create large bending deflections under low voltages, 1-10 V, when applied across their thickness.

The conventional IPMC production technique [1] involves the initial compositing of readily available Nafion polymeric membrane and the surface electroding process. Several other alternative processes have also been investigated to optimize characteristics and elevate actuating performance. For example, casting of nafion solution into membrane [2], and producing nafion films in different configurations such as fibers and fiber bundles by electrospraying [3].

Bending or actuation displacement and force of the IPMC are affected by the amount of water migration, modulus of hydrated polymer, expansion coefficient of moisture. Another characteristic feature which determine bending properties is the thickness of the ionic host polymer sheet, Nafion (a product of DuPont) for instance. Nafion membranes are commercially produced usually at 200 μm thickness and typically used at this measure and coated with metal electrodes on both surfaces of the polymer.

Objectives

In this work, we aim to fabricate membranes from Nafion solution using a tape casting machine. Specifically following the process suggested by Kim and Shahinpoor [2]. Our purpose in this work is to produce Nafion membranes at customized thickness. By doing so, effects of different

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membrane thickness on the actuator characteristics and physical properties of casted membranes can be observed.

Methodology

Nafion solution (DuPont, 20 wt.% in a mixture of aliphatic alcohol and water) is casted following the instructions presented in [2]. We specifically concentrate on membrane thickness effects on bending properties. After fabricating membranes of several thicknesses Pt layers will be deposited by electroless plating method and prepared IPMC actuators will be subjected to actuation experiments. The experiments on the clamped IPMC actuators are based on two boundary conditions as schematically shown in Figure 1: a) actuator tip is blocked to measure blocking or actuating force and b) actuator tip is free to measure actuation displacement [5]. Lee et al. [5] has proposed equivalent bimorph beam model (Figure 2) and predicted two constants namely effective electromechanical coupling constant and effective Youngs modulus E based on measurements described in Figure 1. These constants, however, were computed for the membrane thickness of 200 micron. Note that they are thickness and measured data dependent as expressed in

$$d_{-31} = 2sH^2 / (3VL^2)$$

$$E = 8L(F_{-b1}) / (3WH^2 d_{-31} E_{-3})$$

where V is the input voltage, d_{-31} (m/V) is the effective electromechanical coupling coefficient and F_{-b1} is the measured blocking force, E_{-3} is the electric field. Once the predictions by the experimental data and the model due to Lee et al. [5], [6] are done, we anticipate to obtain empirical equations for the effective constants as a function of membrane thickness that may be used in designing IPMC actuator.

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6927-93, Session 5

Extensional ionic polymer conductor composite actuators with ionic liquids

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Although the Ionic-Polymer-Conductor Composite (IPMC) actuators developed up to date are in the form of bending actuators, from practical applications and fundamental understanding points of view, development of extensional actuators based on IPMC is highly desirable. This talk presents the design, fabrication and characterization of first extensional Ionic Polymer Conductor Composite actuator. In this extensional actuator, the Nafion ionomer matrix, several ionic liquids and the ionomer/conductor composites were employed in the fabrication. It was found that as the ions are driven into the ionomer/conductor composite, an extensional strain of 0.9% was observed while when the ions were expelled from the ionomer/metal composite, a contraction of -1.1% was observed. The results indicate that multiple ions are participating in the charge transport and actuation process. Ionic liquids can greatly improve the strain level of the actuators. A design baseline of future extensional actuators with fast response, much improved strain and stress level by employing multi-layer configuration is advanced based on experiment results. In addition, actuator performance can be further improved with novel electrode design, which reduces the electrode modulus and retains high conductivity. This material system provides a unique platform to investigate various phenomena related to

ion transport and their interaction with the ionomer matrix to realize high electromechanical response.

6927-21, Session 6

Accomplishments and future trends in the field of electroactive polymers

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Electroactive polymers (EAP) have been widely recognized for their abilities to detect changes in physical environments and produce an "intelligent" reaction in response to external stimuli. Due to these unique properties EAP have been effectively utilized in many applications. It is envisioned that, in the near future, the use of electroactive polymers will be further expanded leading to the creation of smart material systems with such functional capabilities as self-control, self-diagnosis and self-repair, similarly to the attributes of biological systems.

This paper represents an effort to summarize the current state of knowledge in the field of electroactive polymers, emphasizing their important role in modern technological developments. An overview of major accomplishments in the field demonstrates that, to date, attention has been focused primarily on enhancing the functional performance of EAP, modifying their properties, and expanding their application range. These efforts have produced tangible results with immense opportunities for future technological developments.

However, a number of important issues regarding the response, performance and properties of electroactive polymers remain unresolved. Such issues concern, in particular, the nonlinear functional response of EAP under certain loading conditions, creep, relaxation, and cyclic fatigue. Adequate understanding of these factors is critical since electroactive polymers are required to perform in dynamic environments involving mechanical vibrations, variable temperatures, and oscillating electric fields. Another important issue concerns the performance of EAP as active elements for vibration, noise and position control. At present, the characteristic energy losses and the effects of material damping on the active control functions of EAP are poorly understood. Furthermore, accelerated mechanical degradation of EAP under dynamic loading conditions is likely to alter not only the mechanical properties of the polymers, but also their functional response as a result of electromechanical coupling. To date, little or no efforts have been made to investigate these effects.

It is clear that a resolution of these important challenges requires strong collaborative research initiatives in order to develop adequate testing protocols, characterize the response of EAP under a broad range of conditions, formulate verifiable constitutive models, and ensure seamless integration of electroactive polymers in the design of smart material systems. These issues are likely to shape future research efforts since only on this basis electroactive polymers will continue to play an important role in stimulating technological progress.

6927-22, Session 6

Polymer nanocomposites as electrostrictive and piezoelectric materials

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Polymer nanocomposites are being investigated as promising multifunctional materials for applications ranging from aerospace structures, automobiles to biomedical devices. Bulk of the research though has been directed towards enhancing mechanical, electrical and thermal properties. Rare investigations on electromechanical properties of these composites have been limited to studying the effect of nanoinclusions on already-electroactive polymers. The current study concentrates on making seemingly inactive polymers electro-active owing to nanoinclusion-polymer interactions. Specifically, the study investigates carbon nanotube, carbon nanofiber and nanoclay-based polymer nanocomposites as electrostrictive and piezoelectric materials.

Thermoplastic polymers like poly(vinylidene fluoride)(PVDF), polyethylene(PE) and thermosetting polyimides like CP2(APB-6FDA), (B-CN)APB-ODPA are selected as matrix materials. PVDF is a strongly polar material and a strong piezoelectric polymer when poled under a DC field and stretched mechanically. Polyethylene is a practically non polar

material which does not show any piezoelectric response. CP2 polyimide has a low dipole moment while (B-CN)APB-ODPA has a stronger dipole moment and is a weakly piezoelectric material. By selecting non polar material like polyethylene and weakly polar CP2 compared to the polar (B-CN)APB-ODPA and PVDF helps us evaluate the effect of nano-inclusion nature along with the matrix dipole moment on the electromechanical properties.

To study the response of the nanocomposite films to an electric field a cantilever actuation setup is used. Samples are electroded with silver and cut into dimensions of 30mm x 5mm and sandwiched between two glass slides with copper leads then suspended in a closed acrylic box. Samples are tested in different configurations, namely monolayer, unimorph and bimorph. DC and AC electric fields are applied and the sample response is studied by capturing a video and analyzing it using an image analysis software. The effect of varying the magnitude of applied field, nano-inclusion content and frequency is studied.

The response of the nanocomposite films to the electric field varies. PVDF-SWNT, CP2-SWNT and (B-CN)APB-ODPA-SWNT samples when tested as monolayers show a bending displacement in the nanocomposite films. PVDF+CNF and PE+SWNT nanocomposites did not show appreciable response as monolayers. PVDF+SWNT+nano clay composites show a weak bending response as monolayers but they show a stronger response as unimorphs. It is also important to stress that the pristine polymers do not show any measurable bending response to the applied field. The results indicate a strong dependence of the actuation response on SWNT content and the polarity of the polymer matrix. High content of SWNTs and dipole moments results in larger bending displacement. The longitudinal strains developed in the bent samples are calculated from the tip displacement of the nanocomposite cantilever using beam bending and/or trigonometric concepts. Figure 1 shows the behavior of strain as a function of applied electric field. At low concentration of nanotubes (B-CN)APB-ODPA-SWNT composites show a stronger response than CP2-SWNT. (B-CN)APB-ODPA has a higher dipole strength compared to CP2 polyimide. A similar trend is seen even at higher concentration of SWNTs where (B-CN)APB-ODPA shows a higher response compared to CP2. It can be inferred that as the dipole moment and SWNT content in the nanocomposite increases, a higher electromechanical response is measured. Thus the nature of the polymer and the content of SWNTs affect the electromechanical response of the nanocomposites. These observations are also supported by the fact that 0.26% SWNT-PVDF composite shows higher response than both 2%SWNT-CP2 and 2%SWNT-(B-CN)APB-ODPA composites. PVDF has the highest dipole moment of all the polymers under study. We also found that PVDF-CNF samples do not show a measurable electromechanical response compared to the composites discussed earlier. Thus along with polymer nature and nano-inclusion content, nature of the nano-inclusions govern the observed actuation response.

An interesting response is demonstrated by the samples on reversing the polarity of the applied field; the sample bends in the same direction indicating a quadratic electromechanical coupling. When the strains are plotted as function of the quadratic electric field we get an excellent linear fit. These observations show that the mechanism driving the electromechanical coupling is electrostriction. For linear dielectric materials the electrostrictive strains (S_{ij}) have a quadratic dependence on applied electric field (E_k);

$$S_{ij} = M_{ijkl} E_k E_l \quad (1)$$

M_{ijkl} is the coefficient of electrostriction and the electromechanical material property. Coefficient of electrostriction shows us how strong the electrostrictive material is. The higher this value more will be the strains seen by a sample under an applied electric field. For a cantilever arrangement the electrostrictive strains are given by

$$S_{13} = M_{1333} E_3^2 \quad (2)$$

where '3' direction is through the thickness. M_{1333} is measured from the strain versus quadratic electric field plots.

All materials found in nature are electrostrictive but most of them do not show a macroscopic strain due to a low coefficient of electrostriction. Figure 2 shows that increasing the SWNT in the polymer matrix increases the coefficient. This enhancement in the coefficient reflects in the macroscopic strains. The coefficient increases with the dipole moment and is highest for PVDF based nanocomposite. Adding nano-inclusions thus results in making dormant electrostrictive materials more effective.

Dielectric relaxation and thermally stimulated current (TSC) experiments are conducted to determine the cause behind the enhanced electrostrictive effect. These tests detect the polarization in the samples as a function of the SWNT loading. The experiments show an increase in induced polarization with the SWNT loading. We believe this enhanced polarization in turn drives the electrostrictive response. The increase in polarization is attributed to induced polarization resulting from the SWNT-polymer interaction, electrostrictive nature SWNTs and polarizability of the SWNTs. Local heating at nanotube sites can also be a factor though the macroscopic sample did not show any temperature increase under an applied field.

Next we evaluate these nanocomposites as piezoelectric materials. PVDF-SWNT and PVDF-SWNT-Nanoclay are poled by a DC field to make them piezoelectric. The samples are then tested using direct and converse piezoelectric effects and resonance spectroscopy to study the effect of the nano-inclusions on the piezoelectric response of PVDF.

Thus this study targets a comprehensive investigation of the electromechanical response of polymer based nanocomposites by investigating the impact of different nano-inclusions, nature of the polymer and the interaction between polymer and nano-inclusions.

6927-23, Session 6

Polyaniline nanofibers as electrode materials for dielectric elastomer

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Dielectric elastomer actuators are devices comprised of electrode/elastomer/electrode structures. They exhibit electromechanical strain when a high electric field is applied due to the attraction and repulsion of charge, which occurs across the dielectric film. Strains 100% or greater are attainable when the electrodes are highly compliant. Structural defects inherent to the elastomer film cause dielectric breakdown, leading to premature failure. Polyaniline nanofibers have been introduced as new compliant electrode materials for their high length/diameter aspect ratio, moderate conductivity, and solution processability. Compliant polyaniline nanofiber electrodes can be readily coated by spraying from dispersion in aqueous or organic solvents. These electrodes are shown to preserve strain, even with the presence of defects. These actuators have also shown high stability over many actuation cycles.

6927-24, Session 6

Self-clearable carbon nanotube electrodes for improved performance of dielectric elastomer actuators

W. Yuan, L. Hu, S. M. Ha, T. M. Lam, G. Gruner, Q. Pei, Univ. of California/Los Angeles

Dielectric elastomer actuators which consist of an electrode/dielectric elastomer/electrode sandwich structure shows greater than 100% electromechanical strain performance when high electrical field is applied. The strain in the dielectric elastomer film occurs due to attraction of opposite charges across the dielectric film and repulsion of similar charges on each compliant electrode. Structural defects present in these elastomers such as gel particles, uneven thickness, and stress concentration may cause dielectric breakdown, leading to premature failure during continuous or repeated actuation. Dielectric breakdown consequently reduces production yield and device lifetime. Carbon nanotubes (CNTs) have been introduced as compliant electrodes for dielectric elastomers. Higher than 100% electromechanical strain was obtained with ultrathin CNT electrodes due to the high aspect ratio and the high electrical conductivity of the nanotubes. These ultrathin CNT electrodes also exhibit fault-tolerance in dielectric elastomers through the local degradation of CNTs during dielectric breakdown. The degraded areas electrically isolate the defects, while keeping the rest of the elastomer active. The "self-clearing" electrodes significantly increase the lifetime of the dielectric elastomers, potentially making the artificial material much more reliable.

6927-56, Poster Session

Tunable transmission grating based on dielectric elastomer actuators

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Optical gratings are used for light steering, wavelength splitting, and filtering in many applications in optics and telecommunication. The effect is based on properties of a periodically structured device, where interference from neighbouring sources (lattice points) create additional diffraction orders. Propagation angles of these orders (except 0th) depend on distance of lattice points and on wavelength of the light itself. Therefore, by changing the lattice constant, direction of propagation can be controlled. Each color has its own set of diffraction orders and by using an appropriate filter - e.g. slits-, a specific color can be selected. A reflective system, based on an EAP actuator has already been presented by M. Aschwanden and A. Stemmer: Polymeric, electrically tunable diffraction grating based on artificial muscles; Optics Letters; Vol. 31, No. 17; September 2006.

A transmissive diffraction grating was produced, using artificial muscle technology. Contrary to reflective devices, the incident waves have to pass the device itself and, depending on the structure, specific regions have a longer optical path, leading to diffraction. Compared to reflection gratings, there is no need for a (stiff) reflective surface. This simplification increases tuning range, the number of processing steps in production is reduced, and integration into optical systems is simplified. Furthermore, the light source can be placed on both sides of the system.

The EAP system is made of an acrylic elastomer membrane (as VHB 9460, 3M), and the electrodes are made of carbon black (Ketjenblack 300). Size and shape of electrodes and grating only depend on application area and can easily be varied. While the electrodes are applied by a simple but precise contact-printing-process, the grating is generated by a soft-lithography process using a transparent elastomer (Elastosil RT 625). To this end, a thin layer is spin-coated over a diffraction master and applied on the actuator before curing at 50 degrees Celsius for 60 minutes. After peeling off the grating master, the tunable, transmissive diffraction grating is ready for use.

6927-66, Poster Session

A cost-effective self-sensing dielectric actuator

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In this paper, we introduce a novel self-sensing technique for dielectric elastomer (DE) actuators. The technique is to adequately measure in-situ impedance variation of the DE under deformation. A standard signal processing technique was introduced to articulately mix and extract actuating and sensing signals, separately. Although the technique is limited to the actuation-bandwidth of several tens of Hz, the general practice of using it may be of good practical uses. With the self-sensing technique, a close-loop actuation system was effectively demonstrated without auxiliary sensors. It should be pointed out that the proposed technique is useful for many attractive robotic applications including space-limited micro-actuation systems and/or multi-DOF systems requiring hyper redundant manipulators. Moreover, the proposed technique is cost-effective.

6927-67, Poster Session

Frequency response of polypyrrole trilayer actuators: towards a better understanding of their dynamics

S. W. John, G. Alici, C. D. Cook, Univ. of Wollongong (Australia)

Conducting polymer trilayer actuators have potential for functional devices, given the low actuation voltages and relatively high stresses and strains; however, their dynamic behaviour needs to be modelled before engineers can effectively incorporate them into practical systems. As a first step towards identifying the dynamics of the trilayer actuator, analysis has been performed by measuring the displacement in response to a voltage signal as a function of frequency. The displacement of the trilayer could then be measured in terms of gain and phase shift for the first time. Resonance has

been identified using this technique, with the highest natural resonance occurring at 500Hz and showing good repeatability between samples. It has been found that the frequency response does not change significantly with geometry or tip load, except for the position of the resonance. A model of the resonant frequency has been derived as a function of the actuator geometry and validated against the experimental results for length, width, polymer thickness and external loading. As the resonant frequency model is dependent on the mechanical properties of the actuator, it can be fitted to the experimental results to estimate unknown parameters, including the mass and elastic modulus of the polypyrrole. This presents the first step in an ongoing effort to understand the frequency response of the actuator. This will assist with future work focussing on identifying the electrochemical mechanisms behind the frequency response, allowing the selection of geometries, optimisation of performance and design of compensating controllers for specific functional applications.

6927-69, Poster Session

Molecular dynamics studies of IPN-CP actuator material

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Interpenetrating Polymer Networks (IPNs) are combinations of two or more cross-linked polymers. The tight entanglement of the polymeric systems ensures a good interpenetration of the two components and therefore good mechanical stability. Moreover, the result can be an improved combination of the properties of its components.

Poly(ethylene oxide) interpenetrated with polybutadiene (PB) has shown promising properties as an actuator material in IPN-CP type actuators when loaded with LiClO₄ in propylene carbonate (PC) [1-2]. Polybutadiene is an electronically conducting polymer, and poly(ethylene oxide) can act as a host and solvent for the Li-salt solution, and is thus an all-polymeric ion-conductive actuator.

To achieve a picture of how the different components - the two polymers, the salt and the solvent - interact on the atomic level in such a complex system, molecular modeling such as Molecular Dynamics (MD) simulations can provide significant help. Here, we present a simulation of a system of 80% PEO (by weight) interpenetrated with 20% PB, and soaked in PC solutions of LiClO₄ with different concentrations. The local structure and dynamics of the systems, and how it changes with concentration, will be discussed. In an effort to more clearly study the Li atom transport and the transport of solvent molecules (which give rise to the actuating mechanism), a series of MD simulations with an electric field gradient over the simulation box has also been undertaken.

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6927-70, Poster Session

Redox level-dependent impedance model for conjugated polymer actuators

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The reduction-oxidation (redox) level of a conjugated polymer has significant impact on its electro-chemo-mechanical properties, such as conductivity, impedance, and Young's modulus. Understanding and modeling the influence of redox level is of interest to both fundamental understanding of conjugated polymers and practical applications of these materials. In this paper a redox level-dependent impedance model is developed by including both ionic diffusion and migration effects and by using perturbation analysis. Experimental measurements under various redox conditions, achieved through applying different DC bias voltages, correlate well with the model prediction and thus validate the proposed model. This work, for the first time, incorporates the effect of redox level into the dynamics of conjugated polymers in an integrative way, and facilitates the use of nonlinear control methods for effectively controlling these materials. A more detailed account of the contributions follows.

The modeling work starts with a nonlinear partial differential equation (PDE) capturing dynamics of ionic movement inside a conjugated polymer under both diffusion and migration effects. As an example, an anion-transporting polypyrrole is considered. The reaction dynamics of anions with polypyrrole is modeled through a time delay. The nonlinear PDE is locally linearized and explicitly solved in the Laplace domain through perturbation analysis around certain redox conditions. The equivalent circuit model consists of three branches that account for double-layer charging, ion diffusion and ion migration, respectively. The resulting impedance model includes the redox level as an explicit parameter. The proposed model degenerates to the diffusive-elastic-metal model proposed by J. Madden (2000) when one ignores the migration dynamics, the reaction dynamics, and the polymer resistance.

Experiments are conducted to verify the proposed model. The conjugated polymer used consists of (mainly) three layers, with two polypyrrole (PPy) layers sandwiching an amorphous polyvinylidene fluoride (PVDF) layer. The PVDF layer stores electrolyte (TBA.PF6 in propylene carbonate), enabling the actuator to work in air. In the experiments, the redox levels of the PPy layers are changed by applying different DC voltages across the conjugated polymer. Then a sinusoidal perturbation voltage is superimposed on the DC voltage. The impedance spectrum is measured from 0.08 Hz to 100 Hz for samples with different sizes and electrolyte concentrations. It is found that, while the proposed model and the diffusive-elastic-metal model are comparable when the redox level is low, the proposed model shows clear advantage in predicting the impedance at higher redox levels.

6927-72, Poster Session

A double-sided electret polymer film-based electrostatic actuator

C. Lee, National Taiwan Univ. (Taiwan)

In this paper, we developed an electrostatic actuator using a double-sided electret polymer film. The electret material was composed of a blended solution of cycloolefin copolymer (COC) and polystyrene(PS) and used to fabricate an actuator thin diaphragm with an electret-metal-electret structure. This double-sided electret material was charged using a corona treatment process. The surface voltage decay curve was measured at 80°C under a high humidity condition. It was found that even at a low concentration of the blended COC-PS solution, the charge storage ability of our electret polymer was more stable than in the case where there was only pure cycloolefin copolymer (COC). Our results showed that our blended electret material performs better than polypropylene (PP) and even has better machining properties than teflon (FEP). The processes we developed to optimize this new electret polymer for actuator development are detailed. The potential to adopt this new electret polymer to develop a speaker system in order to compete with a typical electrostatic loudspeaker or a headphone, which require using bulky and expensive DC/DC converters, are examined as well. The details of how to produce this new blended electret material and its associated fabrication process to produce a new electret loudspeaker are presented.

6927-73, Poster Session

Electromechanical simulation of cellulose-based biomimetic electroactive actuator

S. Jang, J. Kim, Inha Univ. (South Korea); P. Basappa, Norfolk State Univ.

Electro-active paper (EAPap) is new smart material that has a possibility to be used in biomimetic actuator and sensor. It is made by cellulose that is very abundant material in nature. This material is fascinated with its biodegradability, lightweight, large displacement, high mechanical strength and low actuation voltage. Actuation mechanism has been supposed that ionic and piezoelectric effects are affected. However, its electromechanical coupling factor and actuation mechanism is not proved yet. This paper presents the investigation of actuation modeling of water-cellulose mixture, and it simulated using their dielectric properties. From Maxwell-Wagner theory, non-uniform electric field is generated between different dielectric materials, and it makes not only electric displacement but also mechanical force. Mechanical forces are calculated using Maxwell stress tensor method. Also, bending deflection is evaluated from simple beam model and compared with experimental data.

6927-74, Poster Session

Novel electroactive polymer actuator based on ionic networking membrane of poly(styrene-alt-maleic anhydride)-incorporated poly(vinylidene fluoride)

J. Lu, Chonnam National Univ. (South Korea); S. Kim, Korea Research Institute of Chemical Technology (South Korea); S. Lee, I. Oh, Chonnam National Univ. (South Korea)

There is growing interest in searching for new smart materials, which responds to external stimuli by changes in shape or size and can be utilized in biomimetic motions. To develop artificial muscles with improved performance, a novel electro-active polymer actuator was prepared by employing the newly-synthesized ionic networking membrane of poly(styrene-alt-maleic anhydride) (PSMAAn)-incorporated poly(vinylidene fluoride) (PVDF). Scanning electron microscope (SEM) and transmission electron microscopy (TEM) revealed that much smaller and more uniform platinum particles were formed on the surfaces of the actuator fabricated through the electroless-plating technique as well as within its polymer matrix. Under constant voltage excitation, the tip displacement of the actuator constructed with the ionic network membrane was several times larger than that of its Nafion® counterpart of similar thickness without straightening-back. Under the stimulus of alternating-current voltage, the newly-developed actuator displayed an excellent harmonic performance, and the measured mechanical displacement was comparable to that of the Nafion®-based actuator. The nice electromechanical response, especially the large tip displacement, is attributed to two factors: the inherent large ionic-exchange capacity and the unique hydrophilic nanochannels of the ionic networking membrane. The actuator of PSMAAn-incorporated PVDF has some advantages over the most widely-used traditional Nafion-based actuator by diversifying niche applications in biomimetic motion, and the present study may possibly open a new avenue for the design and fabrication of the electro-active polymer with unique functional properties.

6927-75, Poster Session

Self healing properties of Cu-Pt coated ionic polymer actuators

U. Johanson, A. Punning, M. Kruusmaa, A. Aabloo, Tartu Ülikool (Estonia)

Ionic Polymer Metal Composite (IPMC) actuators consisting of sheets of the solid polymer electrolyte (Nafion® type) with Cu²⁺ counter-ions inserted and coated with platinum and copper metal layers have been synthesized and their electromechanical performance upon actuation has been monitored. Resistivity measurements on the electrodes show that the electrical conductivity of the metal electrodes on the membrane surface increases on the cathode side during the actuation process, contradictory to the situation when copper is absent from the metal coating. Therefore we assume that a new layer of Cu is formed between Pt-particles in the electrode layer and also in the Nafion® matrix close to the Pt-electrode on the cathode side. At the same time, Cu is depleted from the anode side during the creation of Cu²⁺ ions. These changes are also detectable from SEM images. Both these electrode reactions occur while the Cu²⁺ ions migrate toward the cathode in the polymer matrix, and thus the process assists to pump water in that direction, causing the actuating motion. This continuous production of Cu²⁺ also represents an elimination of another limitation to the use of IPMCs, since back-diffusion of cations towards the anode will be much less of a problem. Yet another positive factor to take into account is that the number of possible mobile cations increases with several orders of magnitude compared to IPMCs without electrochemical electrode reaction. In IPMCs the number of mobile ions is usually limited by cations initially paired to the polymer -SO₃⁻ groups, while here new Cu²⁺ ions are created at the anode during the actuation process. Therefore the water quantity which can be transported in this system can be significantly higher. This, however, increases the importance of leakage protection at the electrodes. From electrode resistivity measurements it is detected that electrode conductivity is continuously improving upon cycling. These results indicate that the Cu-layers in the samples are rebuilt during the cycling in more evenly distributed mode and in better contact with the Pt particles.

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This phenomenon opens up for longer life-times and better performance for copper-based IPMCs. Unwanted side reactions are related with copper dendrite growth at higher working voltages and insoluble non-conductive copper¹⁺ compound formation. If the muscle actuation was driven at a higher voltage > 4 V - the system clearly short-circuit after 25 cycles. This indicates growth of Cu dendrites, which is known to occur in many other electrode reactions containing systems for example lithium batteries. Dendrite growth was confirmed by SEM. Another observation is the appearance of non-conductive insoluble Cu⁺ compounds on the electrodes. Cu⁺ ions are created through the spontaneous redox reaction between Cu atoms in the metal electrode layer and Cu²⁺ ions in the membrane: $\text{Cu(s)} + \text{Cu}^{2+} \rightarrow 2 \text{Cu}^+$. The Cu⁺ formation was determined by chemical analysis of formed compounds.

6927-76, Poster Session

A multilink manipulator with IPMC joints

A. Hunt, A. Punning, M. Anton, A. Aabloo, M. Kruusmaa, Tartu Ülikool (Estonia)

We present a novel design of an IPMC manipulator with IPMC joints. The manipulator consists of passive rigid links connected with IPMC joints. We show that this kind of a design permits controlling the manipulator using traditional inverse kinematics equations commonly used in robot manipulator control. We demonstrate experimentally that the precision of this kind of a manipulator increases compared to the manipulator consisting of a single IPMC strip. Also the workspace of such a manipulator increases from a circular trajectory to a 2D workspace. The experiments are designed to test the precision of the manipulator using inverse kinematics control in open loop. Furthermore we give a theoretical explanation to the experimental results based on our previous work in IPMC material modeling. We give guidelines for designing such a manipulator based on task constraints, such as required output force and the reachable workspace. We conclude that the novel design significantly decreases the control complexity of IPMC manipulators and brings it closer to real applications. The proposed IPMC manipulator configuration is considered to be suitable for soft manipulation and micromanipulation.

6927-77, Poster Session

ECMD behaviour of free-standing PEDOT films in organic and aqueous electrolytes

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The conducting polymer poly-3,4-ethylenedioxythiophene (PEDOT) can produce moderate electrochemical strains of 1-3 %, and it has been proposed for applications such as micro valves and micro pumps^{2,3}. The size of the anion under polymerisation conditions plays an important role in the actuation of the free standing conducting polymer films^{4,5}. Previous studies on free standing PPy films under isotonic conditions, tested in propylene carbonate as a solvent, have shown a mixed-ionic (both cation and anion-driven) actuation during electrochemical redox reactions^{6,7}. When PEDOT was used under the same conditions predominately cation-driven actuation was observed⁸.

Here we present the results on the electrochemical mechanical deformation (ECMD) properties of free standing poly-3,4-ethylenedioxythiophene films when tested in solutions of different electrolytes (TBACF₃SO₃, LiCF₃SO₃, TBAPF₆, NaPF₆, TMACl and NaDBS) and solvents (propylene carbonate (PC), water) under isotonic conditions. All PEDOT films were prepared potentiostatically (1.0 V, vs. Ag/Ag⁺) from PC solutions of TBACF₃SO₃. The aim was to investigate whether the immobilized CF₃SO₃⁻ anions in the PEDOT film are ion-exchanged during the electrochemical cycling when the actuation tests are done in different electrolyte systems and how that affects actuation performance.

In addition to electrochemical and mechanical deformation properties, the morphologies of the PEDOT films cycled in different electrolytes have been investigated using scanning electron microscopy.

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6927-79, Poster Session

The sensor response of polypyrrole trilayer benders as a function of geometry

S. W. John, G. Alici, G. M. Spinks, Univ. of Wollongong (Australia)

Electroactive cantilever structures, such as conducting polymer trilayer benders, show promise as mechanical force or displacement sensors as they generate a voltage or current when contacted physically. While the mechanisms behind this sensor response have not been fully identified, previous work has proposed the 'deformation induced ion flux' model and has fitted transfer functions to the sensor response, both matching the experimental observations well. The aim of the current work is to further explore the sensor response and identify any effect of input signal or bender geometry. The thickness of conducting polymer, width and length of the benders were all varied and the voltage and current response measured as a function of the input displacement frequency. Comparison of the identified frequency responses showed the dependence on the actuator geometry and type of input. Proportionality of generated signal output to the amplitude of input is also presented and indicates that the sensor response is linear. Future work will explore the sensor response in terms of the geometry and the 'deformation induced ion flux' model.

6927-80, Poster Session

High-precision characterization of dielectric elastomer stack actuators and their material parameters

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Stacked dielectric elastomer actuators (DEA) act as solid state actuators. Due to our multilayer fabrication process actuator arrays with sizes down to 1 mm diameter are achievable. Modeling such electromechanical systems demands the knowledge about the mechanical and electrical parameters of the used materials as well as the real static and dynamic behavior of the system.

In dielectric elastomer actuators the deformation is caused by the Maxwell stress which is dominated by the material's specific permittivity and the electric field strength E . Accordingly, the dielectric layer has to fulfill several requirements. As it is known from alternative materials (e. g. polyacryl) in elastomer actuators the electrical properties of the materials might change with applied mechanical stress or applied voltage. Therefore, we examined the PDMS used in stacked dielectric elastomer actuators regarding such dependencies.

In this paper we present results from testing the permittivity of two different silicones (Elastosil P7670, Wacker Silicones; RTV410, Bayer) versus mechanical stress, frequency of the driving voltage and film thickness. Furthermore, the curing temperature is investigated as it influences the polymerization. Determining the electric breakdown voltage of several ten micrometers thick elastomeric films at different frequencies requires non standard measurement equipment. To perform the tests, an appropriate measurement setup has been designed following international standards. Taking these results into account, several improvements for automated fabrication process can be derived. All characteristics and conclusions will be presented in the full paper.

The exact detection of a DEA stack's deflection requires an elaborate measurement system. The average change of thickness of an activated elastomer stack actuator is up to 20 % of its original shape. Due to the small achievable sizes of actuator elements a density of up to 25 elements per mm₂ is achievable. The resulting movement is not a single displacement of the elements but a rather complex bulk deformation. Therefore, a planar displacement measurement system is necessary. Even very small inhomogeneities in the material and the asymmetric stress caused by the mounting influences the deformation. Using laser displacement sensors offers the possibility of a two-sided measurement. This allows us to determine the actual thickness variation even if the actuator array moves out of plane. To get a two dimensional information of the deflection a positioning stage is added to the setup. In the full paper we will present the measurement system and the design of the appropriate mechanical setup. This includes a prestretching device to clamp the actuators symmetrically and to simulate an uniaxial load. The realized measurement setup has an effective vertical measurement range of 10 mm, a resolution of 100 nm at a sample rate of 20 kHz and allows the measurement of static displacement characteristic and the frequency response of the deflection.

In the full paper we will present the automation of the test setup under consideration of the time-critical signal processing during the measurement. Finally, the accuracy of the whole test setup and results of a typical stacked elastomer actuator are shown.

6927-81, Poster Session

Dielectric elastomer actuators using improved thin film processing and nanosized particles

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Stacked dielectric polymer actuators provide high density of actuator elements. Along with the typical high deformation this topology is very well suited for patterned surface deformation (e.g. tactile displays) and complex bulk deformation (e.g. miniaturized fluid system) as well. The deformation of the film results from the Maxwell stress between the electrodes on the dielectric film and the reciprocal Young's modulus. In order to increase the overall performance of the actuators at relatively low voltages there are consequently three factors: the film thickness, the permittivity and the breakdown voltage.

In this paper we present two different ways of improving the performance of dielectric actuators. First, it is desirable to fabricate dielectric films with a thickness below 20 µm. This can be achieved by high speed spin coating of an uncured elastomer. Analyzing the automated process reveals nine principal process parameters. An adequate design of experiment reduces the number of necessary tests to an acceptable value. In fact, we identified three factors which influence the quality of the film mainly. These are the rotational speed of the spin coater, the spinning time and the spin coater's temperature. Several other parameters influencing the quality of the thin films are detected and first proposals of solving them are given (e.g. the comparison with film coating in deep lithography led to the use of a Gyrset). For this reason the film's quality at high rotational speed of up to 14,000 rpm is improved and the amount of elastomer can be reduced drastically. The quality of the film is described by the mean thickness, variation of the thickness over the film's diameter and the number of defects within the film. With these results we are able to spin thin films with a thickness of less than 5 µm and a thickness variation of about 3%.

Secondly, to improve the performance of dielectric actuators we examined the influence of nanosized particles of metal oxide powder on the permittivity of the elastomer film. Three different materials, namely aluminiumoxide, titaniumdioxide and bariumtitanate with a bulk permittivity of about 10, 100, 1000, respectively, have been used to increase the overall permittivity of the composite. The measured dielectric constant is compared to several models from literature predicting the resulting permittivity of composites made from two different materials. Looyenga's model predicts a permittivity of 3.2 at 10 %vol aluminiumoxide and 3.5 at 10 %vol titaniumdioxide. With measured values of 3.4 and 4.0 the model fits good enough to trust the predicted $\epsilon_r = 5$ for bariumtitanate. This shows an improvement of a factor 1.6 compared to the original permittivity of the pure elastomer.

Improving the composite's permittivity may result in decreased electrical field strength or a higher Young's modulus. To predict the resulting performance of an elastomer actuator the figure of merit k is introduced, containing the three parameters mentioned before. Full characteristics of all produced composites will be shown in the full paper.

6927-82, Poster Session

Frequency response characteristics of IPMC sensors with current/voltage measurements

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Ionic polymer-metal composite (IPMC) is a low-voltage driven soft actuator. It can also be used as a sensor, because an IPMC film generates electro-mechanically coupled charge/voltage when it deflects. Therefore, IPMCs are expected as soft and distributed sensor materials used in biomimetic applications. In this study, we focus on the principle of the IPMC sensor response and the modeling of the sensor characteristics. In the experiment, the frequency responses of the IPMC sensor dynamics from the deflection to the current, or voltage, are measured for some cation species. The IPMC is excited mechanically by swept sine signal. The generated charge or the voltage is measured by a current amplifier or a voltage amplifier, respectively. The measured data are processed in the frequency domain in order to estimate the frequency response function. The difference between the current (or charge) sensing and the voltage sensing are observed. Furthermore, the electrical impedance is measured. This paper shows the charge, current and voltage sensing characteristics and the relation to the impedance. The charge response has relatively flat gain, though the voltage response does not have flat gain. The voltage response varies much with respect to the cation species. These properties of the voltage response are directly related to the impedance dynamics. A simple model based on Onsager's equation is shown in order to explain the experimental data. The model of the current (or charge) sensing transfer function is just a constant. The voltage sensing model consists of the electrical impedance. Though the theory prediction does not match the coefficient, the frequency response characteristics of the model agree with the experimental data.

6927-83, Poster Session

Preisach modeling of IPMC-EMIM actuator

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The IPMC-EMIM actuator is an improved IPMC actuator to replace the water by stable ionic liquids (1-ethyl-3-methylimidazolium trifluoromethanesulfonate ([EtMeIm][TfA])). Just as a general IPMC actuator which uses the solvent of water has hysteresis, so do the IPMC-EMIM actuator exhibits hysteresis like other smart materials such as piezoceramics (PZT), magnetostrictive materials, and shape memory alloys (SMA). Hysteresis can cause it to be unstable in closed loop control. The Preisach Model has been used to model the hysteretic response arising in PZT and SMA. Noting the similarity between IPMC-EMIM and other smart materials, we apply the Preisach model for the hysteresis in the IPMC-EMIM actuator. This paper reviews the basic properties of the Preisach model, discusses control-theoretic issues and presents experimental results for IPMC-EMIM actuator.

6927-84, Poster Session

Preisach modeling of dielectric elastomer EAP actuator

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DE EAP (Dielectric Elastomer ElectroActive Polymer) has advantages in its weight, ease of fabrication and low power consumption. So, there are many efforts applied to various fields in the most recent ten years. But, because of hysteresis, the present modeling is not enough to appear its characteristics. So, in this paper, we propose modeling of DE EAP with Preisach Model that is used to model the hysteretic response arising in PZT and SMA. The modeling of DE EAP with Preisach model is verified by experiment and simulation with various DE EAP actuators.

6927-85, Poster Session

Porous conductive polyblends of polyaniline in poly(methyl methacrylate)

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The conductive polymer polyaniline is typically blended with conventional industrial thermoplastics in order to obtain an electrically conductive polymer blend with adequate mechanical properties. Processing these polyblends into foams yields a porous conductive material that exhibits immense application potential such as dynamic separation media and low-density electrostatic discharge protection. Previous work has reported on the foaming limitations of dry-blended compounds. In the current study, the morphology of a solution-processed blend consisting of an electrically conductive polyaniline-camphor sulfonic acid complex and poly(methyl methacrylate) is explored using a two phase batch foaming setup. The effect of blend composition and processing parameters on the resulting cellular morphology is investigated. Finally, the impact of the underlying microstructure on the electrical conductivity is elucidated.

6927-86, Poster Session

Classification and selection of actuator technologies with consideration of stimuli generation

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Background.

To date, a number of attempts have been made to classify and compare actuators [1-3]. All existing actuator comparisons choose a variety of units that are used to evaluate the relative performances of different actuation technologies. The suitability and importance of chosen "figures of merit" [2] is rarely justified by the fundamental requirement of an actuator. Existing comparisons also typically use active material performance as a source for actuator data, even though a material on its own is not active.

Little or no attempt to classify different actuation technologies and configurations with consideration of the nature and provision of a stimulus has been made. A stimulus generation must be present for an active material to be used as an actuator and the addition of local stimulus generation can severely affect the performance of an actuator. For example, a magnetostrictive alloy has a very high power to weight ratio, but when the required stimulus generation is packaged with the material, the power density reduces approximately one hundred fold. Most figures of merit are only important by the nature of the application of an actuator, but some are always important simply by the intrinsic requirement of an actuator.

Method

With the aim of identifying new areas of research, existing technologies are split into components. These are the material or phenomena that provide mechanical power, the type of stimulus required to "excite" the technology and the geometrical arrangement, or configuration of the technology to manifest as an actuator. This actuator component identification is done in such a way as to allow all combinations of stimulus and actuator technology to be considered for development. The process of the selection strategy is demonstrated through an industrial case study.

EAP actuators (particularly dielectric elastomers) are famously configurable in a large variety of ways due to their compliance. These configurations are considered alongside the configuration of other actuators allowing them to be honestly compared.

Conclusion

Actuator technologies are categorised by means of varying stimuli types and configuration styles. Pre-defined and prioritised figures of merit for actuators are defined and justified. They are used to form a coherent base for the formation of a practical actuator selection strategy suitable for engineers and designers. By the structured nature of categorisation and figures of merit justification, many new areas of potential research interest are identified. These include many not yet considered combinations of actuator configuration and technology along with novel technology combinations to achieve bespoke actuator performance without the need for discrete mechanical systems.

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6927-87, Poster Session

Electric field sensitive poly(p-phenylene vinylene)/polydimethylsiloxane gel

S. Niamlang, A. Sirivat, Chulalongkorn Univ. (Thailand)

PPV/PDMS blends were prepared and investigated as an electroactive polymer actuator. The effects of particle concentration and electric field strength on the deflection of soft and flexible PPV/PDMS blend films, suspended in silicone oil between copper electrodes were investigated. With an external electric field applied, the PPV/PDMS film responds with a significant and rapid bending towards the anode with the amount of bending dependant on the electric field strength, indicating the attractive interaction between the anode and the polarized PPV particles embedded in PDMS network. As the electric field is removed, the PPV/PDMS nearly recovers its original position and shape due to the gravitational force, its elasticity, and the reversible polarized PPV particles. Thus, our PPV/PDMS is a reversible bending system. Finally, we measured the degree of bending, and the dielectrophoresis force, FD, of the PPV/PDMS films when the electric field was applied. The degree of bending and dielectrophoresis force, FD, are linear functions of electric field strength.

6927-88, Poster Session

The electric field around a dielectric elastomer actuator in proximity to the human body

A. C. McKenzie, The Univ. of Auckland (New Zealand); E. P. Calius, Industrial Research Ltd. (New Zealand); I. A. Anderson, The Univ. of Auckland (New Zealand)

Dielectric elastomer actuators (DEAs) are a promising artificial muscle technology that will enable new kinds of prostheses and wearable rehabilitation devices. DEAs are driven by electric fields in the MV/m range and the dielectric elastomer itself is typically 30µm in thickness or more. Large operating voltages, in the order of several kilovolts, are then required to produce useful strains and these large voltages and the resulting electric fields could potentially pose problems when DEAs are used in close proximity to the human body. The fringing electric fields of a DEA in close association with the skin were modelled using finite element methods. The model was verified against a known analytic solution describing the electric field surrounding a capacitor in air. The agreement between the two is good, as the difference is less than 10% unless within 3.7mm of the DEA's lateral edges. As expected, it was found that for a DEA constructed with thinner dielectric layers, the fringe field strength dropped in direct proportion to the reduction in applied voltage, despite the internal field being maintained at the same level. More interestingly,

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modelling the electric field around stacked DEAs showed that for an even number of layers the electric field is an order of magnitude less than for an odd number of layers, due to the cancelling of opposing electric fields.

6927-89, Poster Session

Microwave-powered ionic polymer-metal composite actuators

J. Lee, W. Yim, Univ. of Nevada/Las Vegas; K. J. Kim, Univ. of Nevada/Reno

While past studies of I-EAP actuators have provided important results in understanding the dynamics and control of such systems, the practical implementation for biomimetic robotic systems remains out of reach, mainly due to the complex wiring for a large-degree-of-freedom system and the limitations of carrying a heavy battery for untethered operation. This problem is even worse for micro-scale robotic applications. In this paper we present preliminary modeling results that introduce a microwave based power transmission and control approach for long-term, untethered operations of a robot.

6927-90, Poster Session

Improved electromechanical response in interpenetrating networks of dielectric elastomers

S. M. Ha, Univ. of California/Los Angeles; I. Park, Univ. of Nevada/Reno; R. Pelrine, SRI International; K. J. Kim, Univ. of Nevada/Reno; Q. Pei, Univ. of California/Los Angeles

We have shown interpenetrating polymer network (IPN) composite films as a new category of high actuation performance dielectric elastomers. We will present our recent findings on IPN films based VHB acrylic elastomers. The IPN electroelastomers were prepared by introducing crosslinkable liquid additive into highly prestrained acrylic films and subsequently curing the additive to form the second elastomeric network. The resulting free-standing films exhibited high actuation strain and stress comparable to those of highly-prestrained VHB films. Dynamic mechanical analysis (DMA) showed that these IPN electroelastomers have low viscoelasticity, high mechanical efficiency and improved electro-mechanical coupling factor.

6927-92, Poster Session

Architecture for the semi-automatic assembly of thin-film modular units of dielectric elastomer in a compact macroscopic actuator

M. Randazzo, Istituto Italiano de Tecnologia (Italy); R. Buzio, Nanomed Labs. (Italy); U. Valbusa, Univ. degli Studi di Genova (Italy)

One problem related to the actuation principle of macroscopic dielectric elastomer actuators is the high voltage required, typically in the Kilovolt range, that imposes particular care in the insulation of the whole actuator from the surrounding environment. This high actuation voltage, however, can be drastically reduced if a thin film of dielectric elastomer is used. Despite this, the manufacture of a macroscopic stack-like actuator, starting from thin-films of dielectric elastomer can present many manufacture difficulties, like the handling and the assembly of the films, the power distribution to hundreds or thousands of layers, the presence of defects in one single layer that can cause the complete failure of the whole actuator. In this paper, a fast, semi-automatic procedure is proposed for the manufacture of small modular units of dielectric elastomer, each of them consisting of many layers of rolled thin dielectric film. The proposed geometry allows simple fabrication and can be implemented effectively with a semi-automatic machine. All the manufactured contractile units are independent and take their power from a lateral, compliant supply rail that contacts the sides of two shifted electrodes. This design is very suitable for industrial production: each module can be independently tested and then assembled in a complete macroscopic actuator composed by an unlimited number of these modules. Prototypal actuators have

been manufactured using films of silicone elastomer and VHB acrylate tape, 50um thick. The simple geometry proposed in this paper and the semiautomatic manufacture procedure adopted allowed the simple fabrication of stacked, contractile actuators of several cm of length.

6927-25, Session 7

From dielectric elastomers to cellular ferroelectrets: soft matter as electroactive transducer materials

R. Schwödauer, I. Graz, S. Bauer-Gogonea, S. Bauer, Johannes Kepler Univ. Linz (Austria)

Elastomers and cellular polymers are usually employed on a large scale in packaging applications. They are therefore inexpensive materials that can be processed in large areas. By design, such materials are also attractive as electric field activated polymers (EAPs). In elastomers Maxwell stresses are employed to generate large area expansion rates, while internally charged cellular polymers display a large longitudinal piezoelectric, with piezoelectric d-coefficients comparable to piezoelectric ceramics. Elastomers and cellular polymers are therefore interesting for applications in actuators and sensors. In the presentation a short tour d'horizon through selected applications is given, starting with minimum energy actuators made of dielectric elastomers, followed by transducer applications of cellular polymers, such as microphones, flexible switches and touchpads. Special emphasis is given on the integration of such smart EAP's with flexible macroelectronic components based on amorphous silicon or organic semiconductor transistor devices, used for signal amplification and conditioning. Thereby new application areas are opened for EAP's in flexible sensing for advanced man-machine interfaces, smart skin and textiles, as well as invisible electronics.

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6927-26, Session 7

A dielectric electroactive polymer generator-actuator model for dynamic simulation

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Dielectric electroactive polymer membranes have been shown to have capabilities both as actuators and generators. Recent models of actuators have shown full input to output dynamics that link the electrical energy input to the acceleration of a mass. Models such as these are useful for implementing closed loop control systems and will be necessary in the future for the construction of robust and fault tolerant controls. On the other hand, explanations of the generator behavior of dielectric EAP devices tend to ignore full dynamics. In this paper it is demonstrated that an EAP actuator model with full electrical-mechanical dynamics can be used as a generator model with the generator input force equivalent to the actuator disturbance force. This is a condition analogous to the dynamic model of a DC motor where the definition of a motor or generator depends on whether the goal is to output mechanical energy or to output electrical energy. While the dynamics of mechanical coupling are not necessary in all generator designs, they become important when trying to accurately model systems where the input forces are efficiently matched to the generator. Since the generator and actuator models are equivalent, it can be shown how disturbance inputs can cause energy surges back toward the electrical input. A full model can be used to test the feasibility of capturing this energy in some sort of regeneration scheme. Even if the state of semiconductor technology makes some regeneration schemes impractical, these energy surges may still have implication for the voltage handling capabilities of the driving circuitry. To verify these concepts, it is the goal of this paper to show how any well known algebraic model of an EAP device that relates force to voltage can be used in a dynamic model suitable for closed loop control design. Simulations and experimental results are provided of an actuator model in closed loop control acting in both generator and actuator modes.

6927-27, Session 7

Feasibility studies for a bionic propulsion system of a blimp based on dielectric elastomers

S. A. Michel, EMPA (Switzerland); A. Bormann, Aeroix (Germany); C. Jordi, EMPA (Switzerland); E. Fink, Technische Univ. Berlin (Germany)

In this paper feasibility studies for a blimp with a bionic propulsion system will be presented. After having successfully integrated Dielectric Elastomers (DE) in a cross tail for flight control, a novel biologically inspired propulsion system based on DE is envisaged. The basic idea is to mimic a fish body motion by deforming a) the envelope of the rear lifting body and b) flapping a biologically similar aft-tail. In both cases, planar DEs are used as actuation technology, either fully integrated in the envelope (for a) and/or arranged as a powerful active hinge (for b). Such a novel airship design has an outstanding efficiency, an excellent noise level and very good maneuverability.

At the University of Stuttgart (Nägele and Götz, 2006) the kinematics of various fish-motions were analyzed. The characteristic parameters for classifying fish motion are: Reynolds Number, Strouhal Number, reduced frequency and the active length of the body. In a first theoretical study performed at ETH Zurich and Empa, typical shape and motion for an airship in air were defined, based on known parameters of a fish in water, using the theorem of fluiddynamic similarity.

In a second theoretical study, a collaboration of Empa and Aeroix, the specifications for a design of an airship flying steady-state horizontally indoor with 1 m/s were defined. The critical parameters were identified to be primarily the structural weight and the center of gravity, which are both mainly defined by the number of degrees-of-freedom for the body deformation.

In a first experimental work the concept of an active hull element, which consists of a multi-layer hull material, specially developed for small LTA-objects and several layers of DE actuators was verified. The specific boundary conditions of a slightly pressurized elliptical membrane body were simulated in a biaxial test. It could be shown, that the necessary active strains to reach the specified body deformations were reached by activation voltages below a critical value.

In a second experimental study an aero-elastic aft-tail was designed. Based on fluid dynamic similarity principles the size, shape and stiffness of the aft-tail were determined and tested in preliminary flight test with a 3 meter long blimp. The main goal of 1 m/s flight velocity could be shown.

From these development tests and models we can conclude, that a 6 meter long active blimp, with a novel bionic propulsion system mimicking the fish body motion, is in principle feasible. A indoor-flight of a correctly designed 6 meter long airship should reach a flight velocity of 1 m/s. The key technology is to integrate DE actuators in the blimp envelope. Further studies are necessary to define the final design of the blimp and to clarify the fabrication processes of the active envelope.

6927-28, Session 7

An experimentally validated model of a dielectric elastomer bending actuator

B. M. O'Brien, The Univ. of Auckland (New Zealand); E. P. Calius, Industrial Research Ltd. (New Zealand); S. Xie, I. A. Anderson, The Univ. of Auckland (New Zealand)

For some applications it is desirable to exploit the impressive performance characteristics of Dielectric Elastomers (DEs) in a bending mode, however their inherently planar nature can greatly complicate implementation. Kofod, Paajanen and Bauer have presented Minimum Energy Structures (MES); where the pre-stretch in a DE membrane causes the collapse of an initially planar attached frame. With electrical activation, the structure can then produce useful bending actuation. Key advantages of MES include the ability to fabricate bending actuators in plane, and the elimination of bulky pre-stretch supporting components which are often found in other DE devices.

This paper presents an experimentally validated nonlinear finite element model of a MES-based bending actuator. Model development is presented as well as strategies for dealing with the large displacement and non-

linear behavior of the device. An Ogden model incorporating some viscoelastic effects was used to describe the stress-strain response of the DE material.

Meso-scale triangular (base size ~50mm) actuators with 3 different pre-stretch ratios were fabricated using 3M VHB acrylic films on polyethylene terephthalate (PET) frames. Six actuators of each of these 3 types were tested to quantify experimental scatter. Blocked forces at the tips were compared with the model and gave good correlation. The best actuators produced around 5mN blocked force and 6mm displacement at 2500V, which are good values for a test article whose design has not been optimized.

6927-29, Session 7

PDMS as a dielectric elastomer actuator material

S. J. Patil, E. Smela, Univ. of Maryland/College Park

It has recently been reported that poly (dimethylsiloxane), PDMS, can be used without prestrain in dielectric elastomer actuators (DEAs). Actuators made of 100 μm thick PDMS films with carbon grease electrodes show 15% strain at 10 kV without pre-strain. In the present work, PDMS is fully characterized as a DEA material. Actuator characteristics under a wide range of realistic operating conditions, include dynamic actuation under different loads and speeds, are obtained.

The most common performance metrics for these actuators are stress and strain induced by the electric potential under isotonic (constant force) and isometric (constant length) conditions. Isotonic measurements were performed by applying different voltages and measuring the elongation/contraction of the sample under increasing loads. Isometric measurements of stress were performed under different prestrains. Both sets of measurements were carried out as a function of frequency. In addition, the Young's modulus was also measured as a function of prestrain and frequency.

Work loops are used by biologists to characterize muscles. Work loops can be defined as the capability of muscle to produce mechanical work under periodic motions. The workloop can be for estimating power output capability of muscle. The DEA actuators were also characterized using the work loop technique.

6927-30, Session 7

Ion-implanted compliant and patternable electrodes for miniaturized dielectric elastomer actuators

S. Rosset, M. Niklaus, A. Felber, P. Dubois, H. R. Shea, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Electrodes for macroscale Dielectric Elastomer Actuators (DEA) are typically made of carbon powder or grease. This is a crucial obstacle to the miniaturization of DEAs for which a patternable and cleanroom compatible electrode-creation technique is needed. We have successfully used Filtered Cathodic Vacuum Arc (FCVA) metal ion implantation to create compliant and patternable titanium electrodes for micro-DEAs[1] and showed its limited impact on the mechanical properties of thin (30 μm) PDMS membranes compared to other microfabrication-compatible techniques such as cathodic sputtering[2]. FCVA implantation is also applicable to larger (macroscale) actuators and presents several advantages compared to powder-based methods: a) it is clean to work with, b) it does not add mass or thickness to the actuator, and c) it has a limited impact on the PDMS optical transmission properties, which can therefore be used in optical applications for which transmission is desirable.

While having excellent mechanical properties, electrodes made with titanium ions are prone to oxidation and remain conductive for only a few days [2]. We have made complimentary measurements of the mechanical properties of layers implanted with gold and palladium, which do not oxidize, and have observed a very low impact on membrane's stiffness, comparable to the results for titanium. Electrical resistivity of thin implanted silicone bands was measured when uniaxially stretched for different implanted species. Samples were prepared by spin-coating a thin (25 μm) PDMS (Nusil CF19-2186) layer onto a silicon substrate coated with

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a sacrificial photoresist layer. After curing, the PDMS was implanted in our FCVA chamber and cut into bands 5 mm wide which were released by dissolving the sacrificial layer in acetone. The PDMS bands were mounted in a traction apparatus and were shown to remain conductive up to 47% strain for gold ions. Dielectric breakdown has been measured for sputtered and implanted electrodes. Measurements show that ion implantation does not significantly degrade the dielectric strength of PDMS.

Characterization of the optical transmission of unimplanted and implanted PDMS is underway to evaluate the possible use of ion-implanted EAPs for optical applications.

Ion implantation is an interesting and promising alternative to carbon-based electrodes for micro-actuators. We have made circular membrane actuators with gold-implanted electrodes capable of out-of-plane strains up to 8-10% of their size. When loaded with a pressure of 1kPa, the voltage-induced vertical displacement is reduced to about 2% for an applied voltage of 800V. Ion implantation would also benefit larger (macroscale) actuators, but the main difficulty consists in the development or availability of an implantation system capable of treating large areas.

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6927-31, Session 7

Study on core free rolled actuator based on soft-dielectric EAP

G. M. Kovacs, EMPA (Hungary); Q. Pei, Univ. of California/Los Angeles; L. Düring, EMPA (Switzerland); R. D. Kornbluh, SRI International; S. M. Ha, Univ. of California/Los Angeles

Among the electronic polymers EAPs especially the dielectric elastomers are functional materials that have promising potential as muscle-like actuators due to their inherent compliance and good overall performance. The combination of huge active deformations, high energy densities, good efficiencies and fast response is unique to dielectric elastomers. Furthermore, they are lightweight, have a simple structure and can be easily tailored to various applications.

Planar pre-strain is required for dielectric elastomer film manufactured from VHB 4910 acrylic to attain high electromechanical strain and high elastic energy density. In addition pre-stretching increases the dielectric breakdown strength of the film and as a consequence, higher electric fields can be applied to the DE actuator.

The rolled actuator represents a design where the pre-stretched EAP film is wrapped many times around a spring core in order to form a multilayer actuator system with unidirectional actuation. The freestanding rolled configuration enables the use of the DE film for muscle like linear actuators with a broad application potential. The stress state of the pre-strained acrylic film in the rolled configuration and the required stiff core can cause several serious problems concerning lifetime, size and efficiency of the actuator.

In order to obtain an acceptable specific actuator performance and lifetime the pre-stretching stress has to be essentially reduced or even eliminated. This can be achieved by the interpenetrating polymer network (IPN) process newly developed by Pei (UCLA). Thereby a trifunctional methacrylate monomers is introduced into the highly pre-strained acrylic films and subsequently curing the monomers to form an interpenetrating elastomeric network. The as obtained interpenetrating polymer network (IPN) can effectively support the pre-strain of the acrylic film and consequently eliminate the need for external pre-strain-supporting structures.

In this study a new rolled actuator design is presented based on the IPN post treated VHB material. Due to the stress free state of the wrapped film no spring core is necessary. As a result a significantly longer lifetime and better specific volume efficiency of the actuator has been achieved.

Introductorily, the specific problems on conventional rolled actuators are discussed and the aims for core free rolled actuators are specified. Then some structural design parameters are addressed in order to achieve a

slight shape and reliable working principle. In the main part of the study the manufacturing process of the actuators and some measurement results and experiences are discussed in detail.

6927-32, Session 8

Coupled chemo-electro-mechanical simulation of polyelectrolyte gels as actuators and sensors

T. Wallmersperger, D. Ballhause, B. H. Kröplin, Univ. Stuttgart (Germany); M. Günther, Z. Shi, G. U. Gerlach, Technische Univ. Dresden (Germany)

Polyelectrolyte gels are ductile elastic electroactive materials. They consist of a polymer network with charged groups and a liquid phase with mobile ions. Changing the chemical or electric conditions in the gel-surrounding solution leads to a change of the chemo-electro-mechanical state in the gel phase: diffusion and migration of ions and solvent between the gel and solution phases trigger the swelling or shrinkage of the polymer gel.

In case of chemical stimulation (change of pH or salt concentration), a swelling ratio of up to 100% may be obtained. Due to this large swelling ratio the gels exhibit excellent actuator capabilities.

In this paper, a polyelectrolyte gel placed in a solution bath is investigated. The actuator and sensor capabilities are described by a chemo-electro-mechanical model. The chemical field is represented by a convection-migration-diffusion equation while the electric field is described by a quasi-static Laplace equation. For the mechanical field a partial differential equation of first order in time is applied. Inertia effects are neglected due to the relatively slow swelling/shrinkage process. On the one hand, the coupling between the chemo-electrical and the mechanical field is realised by the differential osmotic pressure stemming from the concentration differences between gel and solution. On the other hand, the mechanical deformation influences the concentration of the bound charged groups in the gel. The three fields are solved simultaneously by applying the Newton Raphson method using finite elements in space and finite differences in time.

The developed model is applied on both, hydrogel actuators and sensors. Numerical results of swelling and bending are given for chemically and electrically stimulated polymer gels. The inverse (sensor-) effect is demonstrated by applying a mechanical deformation on the gel, which results in a change of the chemical and electrical unknowns in the gel.

The validity of the employed numerical model is shown by a comparison of the mechanical and electrical results with experimental measurements.

6927-33, Session 8

Modeling of a thin resonant membrane excited by a compliant capacitor

G. A. Slipper, J. E. Hubbard, Jr., Univ. of Maryland/College Park

Electroactive Polymer Synthetic Jets (E-Jets) exploit instabilities at membrane modal resonances for efficient operation. The resonating membrane is used to induce a significant periodic change in a chamber volume, which is converted to a periodic velocity through a nozzle at one end of an enclosed chamber. The membrane employed in E-Jet devices is a pre-strained viscoelastic dielectric material with a low Young's modulus. Membrane resonances are excited using a compliant capacitor generating periodic Maxwell stress to vary the membrane stiffness in an area sandwiched by compliant electrodes. The presence of modes approximating classical membrane modes has been observed experimentally at frequencies between 100Hz and 1000Hz for a circular membrane 5cm in diameter and 0.1mm thick. An increase in induced velocity performance has been observed for particular membrane resonances higher than the fundamental, thus making it desirable to operate the device at those higher membrane modes. Observed membrane vibration amplitudes are large (typically between 1cm and 2cm) relative to the membrane's thickness. This paper discusses issues involved in modeling this complex dynamic system. Topics addressed include the modeling assumptions, the correlation between the model and experimental observations, electrodynamic considerations, and the impact that the viscoelastic membrane material has on device performance over time.

6927-34, Session 8

A theory of large deformation in soft active materials

Z. Suo, X. Zhao, Harvard Univ.; W. H. Greene, Coventor, Inc.; J. Zhou, Xi'an Jiaotong Univ. (China)

Our interest in active soft materials has been stimulated by recent development in the fields of dielectric elastomer actuators and stimuli-responsive gels. In this talk I'll focus on our new formulation of nonlinear field theory of elastic dielectrics, and the use of the theory to analyze an electromechanical instability of dielectric elastomer actuators.

Two difficulties have long troubled the field theory of finite deformation in dielectric solids. First, when two electric charges are placed inside a dielectric solid, the force between them is not a measurable quantity. Second, when a dielectric solid deforms, the true electric field and true electric displacement are not work conjugates. These difficulties are circumvented in our new formulation of the theory. Imagine that each material particle in a dielectric is attached with a weight and a battery, and prescribe a field of virtual displacement and a field of virtual voltage. Associated with the virtual work done by the weights and inertia, define the nominal stress as the conjugate to the gradient of the virtual displacement. Associated with the virtual work done by the batteries, define the nominal electric displacement as the conjugate to the gradient of virtual voltage.

Our approach does not start with Newton's laws of mechanics and Maxwell-Faraday theory of electrostatics, but produces them as consequences. We show that the notion of Maxwell stress, which is widely used in the literature, has no general theoretical basis. However, for a very special class of materials, which we call ideal dielectric elastomers, the theory recovers the Maxwell stress.

As an illustration of the theory, we analyze the electromechanical instability of dielectric elastomer actuators. We find that the free energy functions of dielectric elastomers are often non-convex, leading to coexistent states. Our calculation shows that stability of the actuators is markedly enhanced by pre-stresses, agreeing with existing experimental observations.

6927-35, Session 8

An advanced finite element model of IPMC

D. Pugal, H. Kasemägi, M. Kruusmaa, A. Aabloo, Tartu Ülikool (Estonia)

This paper presents an electro-mechanical Finite Element Model of an ionic polymer-metal composite (IPMC) material. Mobile counter ions inside the polymer are drifted by an applied electric field, causing mass imbalance inside the material. This is the main cause of the bending motion of this kind of materials. All foregoing physical effects have been considered as time dependent and modeled with FEM. Time dependent mechanics is modeled with continuum mechanics equations. The model also considers the fact that there is a surface of platinum and also a layer, where some amount of Pt is diffused into the polymer backbone. The described basic model has been under development for a while and has been improved over the time. Simulation comparisons with experimental data have shown good harmony. Our previous paper described most of the basic model. Additionally, the model was coupled with equations, which described self-oscillatory behavior of the IPMC material. It included describing electrochemical processes with additional four differential equations. The Finite Element Method turned out to be very reasonable for coupling together and solving all equations as a single package. We were able to achieve reasonably precise model to describe this complicated phenomenon. Our most recent goal has been improving the basic model. Studies have shown that some electrical parameters of an IPMC, such as surface resistance and voltage drop are dependent on the curvature of the IPMC. The new model takes these effects into account to some extent. It has added an extra level of complexity to the model, because now all simulations are done in three dimensional domain. However, the result is advanced visual and numerical behavior of an IPMC with different surface characteristics.

6927-36, Session 8

Modelling electroactive polymer (EAP) actuators for flow control: electro-mechanical coupling and hyperelasticity

F. Rosenblatt, L. Iannucci, J. F. Morrison, Imperial College London (United Kingdom)

Controlling turbulence skin-friction can be achieved by manipulating the coherent structures located in turbulent boundary layers (ref 1). The challenge this presents is to develop actuators that are functional at the spatial scales of those coherent structures (10 m to 0.1mm) and their temporal scale (100kHz). Recent advances in MEMS technology have made such turbulence controls more realistic. Indeed, micro-sensors and micro-actuators can now work at those scales(ref 2). Electroactive polymers (EAP) provide excellent performance(ref 3), are lightweight, flexible, and low cost. Therefore EAPs, and in particular dielectric elastomers (DEAs), provide many potential applications as micro-actuators.

A technique to accurately model EAP, taking into account its non-linearities as well as its large deformations, is being developed. The EAP materials are modelled using hyperelastic material models such as the Mooney-Rivlin strain energy function. Curve fitting of experimental data is performed to estimate the constants for hyperelastic models, and to fully define the EAP material. The experimental data required for this curve-fitting process are obtained from uniaxial, biaxial and planar tension tests. Simulations have been run using two different types of FE software, Ansys and Abaqus. The results from these simulations differ by less than 1% using standard hyperelastic constitutive models. The data obtained using the three experimental tests mentioned above, have been used to run further simulations. The subsequent results, compared to experimental data, are very encouraging. Comparisons with high rate test data to investigate effects due to viscoelasticity or other physical processes has not been considered in the current paper. Furthermore, pre-stretching of the material to enhance properties in certain directions prior to loading is a common technique used by some researchers in their designs: such tests have also not been considered in this paper.

Once a model of the EAP material is constructed, the main challenge in the DEA modelling is the modelling of the electro-mechanical coupling. An electric field applied across its electrodes creates Maxwell forces, resulting in the electrodes moving closer to each other, thereby causing the material to squeeze. The electrodes being closer, the electric field becomes stronger, increasing the Maxwell forces applied on the material. This iterative process continues until the material reaches equilibrium. For small deformations, good modelling approximations can be reached using small displacement linear elastic electrostatic simulations without the need for such a non-linear electro-mechanical coupling process. However, for larger structural deformations, a modelling process that includes a non-linear electro-mechanical coupling is required.

A method has been developed to provide simulations of DEA materials including the effects of both the electro-mechanical coupling and hyperelasticity. This method is applicable to any material. The electro-mechanical coupling is achieved by an iterative simulation of the electrostatic and mechanical processes, using convergence criteria to achieve stable results. The accuracy of the method has been verified using commercial software for small displacement linear elastic electro-elastic simulations.

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6927-37, Session 9

Organics-based energy harvesting and storage system for future aerospace vehicles: overview

M. Taya, Univ. of Washington

Energy harvesting and storage system (EHSS) is increasing important for any vehicles, even for civil-mechanical infrastructures, as US is heavily dependent on foreign oils and the remaining US domestic oil reservoir is decreasing.

The University of Washington, University of Colorado, UCLA and Virginia Tech are working on EHSS under the AFOSR MURI funding where the EHSS based on organics and metallics are emphasized, organic based EHSS are mainly solar energy harvester and polymer thin batteries. Here, I will overview some of EHSS based on organics, (i) dye-sensitized solar cells (DSSC) and polymer based batteries. The advantages of using organic EHSS are, light weight, scalable, and cost-effective as compared with silicon-based technology. These reasons led us to believe that organic EHSS is best-suited for future aerospace vehicles. However, the technical goals are high, (i) energy conversion efficiency based on DSSC beyond 10%, (ii) battery capacity of 400Whr/Kg or more.

I will show also video demo of a small toy airplane with DSSC driven propeller.

6927-38, Session 9

Laminated polymer lithium rechargeable battery

C. Xu, C. Ma, M. Taya, Univ. of Washington

For electric-propelled unmanned vehicles (UAVs), an important system performance index is flight endurance time, which is explicitly related to the available battery energy, system weights and aerodynamic parameters. Due to the lack of the high energy density and power density rechargeable thin film battery, current solar cell powered UAV uses Li/SOCl₂ primary battery as the back up power in the evening because of its high power density (1420 Wh/L) and low temperature performance (-55 to 100°C). Besides the low temperature performance, UAV requires the following characteristics of the battery and supercapacitors: 1) high energy density, 2) high power density, 3) wide temperature range (-50 ~ 100°C), 4) thin film structure for easy integration and 5) load bearing.

Developed thin film battery is comprised of a polymer-lithium ion cell material with barrier-layer packaging and mechanical reinforcing layers. A semi-solid/ solid electrolyte and a mesoporous polymer separator are sandwiched in between of anode and cathode. A composite film with a carbon nanotube (CNT) network serves as the anode and a mesoporous transitional metal oxide Li_xCoO₂ as the cathode, where porous metal sheets serve as the current collector. The CNT network fabrics have high in-plane tensile strength. LiCoO₂ is used as the cathode, because the Co atoms do not migrate to Li layers, so that cathode does not generate flammable gases during charging that create safety problems. Merits of using the porous metal sheet are lightweight; low electric resistance; high strength, strong stability in alkaline solution and flexibility.

The lithium ion containing electrolyte is highly hygroscopic. The battery core is protected from moisture ingress using a barrier-layer packaging with polypropylene as a heat-seal layer on the inside, and aluminum foil as a moisture barrier-layer and toughened epoxy as a tough moldable and bondable layer on the outside.

6927-39, Session 9

Innovative power generators using electroactive polymer artificial muscle

R. D. Kornbluh, S. Chiba, SRI International; M. Waki, Hyper Drive Corp. (Japan); R. Pelrine, SRI International

Electric power generators based on dielectric elastomers, a.k.a. electroactive polymer artificial muscle (EPAM), can take advantage of the high energy density and large strain capability of EPAM to yield devices that are simple, robust and efficient. In August 2007, SRI International and Hyper Drive Co., Ltd. completed an EPAM-based generator prototype

designed to provide on-board power to a navigation buoy and carried out a test of its practical use in Tampa Bay, Florida, USA. The purpose of the test was to evaluate the feasibility for the generator's use as a stable energy source by generating energy from waves and outputting it as electricity. The test was conducted for two weeks. The generator unit had a maximum output energy of 20 J per stroke although lower average energy outputs were achieved during the testing due to very low wave conditions.

The tests show that during even relatively small wave conditions, the generator was able to make net positive power output suggesting that EPAM can be the basis of very simple and efficient wave energy conversion systems.

Experiments using waterwheels with EPAM also succeeded. Micro generators based on waterwheels are already in use. However, as a conventional device is used in these micro generators, the rotation of the waterwheel must be transformed into high-speed rotation to turn the generator. In most cases, it is necessary to make an elevation drop or to modify riverbed structure to increase flow speed, which limits the number of suitable sites for installation. However, waterwheel generators using EPAM do not require high-speed rotation from a converter. A simple cam structure that induces deformation in the EPAM is enough to generate electricity.

The waterwheel generator made as a prototype in this study is small (30 cm in diameter), and can generate electricity of 35 mJ (equal to 35 mW/rotation/sec) using a small quantity of water (280 ml/sec). A generator with an electric output of 5.4-6.0 J is currently being developed as an electric source for special LED to protect agricultural products. Field trials of a waterwheel of 80 cm in diameter are actually being planned using agricultural water. As the waterwheel generator does not require a particular structure, its application is being considered as an electric source for some sensing systems at rivers and in water supply and sewage systems.

As the EPAM generator is lightweight and easy to carry and install, its practical use as a source of electricity for disaster-struck areas and in other emergencies is also being investigated. Its application in agricultural regions and mountains, where electricity supply has been difficult, will support the supply of energy to agriculture, forestry and other local industries.

6927-40, Session 9

Dielectric polymer: scavenging energy from human motion

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More and more sensors are placed on human body for medical application, for sport... But, the short lifetime of the batteries, available on the market, reveal a real problem of autonomy of these systems. A promising alternative is to scavenge the ambient energy such as the mechanical one. Up to now, few scavenging structures have operating frequencies compatible with ambient one. And, a few structures have a large frequency spectrum. Nevertheless, most of these structures are rigid and use vibrations as mechanical source. Few scavengers work on deformation or variation of stress: Pelrine develop the well known generator shoes made with dielectric and working on heel pressure.

For these reasons, we develop a flexible dielectric scavenger that operates in a large frequency spectrum from quasi-static to dynamic range.

Dielectric polymers are a new category of emerging materials. They are generally used as actuators for artificial muscles, binary robotics or mechatronics. Dielectric polymers work as a variable capacitor, and show large deformation when submitted to an electric field. But, they have also great promising performances in generator mode especially in terms of energy density (1.5J.g⁻¹ according to Pelrine).

Thus, we report in this paper a general analytical model for dielectric generator, its validation on simple structures and the development of an innovating application: scavenging energy from human motion on the level of knee.

This study is based on equilibrium between mechanical and electrical stresses. Thermal aspects are neglected in this study. First, mechanical

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characterizations of 3M VHB 4910 polymer have been done to validate and improve an existing model of quasi-linear viscoelasticity. Electrical behaviors of various couple of "polymer-electrode" have been tested to determine the best electrode.

Then, scavenged energy will be calculated in quasi-static and dynamic cycle. First, the material is stretched under a mechanical load. Then, a poling electric field is applied to the polymer. Under this constant electric field, the material is compressed until an equilibrium between elastic and Maxwell stresses is reached. It is the active phase: the variation of capacity generates electricity. Finally, the electric field is cancelled, the material returns to its original dimensions.

Generator cycle can be at constant voltage, constant electric field or constant charge. In our model, we can vary several parameters such as the pre-strain of the polymer, the poling or the mechanical frequency. Our analytical modeling is complete and can be used to design power generator. Centimeter and millimeter membranes made with 3M VHB 4910 dielectric polymer have been fabricated and characterized. For example, according to a given sequence, we test a centimeter square membrane: 1cm side and 63 μ m thick with a pre-stretch equal to 4. In a generator mode, analytical scavenged energy is expected to be 31 μ J and experimental 28 μ J is measured. The relative error is less than 10%.

The innovating application is under development and will take care of miniaturization and poling voltage.

Moreover, a main point under investigation is to develop other technique of fabrication to decrease the sensor dimensions.

6927-41, Session 9

Improving the electrical conductivity by forming Ni powder chains in a shape-memory polymer filled with carbon black

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Shape memory polymers (SMPs) have been a promising smart material under intensive investigation in recent years. In general, SMPs have a high reversible strain (on an order of 100%) as compared with other shape memory materials. It has great potential as actuator in deployable structures and as morphing materials in aero-space applications. One of the most recent research focuses on thermo-responsive SMPs is to eliminate external heaters. Electrically conductive powders, fibers and even nano wires/tubes have been utilized as the fillers to improve the electrical conductivity of polymers. Although electrically conductive fiber and nano wire/tube can significantly enhance the stiffness and strength of polymers, their deformable strain is limited to within a few percent (at the most). Since the recoverable strain in SMPs is normally on the order of hundred percent, there is a potential deformation compatibility problem. As such, electrically conductive powders, such as, carbon black and Ni powder, should be a better choice for conductive SMPs.

In this paper, we try to align Ni particles into chains under a relatively weak magnetic field ($< 0.3T$) to improve the electrical conductivity of shape memory polymer (SMP) filled with carbon black (CB). Four types of samples are fabricated, a. SMP/CB/Ni(chained): SMP filled with CB and aligned Ni particles (Ni: 0.5% in volume) under magnetic field; b. SMP/CB/Ni(random): SMP filled with CB and homogenous nickel particles (Ni: 0.5%); c. SMP/CB: SMP filled with CB; d. SMP/Ni(chained): SMP filled with aligned nickel particles (Ni: 0.5%) under magnetic field.

The alignment of Ni powders and electrically conductive property are investigated in this paper. (1) Optical microscope (transmission) is employed to observe the distributions of Ni chains in a bulk SMP. In-plane parallel Ni chains are clear in the transparent SMP matrix of SMP/Ni(chained). (2) SEM images show that well-aligned parallel Ni chains can be observed along the direction of magnetic field. A typical length of a single Ni chain is about 100-200 μ m with a typical gap of about 50-100 μ m between adjacent parallel chains. The aspect ratio, which is often described for continuous fiber, is about 20-40. (3) Moreover, the volume resistivity of SMP/CB/Ni (chained) is about 10 times lower than that of SMP/CB/Ni(random) and 20 times lower than that of SMP/CB. The improvement of electrical conductivity is completely contributed to the formation of Ni chains. The resistivity of SMP/CB/Ni(random) is just slightly lower than SMP/CB, which is owing to an incorporation of 0.5 % Ni powders. Additionally, we found that the

electrical conductivity is similar in parallel and perpendicular directions against the applied magnetic field. As such, the electrical conductivity is not related to the direction of Ni chains. (4) The specimen shows shape memory effect heated by applying a voltage (30V). The infrared images shows that the average temperature of SMP/CB(10%)/Ni (chained) is 80°C, SMP/CB(10%)/Ni(random) 50°C and SMP/CB 40°C. In the end, the shape recovery velocity and shape recovery ratio of SMP/CB(10%)/Ni (chained) is higher than the other two types.

In conclusion, we succeed to align Ni particles into chains to form observable conduction paths under a relatively weak magnetic field. We have shown that the formation of well-aligned nickel chains (Ni: 0.5 vol.%) improve the electrical conductivity of SMP/CB composite apparently. Moreover, the composite shows favorable shape memory performances.

6927-42, Session 9

Design of dye-sensitized solar cells with new light-harvesting dyes

M. Nagata, M. Kimura, C. Xu, M. Taya, Univ. of Washington

In nature, photosynthetic membrane enables the highly efficient energy conversion from light to chemical energy. Numerous dye molecules are incorporated within the photosynthetic membrane and arranged by the protein molecules. The spatial arrangement of dye molecules within the membrane results in the high efficiency of energy conversion. The study of molecular assembly of chlorophyll derivatives such a porphyrin, phthalocyanine, and naphthalocyanine dyes can be useful as a model of the natural photon-electron conversion. The mechanism of dye-sensitized solar cells (DSSC) is similar to photosynthesis where the conversion is carried out by the photo-excitation electron transfer of natural dyes.

The inorganic solar cells have good conversion efficiency, but they are high-cost, heavy weight, and some based on highly toxic material. Even if the conversion efficiency of DSSCs are still low, DSSCs have marked advantages, light-weight, cost-effective, toxic-free and scalable.

A DSSC consists of nano-crystalline titanium oxide (TiO₂) semiconductor film, dye sensitizer, redox electrolyte, and counter electrode. Usually, TiO₂ film adsorbed with ruthenium complex dye can harvest the photon energy in the region of visible light. We established the processing route of DSSC samples and the characterization of DSSC data scientifically, and developed DSSC with higher energy conversion efficiency close to 8 %.

However, the main drawback of ruthenium-based sensitizers is their lack of absorption in the red region of the visible spectrum and near infra-red(IR) region. Phthalocyanine and naphthalocyanine dyes are well known for their intense absorption in the red and near-IR regions, and they are also stable to light or heat. Therefore, they are excellent candidates as dye sensitizers of DSSC. We synthesized novel phthalocyanines and naphthalocyanines having carboxylic acid segments. These dyes can absorb in the red and near-IR regions and adsorb onto the surface of TiO₂. The function of the carboxylic acid group of the dyes is to graft the sensitizer onto the semiconductor surface and to provide intimate electronic coupling between dyes and TiO₂.

TiO₂ film which combined ruthenium complex and naphthalocyanine can absorb broad light waves. However the efficiency of the DSSC with such a multi-dye system is still low (2.6%), because the energy transfer from the dye with low to intermediate light waves to the dyes of higher light wave absorption occurred, followed by the low energy transfer of the dyes with higher absorption waves to the TiO₂ layer and also dyes aggregation took place. The aggregation of dyes in DSSC could be controlled by a ligand or a coadsorbent like a proteins or a carotenoid of photosynthesis. As other solution, we are synthesizing new dyes that contain three tert-butyl and one carboxylic acid groups that act as electron donating and withdrawing group respectively.

6927-43, Session 10

Dynamic modeling of underwater vehicles actuated by soft actuators

S. Gutta, J. Lee, W. Yim, Univ. of Nevada/Las Vegas; K. J. Kim, Univ. of Nevada/Reno

Ionic Polymer Metal Composite (IPMC), has been considered to be a potential candidate for actuating underwater robotic vehicle due to its large

deformation capability in aqueous environments. This paper deals with dynamic modeling of small scale underwater vehicle driven by soft cilia-type propulsor. This type of actuator is realized using the ionic polymer metal composite (IPMC). Finite element method is used for modeling a soft IPMC actuator interacting with fluid medium. In this modeling technique, local coordinate frame is attached in each beam element. This local coordinate frame undergoes rigid body motion along with the element and elastic deflection of each element is modeled using a large deflection mechanical beam model. Along with a RC electrical model the proposed modeling approach can be useful for formulating equations of motion for the underwater vehicle activated by cilia-type flexible actuator. In this work, hydrodynamic forces or resisting forces acting normal and tangential directions of the flexible actuator surface are considered as an input to the model as well as an input voltage applied to the IPMC. To validate the proposed modeling technique, both computer simulation and experiment are conducted and found to be in good agreement and can be valuable tools for developing both open-loop and closed-loop control system for such underwater vehicles.

6927-44, Session 10

Bio-inspired tactile sensor with arrayed structures based on electroactive polymers

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We design and fabricate a tactile sensor with arrayed structure based on Flemion with water as solvent. Several mechano-electro relationships were obtained when different mechanical input pulses were applied. According to the experiment results, Flemion-based composite could survive much longer time as sensor materials than that as actuator materials in air. By proper design and fabrication, a tactile sensor for potential three-dimensional sensing with large area could be achieved based on this material. Electroactive based polymers would be a good candidate for bio-related sensors especially for artificial derma applications.

6927-45, Session 10

An adaptive control method for dielectric elastomer devices

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The future of Dielectric Elastomer (DE) technology lies in miniaturizing individual elements and utilizing them in array configurations, thereby increasing system fault tolerance and reducing operating voltages. In the interests of device portability, accuracy, and reliability, integrated real-time closed loop control of DEs is also highly desirable, particularly in devices having multiple degrees of freedom.

A low bandwidth digital control method for DE devices utilizing Pulse Width Modulation (PWM) is presented in this paper. The amplitude and the duty cycle of the PWM signal controls the current flow through a DE, enabling continuous control of both the displacement and speed. A full range of motion can be achieved with a duty cycle anywhere between 2-100%. Closed loop control is achieved by measuring the rate of change of the voltage across the DE in response to changes in the input current generated by a digital sensory signal overlaid on the control signal. This allows capacitance, charge, strain state, and Maxwell pressure to be inferred. Real-time adaptive control of the current results in increased electromechanical stability and avoids the increased susceptibility to breakdown due to externally induced deformation associated with a constant voltage regime.

This adaptive control method has three core strengths: the DEs are effectively decoupled from the relatively slow dynamics of the power supply, enabling faster and more effective distribution of power; the sensory signal can be generated with minimal additional components, a significant advantage over existing self-sensing systems; and multiple DEs can be controlled independently and in parallel using a single power supply set to a fixed voltage.

6927-46, Session 10

Development of a touch mode pressure sensor using electroactive polymers (EAP)

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Accurate measurements of pressure fluctuations in fluid flows at small temporal, $O(1)$ kHz, and 'meso' spatial scales, $O(10-100)$ μm , are of critical importance in a number of applications such as the study and control of turbulent boundary layers at high Reynolds numbers¹ and quantification of vorticity within super-fluids². While MEMS technology is enabling important advances in the performance of miniaturized pressure sensors, the challenge posed by the diminishing sensitivity with decreasing sensor size remains an important issue. Preliminary work on the development of a novel transducer design is presented. The core features of this novel design take advantage of both the increased sensitivity associated with a capacitance-based sensor operating in touch mode³ and the properties of EAP⁴ which have not hitherto been used for this application. EAP have high electromechanical efficiency, are capable of very large strains and can also be operated so that the diaphragm is operating as a constant displacement device through feedback control electronics.

A macro-scale, proof-of-concept prototype (diaphragm diameter of 10 mm) was built to test the performance of the sensor for a variety of geometrical configurations (e.g. varied air gap height to diaphragm thickness and diameter to thickness ratios). The size of the air gap in the prototype can be altered by moving the stationary electrode relative to the diaphragm using a micrometer, while diaphragms with two different thicknesses (50 μm and 100 μm) are used. Two different EAP materials were tested for the sensor diaphragm, namely NUSIL MED 4905 and MED 4930. A mixture of graphite powder embedded in a silicone matrix was used as a compliant electrode on the surface of the diaphragm. This conductive material was specially developed to yield stable and robust electrodes that can be sprayed on using conventional air spray techniques. Conductivity through the graphite/silicone mixture is achieved with as little as 7% volume loading of graphite.

The capacitance of the prototype, measured with an LCR meter, is reported for different static pressures and bias voltages in order to assess the sensitivity of the transducer. These empirical results are compared to a finite element analysis (FEA) model of the sensor. The FEA model uses an electro-mechanical coupling to represent the behavior of the EAP membrane. Due to the very low strains present in this sensor, the elastomer is approximated as a linear elastic material. The FEA model is used for design optimization purposes and to predict transducer sensitivity and dynamical response at the meso-scale.

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6927-47, Session 10

Potentials of thermally expandable polymers with embedded skeletons for actuator applications

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This paper presents strategies for material selection and design optimization of an electro-thermal polymeric actuator with an embedded skeleton. This polymeric actuator is a competitive candidate for applications where the compliant dielectric elastomer actuators cannot be applied.

Dielectric elastomer actuators with high work density can deliver a large strain at a driving voltage of several thousand volts. They are useful for

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applications where a relatively large displacement but a small load is required, for example, as a driver for a scanning mirror or a miniaturized low pressure pump. However, their relative compliance makes them unsuited for moderate or large loading. Therefore, the high work density may not be efficiently exploited.

On the other hand, thermally expandable polymers possess high work density, adequate stiffness and high actuation stress. In addition, they are capable of delivering moderate strain at a low driving voltage. Recent development shows that embedding a skeleton in the polymer could improve the thermo-mechanical actuation capability as well as the response time (see Applied Physics Letters, 2007, vol. 90, Art. 214103). The skeleton is responsible for heat transfer and confinement of the expansion polymer. This leads to anisotropic expansion and stiffness reinforcement, of which both are enhanced in the actuation direction. A design example, consisting of a SU-8 epoxy expander and a silicon skeleton, achieves at least 2.7 times higher actuation stress than the bare SU-8, while delivering as much thermal strain as the bare SU-8.

In the exercise of material selection, various material combinations and performance criteria have been considered. The evaluation shows that the composites based on poly-dimethyl-siloxane have the highest thermal strains; the composites based on liquid crystal polymer exhibit the highest actuation stress; Nylon-containing composites exhibit the highest actuation stress; SU-8-containing composites deliver the highest work density. It is shown that, as a result of the confinement effect of stiff skeleton, Poisson's ratio significantly affects the actuation capability, in particular the thermal stress and work density.

Polymeric components largely determine the level of actuation performance but the skeleton components determine the effective thermal diffusivity and stiffness reinforcement. However, a 100 % polymeric actuator design without skeleton material does not necessarily deliver better actuation than the one containing less polymer. This is because the polymeric strain enhancement caused by the skeleton confinement decreases with the polymeric content. Design optimization shows that 20-30 % of skeleton content could in fact maximize the actuation strain and work density of the polymer actuators. In addition, the skeleton content significantly improves the thermal diffusivity, and consequently, the characteristic thermal response time.

A design case for maximum work density shows that the optimum design containing 70 % SU-8 outperforms the 100% bare SU-8 in almost every aspect. The optimum design shows 2.2 times higher effective Young's modulus, 2.5 times higher thermal stress, 2.6 times higher work density, and 5% higher CTE, as compared to the bare SU-8 in the actuation direction. In addition, it reduces thermal response time by half. It is concluded that design optimization is a rewarding exercise in addition to careful material selection.

6927-48, Session 10

The application of polypyrrole trilayer actuators in microfluidics and robotics

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Trilayer actuators have been constructed using polypyrrole (PPy) films doped with dodecylbenzene sulfonate (DBS), a large immobile anion which creates conducting polymer actuators with predominantly cation driven movement.^{1,2} Identical 5-20 μm PPy/DBS films were grown on either side of a 110 μm PVDF membrane to serve as working and counter electrodes with respect to each other, using a galvanostatic preparation at 0.05 mA at 4 $^{\circ}\text{C}$ in 0.05 M pyrrole and 0.06 M aqueous NaDBS. This system provides an alternative to previous PPy/DBS bilayer and trilayer actuator designs.^{3,4}

The performance of the trilayer actuator was tested using potential step experiments between 0.8 and +0.8 V (Ag/AgCl) in aqueous solutions of 0.2 M tetramethylammonium chloride or 0.1 to 0.5 M NaCl, at different frequencies (0.03 to 10 Hz) and for different trilayer lengths (1 to 2.5 cm). The extent of deflection was measured using a CCD camera to record screenshots of the trilayer, and software was written to monitor the position of pixels at different points on the PPy trilayer. Satisfactory deflections in the range of 1-3 mm were observed for 10 μm thick PPy layers of 1.5 to 2.5 cm in length when operated at 1-5 Hz. The actuation behaviour was monitored for over 40,000 cycles at applied frequency of 1 Hz.

The trilayer actuators were examined in a fluidics channels to test the movement of fluid around the actuator in a confined channel. Mathematical modelling using finite element analysis of the trilayer movement was used to determine the development of vortices within the fluid and to predict overall fluid movement and flow rates. 5 The trilayers were also used to construct a 'fish-tail' which was positioned at the back of a self-driven robotic fish, including on-board microchip controller and battery power source.

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6927-49, Session 10

An electroactive polymer-based concept for vibration reduction via adaptive supports

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A concept for the suppression of resonant vibration of an elastic system undergoing forced vibration coupled to electroactive polymer (EAP) actuators based on dielectric elastomers is demonstrated. The actuators are utilized to vary the stiffness of the end support of a clamped beam, which is forced to harmonic vibration via a piezoelectric patch. Due to the nonlinear dependency of the elastic modulus of the EAP material, the modulus can be changed by inducing an electrostrictive deformation. The resulting change in stiffness of the EAP actuator leads to a shift of the resonance frequencies of the vibrating beam, enabling an effective reduction of the vibration amplitude by an external electric signal. Using a custom-built setup employing an aluminium vibrating beam coupled on both sides to electroded strips of VHB tape, a reduction of the resonance amplitude of -20 dB was achieved. The corresponding shift of the resonance frequency was typically +4 Hz. The frequency of the driving force of the beam was 6 Hz in the first mode and 20 Hz in the second mode. The impact of this concept of vibration reduction on different scenarios of forced vibration is evaluated.

6927-50, Session 10

Plastic muscles as lightweight, low-voltage actuators, and sensors

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Discover Technologies, utilizing proprietary technology licensed from Virginia Tech, has developed a new class of IPMCs that can operate in a dry state for long periods of time. These materials are referred to under the trade name of 'plastic muscles.' Discover Technologies has plans to begin offering these materials as commercial products in the near future.

Discover Technologies has developed a unique fabrication process that reduces the cost of the materials and permits large scale manufacturing. The details of this process will not be revealed, but a thorough discussion of the behavior of the plastic muscles as electroactive polymer actuators and sensors will be presented.

The bending actuation behavior of the plastic muscles will be presented, including force and strain measurements as a function of input voltage, actuator thickness, time, and frequency. This presentation will also include a characterization of the extensional (thickness mode) behavior of the actuators. The behavior of the plastic muscles as sensors will also be discussed, including measurements of the charge and current sensitivity as a function of frequency and thickness. The electrical properties of

the plastic muscles will also be presented, including a discussion of the power requirements, efficiency, and energy density of the materials. Finally, characterizations of the long-term stability of the plastic muscles' properties during continuous cycling and storage will be presented. In addition to these characterizations, comparisons to other types of electroactive polymers and smart materials will be made.

6927-51, Session 11

Chitosan-cellulose blended electroactive paper actuator

J. Kim, Z. Cai, Y. Chen, A. S. Pinter, Inha Univ. (South Korea)

Cellulose based Electro-Active Paper (EAPap) has been reported as a smart material that has merits in terms of lightweight, dry condition, biodegradability, sustainability, large displacement output and low actuation voltage. However, its actuator performance is sensitive to humidity: its maximum bending performance was shown at high humidity condition. To overcome this drawback, we introduce an EAPap made with cellulose and chitosan blend. Chitosan-cellulose blend films with varied mixing ratio were prepared by dissolving the polymers in trifluoroacetic acid as a co-solvent followed by spincoating onto glass substrates.

A bending EAPap actuator is made by depositing thin gold electrodes on both sides of the cellulose-chitosan films. The performance of the EAPap actuator is evaluated in terms of free bending displacement and blocked force with respect to the actuation frequency, activation voltage, humidity level and content of chitosan. Primary results show that this chitosan-cellulose based bending actuator is less sensitive to humidity: it shows much high bending displacement (about 4mm) at room humidity condition. The actuation principle is also discussed.

6927-52, Session 11

The development of electrically driven mechanochemical actuators that act as artificial muscle

L. Rasmussen, Ras Labs., LLC; L. D. Meixler, Princeton Univ.; D. Harper, K. Park, TRI/Princeton

Ras Labs, LLC, is committed to producing a variety of electroresponsive smart materials that are strong, resilient, and respond quickly and repeatedly to electrical stimuli. By effectively combining the synthetic expertise of Ras Labs with the plasma expertise of the Princeton University Plasma Physics Laboratory (PPPL), Ras Labs is actively developing superior electroresponsive materials and actuators. One of the biggest challenges was the interface between the embedded electric electrodes and the electroresponsive material because of the pronounced movement of the electroresponsive material. If the electroresponsive material moved very quickly, the electric lead would often be left behind and thus become detached. Preliminary experiments explored the bonding between these electroresponsive materials with plasma treated metals provided by PPPL. The results were encouraging, with much better bond strengths in the plasma treated metals compared to the untreated control. Ras Labs expanded upon improving the attachment of the embedded electric leads to the electroresponsive materials in these actuators using plasma treatment and other treatments to non-corrosive metal leads at PPPL. Water drop contact angle tests were performed on plasma treated stainless steel and titanium. The strength of the metal-polymer interface was determined at the Textile Research Institute (TRI) using modified T-peel tests on samples of electroresponsive material sandwiched between plasma treated stainless steel and titanium foils. Based on the water drop contact angle tests and the T-peel tests, nitrogen plasma treatment of titanium produced the best metal-polymer interface. Metallic plasma treatment allows for the embedded electric leads and the electroresponsive material to work and move as a unit, with no detachment, by significantly improving the interface between the electric leads and the electroresponsive material.

6927-54, Session 12

Smart sunglasses with tuneable shade

C. Ma, M. Taya, C. Xu, Univ. of Washington

This presented study discusses the design, process, optical and electrical performance of prototype smart sunglasses based on cathodic electrochromic (EC) polymers, which show several merits compared with traditional materials for sunglasses lens as well as other smart window materials. It is a multilayer design of device. The conjugated polymer, poly [3,3-dimethyl-3,4-dihydro-2H-thieno [3,4-b][1,4]dioxepine] (PProDOT-Me2), is utilized as the electrochromic working layer. The counter layer of the device is vanadium oxide (V2O5) film, which serves as an ion storage layer. There is also a polymer gel electrolyte as the ionic transport layer, sandwiched between the working and counter layers. The characters of prototype device are reported, including transmittance (%T), driving power, response time, open circuit memory and lifetime.

6927-55, Session 12

Design and position control of AF lens actuator for mobile phone using IPMC EMIM

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In the conventional AF (autofocus) lens actuating system the VCM actuator is used. It has disadvantage in miniaturizing and high power consumption which is essential to the actuator for the mobile device. The IPMC actuator is one of the attractive smart materials that have simple mechanism and low power consumption. However, it also has disadvantage in a loss of performance due to evaporation of water in a dry condition. And in order to improve this property, the use of highly stable ionic liquids (1-ethyl-3-methylimidazolium trifluoromethanesulfonate ([EtMeIm][TfA])) to replace water is explored. This paper proposes an AF lens actuator for mobile phone using IPMC-EMIM containing ionic liquids. The proposed actuator was designed and analyzed. The designed actuator is verified by experiment and the simple position control algorithm is applied.

6927-57, Session 12

Development of an electroactive polymer actuator based on NBR for micro optical zoom lens

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As many types of information technology products such as cellular phones incorporate optical information capturing capabilities, adoption of a high resolution miniaturized optical lens system becomes norm in the portable IT device manufacturing industry. Noting the limited spatial space and the strict requirement of high power efficiency of the portable apparatus, designing the high resolution optical imaging component device has been always challenging. Although a software based digital magnification technique that is popularly employed to mimic a zooming function in most of current version of cellular phones benefits low cost, easy manufacturing, and power efficiency, it still suffers from competing with a stand-alone digital camera in term of the acquired image quality. Then a full optical micro-zoom lens system might be a viable solution for the highly integrated portable IT products. However a complicated bulky mechanism of the optical zoom lens system hampers the simple adoption of the component into the portable devices. Recognizing the advantages on specific power provided by the direct drive capability of EAP actuators, application of the EAPs to the micro-zoom lens system might be worth. The objective of the present work is to demonstrate the efficiency and feasibility of NBR (Nitrile Butadiene Rubber) based conducting polymer actuator that is fabricated into a micro zoom lens driver. Unlike the traditional conducting polymer that normally operates in a liquid, the proposed actuator successfully provides fairly effective driving performance for the zoom lens system in a dry environment.

6927-58, Session 12

Application of ionic polymer-metal composites for auto-focusing compact camera modules

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The method we used for increasing bending response is an anisotropic O₂ plasma treatment. This treatment increases surface area of IPMC, which is an advantage in accumulating charges in IPMC actuation. Additionally, we found that IPMCs bent easily with a large displacement in the direction normal to the anisotropic plasma treatment. Furthermore, we observed surface coating of IPMCs with polyurethane or silicone is useful for increasing blocking force and reliability of IPMCs. Especially, when ionic liquids are used for electrolyte, the coating prevents the leaking of ionic liquid from electrode surface of IPMC.

6927-91, Session 12

Fast bender actuators for fish-like aquatic robots

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Small, highly-mobile "swimming" robots are desired for underwater monitoring operations, including pollution detection, video mapping and other tasks. Actuator materials of all types are of interest for any application where space is limited. This constraint certainly applies to the small-scale swimming robot, where multiple small actuators are needed for forward/backward propulsion, steering and diving/surfacing. A number of previous studies have demonstrated propulsion of floating objects using IPMC type polymer actuators or piezoceramic actuators. Here, we show how propulsion is also possible using a multi-layer polypyrrole bimorph actuator. The actuator is based on our previously published work showing very fast resonance actuation in polypyrrole bending-type actuators. The effect of polypyrrole composition, electrolyte composition, actuator and fin shape, boat shape, actuator voltage amplitude and frequency and polymer encapsulation have all been investigated for their affect on boat speed, maneuverability and longevity.

The bending actuator is a trilayer structure, in which the gold-PVDF (porous poly(vinylidene fluoride) membrane) substrate was coated on both sides with polypyrrole layers to form an electrochemical cell. Polypyrrole films on gold coated PVDF were grown galvanostatically at a current density of 0.10 mA/cm² for 12 hours from propylene carbonate (PC) solution containing 0.1 M Li-TFSI-, 0.1 M pyrrole and 1% (w/w) water. The polypyrrole deposited PVDF was thoroughly rinsed with PC and stored in 0.1 M Li-TFSI- / PC solution. The edges of the bulk film were trimmed off and the bending actuators were prepared as rectangular strips typically 2mm wide and 25 mm long.

These actuators gave fast operation in air (to 90 Hz), and were able to propel a self-contained "boat". The boat contained a battery, receiver unit and electronic circuit attached to the actuator. Thus, the boat could be operated by remote control, and by varying the frequency and duty cycle applied to the actuator, the speed and direction of the boat could be controlled. The speed of the boat approximately correlated with the thrust force measured independently for the actuators. Recent results describing the effect of polymer formulations and attempts to encapsulate the actuators will be described.

6927-59, Session 13

Mechanical cell stimulation with dielectric elastomer actuators

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Mechanical forces serve as an anabolic stimulus for cells. In particular the development programs of all structural tissues, such as bones, muscles, and connective tissues, are modulated by mechanical stimuli. Furthermore, normal functioning of tissues, including blood vessels, skin,

and nervous tissue, are influenced by mechanical forces.

So far, these processes were studied with machines applying mechanical stimuli to growing cells and tissue in vitro by stretching flexible membranes with vacuum or moving pistons. These bioreactors suffer from very limited spatial and temporal resolution, heat generating, voluminous actuators and the use of contaminating lubricants. Additionally, they offer little flexibility in the geometric arrangement of the applied mechanical stimuli.

To overcome these limitations, we use the advantages (large strain and high stresses) of electroactive polymers by integrating the actuator into the deformable membrane. Our dielectric elastomer actuator based bioreactor can stimulate cells and tissue with a wide range of temporal and spatial force patterns. The device is fully compatible with standard incubators (requiring no lubrication or maintenance) and it even allows for convenient observation under a light microscope while cells and tissue are actuated.

The soft materials based device consists of two dielectric elastomer actuators arranged such that the volume containing cells and tissues remain field-free. Especially, the grounding of the top and bottom electrodes and an electrode reaching into the cell medium ensure that the high actuation voltages (up to 5 kV) do not affect the potential and ion distribution in the liquid medium.

The actuator electrode facing the liquid compartment is sealed with an additional layer of a prestretched acrylic elastomer film (VHB 9460, 3M). To obtain a bio-compatible layer inside of the liquid container, we spin-coat a 15 µm thin PDMS layer onto the acrylic sealing layer, sterilize the device by UV treatment and coat the top layer with fibronectin.

The bioreactor was tested under experimental conditions (37 °C and 5 % CO₂) for 48 hours at frequencies ranging from 0.01 Hz to 5 Hz and unidirectional strains of up to 25 %. Furthermore, we have analysed the response of HeLa, C2C12 myoblasts, and Vero cells to different strains (0 - 15 %) and frequencies (0.1 - 0.3 Hz). The cells were uni-directionally stretched for eight hours and afterwards fixed, permeabilized and stained with phalloidin Alexa Fluor 488. The fluorescent actin filaments were imaged with a fluorescent light microscope to observe the change of the cytoskeleton caused by the mechanical stimuli.

6927-60, Session 13

Even larger deformations of dielectric elastomer membranes through specialized dynamic actuation

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Dielectric elastomer membranes configured for pumping mode actuation are shown to achieve much larger deformations than previously reported through leveraging. These results provide new insight into the differences observed between quasi-static and dynamic actuation and presents a new challenge to modeling efforts. Dielectric elastomer membrane actuators are a potentially enabling technology for soft robotics and biomedical devices such as implants and surgical tools. In this paper, an experimental dynamic analysis is conducted to investigate the dynamic response of a dielectric elastomer membrane due to (i) a time-varying pressure input and (ii) a time-varying voltage input. For the time-varying pressure experiments, the prestretched membrane is inflated and deflated mechanically while a constant voltage is applied. The membrane is cycled between various predetermined inflation states, the largest of which is nearly hemispherical, which with an applied constant voltage of 3 kV corresponds to a maximum actuation strain at the pole of 28%. For the time varying voltage experiments, the membrane is passively inflated to various predetermined states, and then actuated by a dynamic electrical signal. Two key system parameters were varied during this set of experiments: the chamber volume and the voltage signal offset. The chamber volume experiments reveal that increasing the size of the chamber onto which the membrane is clamped will increase the deformations as well as cause the membrane's resonance peaks to shift and change in number. For prestretched dielectric elastomer membranes at the smallest chamber volume, the maximum actuation displacement is 81 microns; while at the largest chamber volume, the maximum actuation displacement is 1431 microns. This corresponds to a 1767% increase in maximum pole displacement. In addition, actuating the membrane at the resonance

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frequencies provides hundreds of percent increase in strain compared to the quasi-static value. The voltage signal offset experiments show that adding offset to the input signal causes the membrane to oscillate at two distinct frequencies rather than one and also presents a unique opportunity to increase the output displacement without electrically overloading the membrane. Experiments to capture the entire motion of the membrane reveal that classical membrane mode shapes are electrically generated although all points of the membrane do not pass through equilibrium at the same moments in time.

6927-61, Session 13

Effects of polymer topology on electromechanical performance of novel ionic polymer transducers

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From the inside-out, ionic polymer transducers (IPTs) are composite devices consisting of a central ionomer membrane in contact with high surface area interpenetrating electrodes, where both components are swollen with an ion-conducting diluent. Under the application of a voltage the device facilitates conversion of the electrical input into a mechanical response (e.g. cantilever bending or extension). The present study aims to investigate how introducing controlled levels of branching into the ionomer affects material properties and the resulting electromechanical performance. Previous studies of similar NafionTM-based devices suggest that charge accumulation in the interfacial region between the electrodes' conducting particles and ionomer is in direct correlation with the resulting mechanical deformation.[1] Furthermore, charge transport and diluent uptake of the ionomer are directly proportional to strain performance in such actuators.[2] These relationships suggest that controlled changes in morphology due to architectural design of the ionomer may significantly affect IPT performance.

The present study involves the synthesis and characterization of novel highly-branched ionomeric polysulfones for application in IPTs. The overall goal is to develop an ionomer that is compatible with existing ionic liquid[3] and electrode[4] technology, displays high saturated modulus, shows long lifetime under actuation, and attains ionic conductivity resulting in high strain per applied voltage and sensitivity under deflection. The specific system under development is composed of an oligomeric sulfonated polysulfone (A2) and tris(4-fluorophenyl) phosphine oxide (B3) as the branch unit. The use of oligomeric A2 units has shown increased mechanical properties in other branched systems[5] and will provide a highly-branched system with a high concentration of end-groups subject to further functionalization. Selection of the proper end-group chemistry may aid in tuning the surface and bulk properties for better compatibility with other IPT components.

The use of NafionTM as a model ionomer system for the development of IPT technology sets the stage for the complex interactions that exist in understanding the mechanisms of transduction in this technology. In light of this fact, full chemical, structural, and physical characterization of these novel branched polysulfone ionomers is carried out. The ionic content, chemical structure, purity, and molecular weight of the starting monomers and resulting polymers are confirmed with multi-atomic nuclear magnetic resonance (NMR), titration, chemical analysis, thermal analysis (TGA, DSC, DMA) and size exclusion chromatography (SEC). The degree of branching in these materials is specifically characterized with ³¹P-NMR through the use of spectroscopic tags at the branch points. Effects of this branching on morphology and physical property indicators for transduction are characterized by SEC, dynamic light scattering (DLS), liquid and solid state small angle x-ray scattering (SAXS), dielectric spectroscopy, and impedance analysis. Direct methods for fabricating and characterizing these novel IPTs are under development simultaneously with many of the previously named techniques in the presence of ionic liquids. This process attempts to account for the interactions among the components of the IPT to further understand the complex contributions of the material properties to the overall process of electromechanical transduction. This information

will be compared with those trends arising from similar NafionTM devices while helping establish the positive or negative effects of controlled branching on transduction performance.

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6927-63, Session 13

Multistacked actuator based on synthetic elastomer: optimal design and control

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The multi-stacked actuator without prestrain has many advantages over the other dielectric elastomer actuators (DEA) developed up to now. In this paper, the optimized shape of multi-stacked actuator has been proposed. The active region of the actuator is affected by the non-active region of the non-prestrained dielectric elastomer in general. Therefore, in the design of actuator the geometry of the actuator should be optimized by increasing the active region and reducing the non-active region of the actuator. The simulation and experimental studies are conducted according to the different geometries of multi-stacked actuator such as circular, rectangular and trapezoid actuator. The results show that the trapezoid actuator has better performance than the others. Moreover, a new method on controlling the multi-stacked actuator is introduced. In this method, the actuator itself is used to measure its displacement without any additional sensor. Several preliminary tests are performed with the optimized prototypes of the actuator and its performances are evaluated.

6927-64, Session 13

Modeling and control of an IPMC actuator

K. K. Leang, Y. Shan, Virginia Commonwealth Univ.

In this paper, we report recent efforts on the fabrication, characterization, and control of a Nafion-based ionic polymer metal composite (IPMC) actuator. IPMCs are innovative materials that offer combined sensing and actuating ability in a flexible, lightweight, and low-power consuming package. As such, they have been exploited in robotics and a wide variety of biomedical devices, for example, as fins for propelling aquatic robots and as an injector for drug delivery. One of the main challenges of IPMC-based actuators is precision control of their movements, in particular, because IPMCs exhibit significant nonlinearities and time-varying behaviors. To overcome some of these limitations, we describe recent results on fabrication, characterization, and control of an IPMC actuator. First, experiments were conducted to characterize the actuator's force output, as well as its dynamic response. Based on these results, a model was developed to describe the behavior of the actuator. Finally, we present a feedforward-based control technique to enhance the IPMC's precision in terms of quasi-static (and dynamic) positioning. Experimental results are presented to demonstrate efficacy of the approach.

6927-65, Session 13

Inflated dielectric EAP actuator for eyeball's movements: fabrication, analysis, and experiments

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Abstract: Bio-mimetic actuators are inspired to the human or animal organ and they are aimed at replicating actions exerted by the main organic muscles. In this paper, inflated EAP actuator based on acrylic elastomer (3M VHB 4910) is fabricated for the movements of eyeballs initially. Two or more sheets of acrylic elastomer electrodes with conductive carbon grease are stick to an elastic deformable backbone structure. The acrylic elastomer can not be prestrained before sticking to the backbone structure whereas they can be prestrained by air inside the actuator after the connecting process. In contrast, Contractile folded actuators based on the silicone dielectric elastomer used for eyeball's movements exhibit good performance at a certain degree. However, the actuator's linear characteristic limits the eyeball's movements largely, only 1-DOF available. If we expect to simulate the movements of native eyeball more exactly, that is to say, multi-DOF movements, the inflated dielectric EAP actuator qualifies for it appropriately. Comparing with traditional actuators supported by any mechanical core structures, inflated dielectric actuator is lighter and more flexible. Moreover, there is grand potential for the inflated actuator to be applied in the miniaturization domains when no problems exist in the whole process of fabrication. Theoretically, the rate of deformation of the inflated dielectric actuator when activated is determined by the applied voltage and the prestrained rate. The surface area of the activated dielectric inflated actuator is about 1.0-2.0 times as large as the original one. Finite Element Method is used for analysis of the inflated actuator. We define a spherical symmetrical Finite Element Method model with electrostatic and radial bulk modulus nonlinearity for the acrylic elastomer. The results of finite element analysis predicts the deformation and stress of the actuator with the inflated air inside. And the fatigue point of the elastomer can be used to instruct our design and optimization of the actuator. Also, preliminary experiments are conducted in order to verify their principle of operations and to quantify their active deformation potential. The experimental results (the surface area of the activated actuator) are in accordance with the theoretical ones mentioned above. An auxiliary transmission mechanism connecting the eyeball and the inflated actuator in order to achieve the movements of the eyeball is developed. The experiments reveal that the minimum angle of the movement of the eyeball is up to ± 45 degrees while ± 25 degrees produced by the contractile folded actuator. The system under study at present is considerably simplified and consists of a sphere (eyeball) with a radius of 15mm, which is hinged with negligible friction on a central vertical axis of radius rotation. The challenge task of this study is to achieve the programmable movements of the eyeball and perform different kinds of emotional expressions of the native eyes which requires the correspondence movements between two eyeballs.

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6928-01, Session 1

Multisource power harvesting for fuel-less air vehicles

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Unmanned aerial vehicles typically have limited flight time due to their reconnaissance payload requirements and their restricted scale. A microwave/solar powered flight vehicle, on the other hand, can remain in-theater continuously by harvesting electromagnetic radiation using on-board antennas and solar panels. A rectifying antenna, or rectenna, is used to harvest power and rectify it into a form usable by the on-board electric motor, actuators, and other electronics. Discussed is the design of the antenna and rectifying circuit as a lightweight, integrated structural component that is tuned to maximize the efficiency of the aircraft as well as the power conversion and delivery system. In addition, power from the solar arrays is stored and converted in order to supplement the power harvested from the antennas. Novel designs for compact antenna structures are discussed that use micro-lithography methods for construction; these elements permit antennas to increase their specific energy harvesting potential. In-flight structural transformation is shown to play a crucial role in maximizing power available to fuel-less aircraft, since antenna orientation and shape affect the amount of transmitted power received by the vehicle. Key parameters and design issues are presented as well as an assessment of the feasibility of such a system.

6928-02, Session 1

Scaling laws for vibration energy harvesters

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Four classes of vibration energy harvesters have received attention, inductive (based on Faraday's law), piezoelectric (based on electromechanical coupling), electrostatic, and hybrid piezoelectric/magnetostrictive. As electronic circuits for sensors and wireless communications shrink and demand less power, there is great interest in reducing the size of energy harvesters that might be used to power wireless sensor networks, rather than relying on batteries. Current generation inductive energy harvesters of order a few in^3 generate about 1 mW/in^3 (conditioned power) under 50 milli-g vibrations over a range of 15 to 100 Hz. Purely piezo harvesters produce typically a factor of 5 to 10 less power at comparable sizes and vibration conditions. In both cases, harvested power scales with the square of the vibration acceleration.

Simple scaling laws have been derived based on the physical principles of inductive, piezo and hybrid piezo/magnetostrictive energy harvesters operating under specified vibration conditions of acceleration and frequency. These principles include the number of turns that can be accommodated in an inductive device, the electrode spacing of a piezo device, and the size and displacement of the proof mass under harmonic conditions in either case. The results indicate that inductive energy harvesters scale least favorably with decreasing size (linear dimensions given by l) with power harvested varying as harvester volume squared. Power from piezoelectric energy harvesters scale as volume^{4/3}. So at reduced size, piezo harvesters have an advantage over inductive harvesters but still produce less power per unit volume than inductive harvesters do at larger dimensions.

Hybrid piezoelectric/magnetostrictive energy harvesters can be purely vibrational, requiring a proof mass, in which case their power scales as volume^{2/3}. However, if they operate from changes in an external field, their power harvested can be independent of size.

6928-03, Session 1

High-efficiency, inductive vibration energy harvesters

R. C. O'Handley, Massachusetts Institute of Technology; A. Sliiski, J. Simon, Ferro Solutions, Inc.; D. Bono, Massachusetts Institute of Technology; J. Huang, Ferro Solutions, Inc.

Inductive vibration energy harvesters (I-VEHs) are essentially linear motors working in reverse. They operate on the basis of Faraday's law of induction in the form $F = I l B$, where F is the force on the proof mass due to the vibration, I is the current generated, l is the length of the N-turn coil cut by the magnetic flux density, B . In an I-VEH, a permanent magnet and coil are usually coupled by a spring so that the flux through the coil changes under the influence of an external vibration; the vibration must be characterized by at least two parameters, the vibration frequency (or frequency spectrum) and either the displacement, velocity or acceleration of the vibration source. In their most sensitive embodiments, I-VEHs are called geophones; they produce a voltage characteristic of very weak geological vibrations such as earth tremors.

Ferro Solutions has refined the design of linear I-VEHs having a volume of a few in^3 and incorporating several patented innovations. These devices now achieve a conditioned output power density of 1 mW/in^3 from vibrations of 50 milli-g over a frequency range from 10 to 100 Hz. Fields of application where these harvesters are being tested will be reviewed.

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6928-04, Session 1

Stiffness nonlinearity as a means for resonance frequency tuning and enhancing mechanical robustness of vibration power harvesters

J. J. Loverich, R. Geiger, Y. Liu, J. E. Frank, KCF Technologies, Inc.

Power harvesting is becoming an increasingly important enabling technology for low-power autonomous measurement/data acquisition systems. This paper is focused on a particular type of power harvesting in which energy in movement of structures is parasitically converted to stored electric charge. Because host structures in such applications often have high structural impedance and consistent periodic movement, typical harvester designs use mechanical resonance to maximize the harvested energy and more specifically their power generation density. In such applications, tuning of the vibration power harvesters' resonance frequency is required to match the host structures' forcing frequency. While tuning can be achieved by adjusting the harvesters' proof mass and/or stiffness, in practice, a more desirable method of tuning is to modify the harvester boundary conditions. This is particularly important in manufacturing where it may be undesirable to adhere to tight tolerances and specific fabrication methods required to produce a precise resonance frequency for a high quality factor (Q) device.

This paper presents a method of adjusting the boundary conditions of nonlinear stiffness elements as a means of tuning the resonance frequency of vibration power harvesters. This new harvester architecture consists of two sets of bimorph piezoelectric disks located on either side of a proof mass. By reducing the distance between the two external boundary conditions, the mode of deformation of the bimorphs is altered from bending to an in-plane stretch mode. For low level vibration, the harvester operates similarly to a linear resonant system; however, for high vibration levels the stiffness variation reduces the system's Q and alters the frequency of its transmissibility maxima. This behavior is advantageous for many industrial applications where a high level of sensitivity is required for low vibration levels (i.e. a high Q system for low vibration) and mechanical robustness is desired for shock and high vibration levels (i.e. a low Q system for high vibration).

In this paper it is shown that the resonance frequency of a harvester can be experimentally varied between 56 and 62 Hz by adjusting the boundary location by 0.5 mm. This frequency range is adequate to compensate for a wide variation in manufacturing tolerances and frequency variation of a host structure (e.g., slip in a loaded electromagnetic motor). For a nominal "low" vibration level of 2 mm/s, the harvester has a similar Q to a linear system but its Q is reduced by one third at a "high" vibration level of 10 mm/s. The experimental results are in agreement with simulations based

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on measured quasi-static stiffness.

Vibration power harvesting technology is reaching commercialization in several emerging markets and there are a number of commercially available harvesters. However, the concepts proposed in this paper are important to reducing device cost and improving robustness. For many applications, these factors are critical in ubiquitous deployment of vibration power harvesting technology as an alternative to batteries.

6928-05, Session 1

Microsolenoid electromagnetic power harvesting for vibrating systems

T. Reissman, J. S. Park, E. Garcia, Cornell Univ.

The field of renewable energy has recently taken a surge with the advent of power harvesting systems. Much of the work previously done has focused primarily on dipole materials such as piezoelectric generators due to their high energy density. Exploring other vibration conversion techniques, electromagnetism has been theorized to be highly viable as well. In fact, in the presence of strong magnetic fields, its energy density can approach that of piezoelectric systems. The key aspects to its usefulness lie in maximizing the rate of change of magnetic flux and maximizing the electric potential from the electromotive force. The specifics of this research include the descriptions of the electromagnetic theory, fabrication, and performance of a MEMS solenoid generator as a power harvesting device attached to a vibrating system.

The power harvesting device described is a micro-solenoid that utilizes a Neodymium-Iron-Boron magnet to generate large intensity magnetic fields on the order of 0.69 Tesla with relatively small magnet sizes, approximately 4.1E-07 cubic meters or 0.025 cubic inches. The relative motion of the magnet and copper MEMS coil are dictated by the vibration of the system the micro-solenoid is attached to and the principles of electromagnetic induction within the solenoid. Using mechanics and electromagnetism, theoretical simulations indicate a power output of 53.3 microwatts per coil layer design, with 15 turns per layer. The number of turns is important, as it is approximated as being proportional to the electric potential produced by the electromotive force. Hence, a doubling of the turns indicates a near doubling of the micro-solenoid's power density.

To produce such devices, fabrication is achieved by CMOS methods. Single coil layers are outlined via MEMS lithography. Precise copper coils are then deposited at a controlled electroplating rate so as to produce low resistance values and prevent shorts between the individual coil turns. Connecting layers are then outlined by restarting the lithography procedure. Finally, subsequent coil layers are built on top of pre-existing layers to produce a three-dimensional MEMS solenoid generator. Resistance measurements show agreement with original design values, approximately 3 to 30 percent. Variations are accounted for with a topology analysis of the devices using a profilometer.

Experimental testing of the devices shows approximately 12.5 microwatts per coil layer, with the magnet oscillating 2 millimeters above the solenoid at a frequency of 27 Hertz. Performance improvements on the order of four times the power output are expected with displacement of the magnet through the center of the coils. This functional increase can be accounted for by analyzing the magnetic field profile of the coil using the law of Biot and Savart. In conclusion, electromagnetic devices have been shown to be feasible as power harvesters in vibrating systems for low power devices.

6928-06, Session 1

Vibrational energy harvesters with nonlinear compliance

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Vibration powered electrical generators typically feature a mass/spring resonant system to amplify small background vibrations. The compliance element in these resonant systems can become non-linear as a result of manufacturing limitations, physical operating constraints, or by deliberate design. The characteristics of mass/spring resonant systems with non-linear compliance elements are well known but have not been widely applied within the field of energy harvesting. In this paper we present an overview of possible sources of non-linearities within an energy harvesting system and show how the deliberate incorporation of non-linear behaviour

within a design can be beneficial. Finally we present a design for a vibration powered generator, with non-linear characteristics, for use in an aerospace application and give simulated and measured results of its behaviour.

6928-07, Session 2

Ambient energy harvesting using ferroelectric materials

D. Guyomar, G. Sebald, S. Pruvost, M. Lallart, Institut National des Sciences Appliquées de Lyon (France)

The current trend in electronic devices is their integration in most of common systems in order to extend the number of functions and to improve their reliability. Moreover, the recent progresses in ultralow-power electronics allow powering complex systems using either batteries or environmental energy harvesting. Although large efforts in battery research have been made, such powering solution raises the problem of limited lifespan and complex recycling process. The current energy requirement thus leads to the research of other energy sources for mobile electronics. Strong research effort and industrial development deal with energy harvesting using piezoelectric materials, one of the most promising solutions for direct power supply and energy storage for low power wearable devices. Recent work on Synchronized Switch Harvesting (SSH) shows very high effectiveness improvement of energy harvesting from vibration compared to standard harvesting techniques.

Thermal energy is rarely harvested due to the difficulty of getting efficient devices. However, the energy potential of such a source is one of the most important. This paper deals with the energy harvesting with ferroelectric materials using their pyroelectric / electrocaloric effect. Theoretical and experimental validation of thermal energy harvesting using PVDF films and SSH technique is presented and discussed. A power of 1mW may be generated with a 4°C temperature variation at 0.2Hz with 32g of active material.

Finally, standard thermodynamic cycles may be adapted, such as Ericsson or Stirling cycles in order to improve energy conversion effectiveness. Energy harvesting cycles are presented and experimental validation is then discussed in terms of effectiveness and comparison with Carnot cycles. Experimental converted energy as high as 50 mJ.cm⁻³ have been measured with a 10°C temperature variation, corresponding to 5% of Carnot efficiency.

6928-08, Session 2

Energy scavenging for wireless sensor networks in induction motors

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Measuring signals of vibrations, sounds and currents is a conventional condition monitoring method for induction motors. With the development of the wireless sensing, wireless sensors now provide a means of accessing and measuring useful signals inside the motor where the phenomena responsible for failure occur. These sensors are capable of not merely sensing, but also processing, storage and eventually communication. Since all these activities require power that is supplied conventionally by batteries, the useful life of the sensor node is limited by the life of the battery. This paper describes two designs of the energy scavengers capable of collecting energy one from the fringing field in a three-phase induction motor, the other from the small magnets and the motion of the rotor. The field in the magnetic field is converted to electrical energy for use in intelligent wireless sensor nodes which are available from crossbow, Inc. In the first design, the alternating magnetic field in a three phase induction motor is first measured by the hall-effect sensors. A coil wound on a ferrite core attached on the stator windings harvests the leaked energy. The experimental results are compared to the theoretical calculations of induced voltage. The second design is using two small magnets instead of the fringing field from the motor. The coil is attached on a plastic ring assembled on the shaft of the rotor. The paper describes results from tests conducted with a prototype coil that is used to power wireless sensor nodes in a motor running at full speed. Both of the designs can power the sensor nodes.

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6928-09, Session 2

Energy management of multicomponent power harvesting systems

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Recent advancements in power harvesting systems have concentrated primarily on optimization of isolated energy conversion techniques, such as piezoelectric generators, electromagnetic inductors, thermal generators, etc, but less focus on combining such systems for superpositioning effects and likewise less emphasis on storing of such converted energy for use by other devices. The purpose of this work is to contribute to the power harvesting literature by analyzing an integrated piezoelectric and electromagnetic system and presenting a full-wave rectifying design utilizing new circuitry technology for energy management and storage, using power harvesting devices as the energy sources. Primary emphasis is on the frequency analysis of the combination energy conversion techniques, operating as one device, with the same vibrating system, and energy conversion efficiency of the alternating to direct current management, or storage, circuit.

The grouping together of piezoelectric and electromagnetic devices offers a vast increase in the performance of a single power harvesting device. Conceptually, the premise for a piezoelectric cantilever beam is it can be tuned to have its resonance occur near the frequency of the driving system, thus maximizing its voltage output. Likewise, for an electromagnetic inductor, the magnet and coil function in a similar way to a low-pass filter, allowing the inductance, resistance, and opposing magnetic field intensities to be tunable parameters for maximizing the electric potential within the frequency range of the driving system. For most mechanical systems, the vibrating frequency is quite low, creating large inefficiencies for small piezoelectric devices because of their natural frequencies lying outside the principal driving frequency range. To lower the piezoelectric's resonance frequency, typical techniques include making the lengths longer or addition of tip masses. For small portable power harvesters, long lengths are prohibitive and tip masses can be wasteful in terms of kinetic energy. A better alternative is to make the tip mass contribute to the energy conversion by making it a magnet for an electromagnetic inductor as well. With this combination system, the piezoelectric can be tuned both passively and actively to be at a closer resonance to that of the vibrating system. Analysis shows that the electromotive force can act as an active element on the system for frequency tuning and energy conversion optimization. Both energy conversion techniques then act out of phase to produce a superpositioning effect, creating a smoother energy source for the management, or storage circuit.

For energy management, or storage, the system will accumulate energy from characteristically very low-level ambient power sources, and deliver it to a load when a sufficient amount has been stored. An energy management unit comprising of efficient rectification, battery control circuitry, and load cycling is therefore necessary. Present methods for rectification employ diodes in a half-wave configuration. The half-wave configuration, along with the diode voltage drop, contribute to low conversion efficiencies. Efficiency improvements are possible by constructing a full-wave rectifier design with new, ultra-low threshold voltage MOSFET switching devices. In addition, utilization of small lithium ion batteries, along with battery supervisory circuitry, can create excellent storage for the accumulated energy. The reasoning for this is that lithium ion batteries are superior to capacitors, even the new ultracapacitors, in terms of Joules per gram and have lower self discharge per Joule.

6928-10, Session 2

Power conditioning for energy harvesting

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Vibration powered electrical generators produce a raw AC electrical output that often needs to be converted into DC for use by the load systems. There are many possible ways to achieve this conversion (rectification) however the specific application of vibration energy harvesting requires a solution that is a delicate balance between efficiency, converter quiescent loss and impact upon the resonant generator operation. In this paper we present models of vibration powered generators referred to the electrical side and show how these interact with typical rectification schemes. Further to this we present a unity power factor power converter, realised at ultra

low powers, designed for an aerospace energy harvesting application. Theoretical models are validated with measured results.

6928-11, Session 2

Parameter optimization of a magnetostrictive vibration-based energy harvester

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Due to the recent advances in the fields of fabrication, computing, and electronics, small size and low power-consumption sensors and actuators have become a reality. New devices that operate with minimal power requirements invaded the consumer market and are now an essential part of our daily life. To cope with the rapid growth in low-power consumption technologies, researchers have established a new and flourishing area in vibrations known as vibration-based energy harvesting. This science deals with scavenging of otherwise waste mechanical energy and transforming it into electrical energy to self-power and maintain a device operation.

In the past, various types of energy harvesters have been proposed and utilized. Those include electromagnetic, electrostatic, and piezoelectric with the latter being the most commonly implemented. The piezoelectric energy harvesters have several advantages including their compactness, MEMS compatibility, and their high single-crystal coupling. At the same time, they have several disadvantages that include, depolarization, brittleness, poor electromechanical coupling, charge leakage, and high output impedance. To overcome some of these shortcomings, a new class of energy harvesters based on the use of magnetostrictive materials is proposed. These materials generate a magnetic field in response to the applied strain and have several advantages which include high flexibility and ultra-high coupling coefficients.

In this work, we aim at optimizing the power harvested from a magnetostrictive device. Previous optimization schemes were directed towards optimizing the output power of piezoelectric energy harvesters. The optimization results were very encouraging as they illustrated that the output power increases significantly at an optimal choice of the load resistance and frequency of excitation. In addition to these parameters, we show that a magnetostrictive energy harvester can be optimized with respect to its mechanical prestress and its magnetic bias. Using a lumped-parameter model, we derive analytical expressions for the optimal values and discuss their dependence on the excitation frequency, the coupling coefficient, and the load resistance.

6928-13, Session 3

Performance comparison of implantable piezoelectric energy harvesters

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This paper presents experimental results that demonstrate energy generating performance of circular piezoelectric diaphragm harvesters for use in electronic implants. The piezoelectric energy generators are designed to transfer internal biomechanical forces into electrical energy that can be stored and used to power other in vivo devices. Accordingly, such energy harvesters can eliminate complicated procedures for replacement of batteries in active implants by possibly increasing the longevity or capacity of batteries.

Two types of piezoelectric materials being are being studied, including PZT and PMN-PT, which is an advanced crystalline material. PMN-PT has higher electromechanical coupling coefficients, and thus exhibits improved potential over the more common piezoelectric material, PZT.

Analytical results indicate that PMN-PT harvesters can generate more power than PZT harvesters to meet power requirement for specific implantable medical devices. It is also found that edge condition, thickness of bonding layer, and a degree of symmetry in fabrication for the unimorph circular diaphragms affect the energy generating performance significantly.

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6928-14, Session 3

Thermal energy harvesting by piezo-SMA composite

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Hybrid composite comprised of shape memory alloy (SMA) laminate with piezo ceramic material to transform thermomechanical energy into electrical energy had been examined in the previous study by Namli et al. Present work shows the results of experimental work by using the proposed laminated model. Deformed martensitic SMA laminate together with piezo ceramic is constrained such a way that the total deformation of the composite is zero. Recovery stress generated during reverse transformation in heating part of thermal cycle is converted into electrical energy by piezo ceramic material. The stress is released during the cooling part of the thermal cycle. Efficiency of the system is examined. The thermal energy harvester is capable of producing an output power of a few 100 mW from temperature cycle of 10 to 20 °C with 0.5 Hertz

6928-15, Session 3

Active broadband piezoelectric vibration energy harvesting

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Abstract: Converting ambient mechanical vibration power to electricity using piezoelectric devices, known as piezoelectric vibration energy harvesting, has been envisioned as an enabling technology for many wireless sensor network applications. Typical vibration energy harvesting devices are comprised of a seismic mass and a piezoelectric transducer, which operate effectively at a single specific frequency, usually corresponding to the fundamental mechanical resonant frequency. These devices can be modeled as a spring-mass-damper system, for which decreasing the mechanical damping increases the harvested electrical power at the resonance frequency. However, this also narrows the half power bandwidth, making the device less robust. This seemingly unavoidable design tradeoff between gain and bandwidth in a device can be alleviated if we address the problem from the system-level point of view.

In a piezoelectric energy harvesting system, the energy harvesting circuit is the interface between a piezoelectric device and the electrical load. A conventional view of this interface is based on voltage translation and impedance matching concepts. In fact, an energy harvesting circuit is also responsible for applying electrical boundary conditions, such as voltage and current to the piezoelectric device for each energy conversion cycle. As a result, it influences the system dynamics through the mutual electro-mechanical coupling of piezoelectricity. This is typically done using a passive circuit such as a diode rectifier or a semi-passive circuit with synchronized charge extraction that has a limited effect on the system's frequency response.

Utilizing bidirectional switching mode power electronics, on the other hand, the active energy harvesting circuit could apply an arbitrary alternating electrical boundary condition to piezoelectric devices making it possible to negotiate with piezoelectric devices to achieve a system with both maximum harvested power and optimum bandwidth. A unique characteristic of active energy harvesting is that although the average power flows from the piezoelectric device to the electrical load and energy storage, the instantaneous power flux between the piezoelectric device and the power storage unit is bidirectional. Because of this, the classical spring-mass-damper model of energy harvesting system in which electrical harvesting is modeled as a damper is no longer valid. Instead, a more appropriate model should include a mechanical transducer that directly interacts with and changes the mechanical dynamics.

This paper focuses on the frequency-broadening effect of active energy harvesting. Other aspects of active energy harvesting such as mechanical impedance matching, electro-mechanical coupling and more are not discussed in depth. In this paper, first a one-degree-of-freedom dynamic model of active energy harvesting is established that serves as a theoretical basis and leads to following discussion:

- Power frequency bandwidth of active energy harvesting using ideal power electronics

- Voltage or current limited operation of active energy harvesting
 - Power frequency bandwidth related to efficiency of power electronics
- Second, the control algorithm that implements the optimized power and bandwidth are discussed, which includes following:
- Base acceleration feed forward algorithms
 - Seismic mass acceleration phase lock loop algorithms
 - Sensorless control algorithms
 - Stability and sensitivity to parameter changes of the control algorithms

Finally, experimental work is presented. In the experiment, a highly efficient bidirectional power inverter was used to drive a piezoelectric cantilever vibration energy harvester. The harvester was excited by an electromagnetic shaker. MEMS accelerometers were used to monitor both base and seismic mass accelerations, which are sensing signals for the controller. The control algorithm was embedded into a DSpace real-time hardware system that also serves as the analog to digital data acquisition and provides switching signals to the power electronics. The voltage and current on the piezoelectric device and power flow into the electrical load through power electronics were measured via electrical means. In the experiment the power consumption of the control and sensing circuit was not included in the power consideration although the self power consumption of the inverter is included. An optimized diode rectifier harvesting circuit was also built for comparison. Results show that active energy harvesting achieved 10 time broader half power bandwidth than the optimized diode rectifier circuit for the same piezoelectric cantilever harvester and vibration excitation. Meanwhile the harvested power at the resonance frequency is improved by factor of four comparing to that of rectifier circuit. Those experimental results agree with the theoretical predictions.

6928-16, Session 3

Increasing the power scavenged by beam-mass systems from vibration sources

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Abstract

The concept and practice of energy scavenging

from the environment have been receiving much attention in recent years. An example of energy scavenging is the conversion of the energy of vibration sources, which is usually neglected, into usable but small amount of electricity to power micro-electronic devices; see, e.g., Refs. [1-6] and references therein. Examples of vibration sources, the energy of which to be scavenged, are buildings, bridges, cars, trains, aircraft, ships, manufacturing tools, etc.

A device that scavenges energy efficiently from the environment is called an energy scavenger. One type of energy scavenger consists of a cantilever beam on which piezoelectric films and a mass are mounted. This device will be referred to as either an energy scavenger or a beam-mass system. The mass at the tip of the cantilever beam is known as the proof mass. When a scavenger is mounted on a vibration source, say a panel, the cantilever beam would vibrate. The vibration of the beam is converted into electricity by the piezoelectric films.

In this paper, it is shown that when multiple piezoelectric films (see, e.g., Ref. [7]) with optimal shapes are mounted on a beam-mass system, the scavenged power can be increased by a factor of 5-10. This paper presents an improvement of the designs reported in Refs. [2-6].

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6928-17, Session 3

Self-tuning rotation energy harvesters

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Most vibration energy harvesters are based on tuning a harmonic oscillator (permanent magnet coupled by a spring to an induction coil, or mass-loaded, piezo cantilever, for example) to the frequency of the strongest vibrations in a given environment. However, in many cases, the principal vibration frequency drifts or shifts significantly over time. For this reason, there is interest in harvesters of mechanical energy that can actively or passively track the strongest vibration frequency. Roundy [1] has outlined the limitations and capabilities of various active means of self-tuning linear vibration energy harvesters. One challenge with harvesters of rotational energy is to avoid having any springs configured in a way that would cause them to be pinned above a certain rotation speed; this essentially precludes the use of a radially-oriented linear harvester that would attempt to draw energy from the ± 1 g acceleration due to gravity when the rotation is about a horizontal axis. We have designed, fabricated and tested several rotational energy harvesters that automatically track the angular frequency of the source of rotational energy. Two of them will be described.

In one design, a linear inductive energy harvester (magnet and surrounding coil) are aligned circumferentially at a distance R from the axis of rotation of a mechanical object that rotates at an angular speed. The mass and coil are supported by radially-oriented leaf springs of very small stiffness and length $r < R$. As the mechanical part rotates, the proof mass (magnet) experiences an acceleration. Because of the restorative effect of the centrifugal force on the proof mass as it falls under the action of gravity, its resonance frequency can be calculated to be proportional. That is, the length of the leaf springs must extend essentially from the hub to the proof mass, which is not always possible. A mechanically more complicated but more versatile variation on this concept makes use of a mass secondary to the magnet/proof mass. The secondary mass is configured to lower the resonance frequency of the harvester described by Eq. 1. The ratio $M1/M2$ can be adjusted so that precise angular speed tracking can be achieved in the harvester over a broad range. This rotational energy harvester produces a conditioned output of 0.32 W over a range of 150 to 200 RPM.

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6928-19, Session 3

Piezoelectric energy harvesting from an L-shaped beam-mass structure

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Cantilevered piezoelectric energy harvesters have been extensively considered in the literature. Mostly, a traditional cantilevered beam with one or more piezoceramic layers is located on a vibrating host structure and the motion of the host structure results in vibrations of the harvester beam yielding a dynamic voltage output. In this paper, we present a novel harvesting device; a flexible L-shaped beam-mass structure with a two-to-one internal resonance to a primary resonance. The structure is driven through base excitation and piezoceramic layers are attached on its faces for voltage generation. The voltage output of the L-shaped harvester is compared with that of a traditional cantilever for resonance excitation and superiority of the L-shaped harvester is demonstrated. This work persuades the energy harvesting community to pursue non-traditional structures to use with piezoelectric energy harvesting.

6928-20, Session 4

Vibro-acoustics and wave propagation of novel chiral honeycombs

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A new class of auxetic cellular solids has been recently developed for enhanced mechanical performance and reduced modal density characteristics for middle and high-frequency behavior. Contrary to classic centrosymmetric auxetic (negative Poisson's ratio) honeycombs, these cellular solids have isotropic in-plane properties with a Poisson's ratio close to -1, and feature enhanced out-of-plane strength and synclastic curvature. The flexural and S-H wave propagation behaviour is modelled for these honeycomb structures, and their modal densities estimated by their pass-stop band frequency distributions and integrated over the propagation constant intervals. Experimental tests carried out with non-contact scanning laser vibrometers are used to detect the modal density distributions and their dependence over the unit cell topology.

6928-21, Session 4

Characterization of porous substrates for biochemical energy conversion devices

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Biocell is an energy-conversion device that converts chemical energy available in adenosine triphosphate (ATP) into electrical power by means of active proteins reconstituted in bilayer lipid membranes (BLMs). This concept, developed at Virginia Tech, introduced a new, ubiquitous source for electrical power from ATP that is synthesized naturally in living cells. The active component in the Biocell is the ATPase proteins, which are reconstituted into phospholipid membranes formed in the pores of porous substrates. The BLMs formed in porous substrates, also referred to as suspended BLMs, are used as a tool for in vitro characterization of proteins, to fabricate biosensors, and as host membranes for energy-conversion processes. Constructing a Biocell with repeatable performance characteristics requires a clear picture of the interactions between the different components. Our current techniques for fabricating and analyzing BLM formation and protein insertion are inhibited by the type of substrates used in the assembly process. Currently, ATPase proteins are incorporated into millions of nano-BLMs formed across the pores of track-etched polycarbonate substrates. Uncertainties in the number of pores, the number of failed BLMs, and the success rate of protein insertion limit the precision of electrical impedance measurements and mask the true power production capability due to ATP hydrolysis. In order to circumvent these issues, we plan to use single and few-pore substrates that will reduce the effects of failed BLMs and create a more-focused test-bed for studying lipid formation and protein insertion. Advances in micro- and nano-fabrication techniques for silicon-based substrates make it possible to manufacture organized arrays of pores of only a few nanometers in diameter for supporting lipid bilayer membranes. Silicon-based membrane substrates from Applied NanoStructures are characterized for their use in suspended BLM applications. Specifically, we perform atomic force microscopy (AFM), X-ray photoelectric spectroscopy (XPS), contact angle measurements, and electrical impedance measurements in order to fully describe the geometry, topology, surface chemistry, and electrical properties of these porous wafers and how they influence BLM self-assembly. We then examine the formation of BLMs on these substrates and investigate ATPase protein insertion through both electrical impedance analysis and electrical power measurements. The goal of this work is to enable the development of a reliable and precise platform for forming suspended BLMs and studying the functions of active proteins on the molecular level.

6928-22, Session 4

Thermoelectric properties and microstructures of CoSb₃ and SiGe TE materials by spark plasma sintering

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Spark Plasma Sintering (SPS) method is performed under various sintering conditions such as heating/cooling rate, maximum sintering temperature, pressure, duration time, and vacuum chamber condition in order to make sintered thermoelectric (TE) materials with the maximum density (or least porosity) and higher figure of merit (ZT). By virtue of SPS process, CoSb₃ and SiGe TE materials with high density are obtained in a short time compared to other traditional sintering methods. The sintered specimens were characterized by X-ray diffraction (XRD), Scanning Electron Microscope (SEM), and Transmission Electron Microscope (TEM) to study more accurately the microstructures. Thermoelectric properties such as thermal conductivity, electrical conductivity, and Seebeck coefficient were measured at room temperature (300K). In case of CoSb₃, the figure of merit is 0.045. Higher ZT values are expected if the TE properties are measured at higher temperatures. The thermal conductivity of CoSb₃ sintered by SPS process is higher than that of CoSb₃ sintered by other methods. Seebeck coefficient of CoSb₃ by SPS process is also higher than that of CoSb₃ from other sintering methods. Thus, the dimensionless figure of merit (ZT) of SPS-processed CoSb₃ increased as compared with that of those sintered by other methods. This is due to the fact that Seebeck coefficient is square proportional to ZT value, it compensated for the increase of thermal conductivity.

6928-23, Session 5

Development of adaptive helicopter seat systems for aircrew vibration mitigation

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Helicopters operate in a highly complex unsteady aerodynamic environment caused by the cyclic variation of aerodynamic and inertial loads from the rotating blades. The vibratory energy transferred throughout the vehicle does not only cause damage to aircraft structural components and incurs high maintenance costs, but also creates a severe environment for the aircrew. Long-term exposure to the repetitive vibration transferred through helicopter seat can cause spine and neck injuries to the aircrew, and lead to occupational health concerns. This problem becomes more severe when new instruments, such as the Head-Up-Display and Night Vision Goggle, are integrated to pilot helmets on modern military helicopters.

Currently, vibration isolation is achieved passively through seat cushions installed between the seat frame and the aircrew. In this paper, extensive vibration test of a typical helicopter pilot seat under flight conditions as well as simulated vibration profiles using a mechanical shaker and a dummy pilot configuration in the laboratory environment have been conducted. The system configuration for flight test is shown in Figure 1. Both test results showed that the conventional passive seat cushion system is difficult to provide satisfactory vibration mitigation performance due to the broad vibration frequency range in which helicopters typically operate and the varied pilot configurations. In particular, a low frequency amplification effect around 6Hz was observed. Since this identified frequency band covers human abdominal resonant frequency, the amplified vibration can cause severe harm to the aircrew health.

To improve ride quality of the vehicle, an effective approach is to develop adaptive helicopter seat systems to optimize vibration mitigation performance. An adaptive hybrid helicopter seat system has been developed by National Research Council Canada to reduce the vibration levels transmitted to the aircrew. The immediate objective is to mitigate the vibration levels at pilot helmet location to avoid spine and neck injuries. The adaptive hybrid helicopter seat system consists of an active actuation system to counteract the N/rev harmonic peaks of helicopter blade passage frequency and an optimized passive cushion system to reduce the low frequency amplification effect, as shown in Figure 2. An adaptive control law is developed to provide adaptation capability of the system and achieve optimized vibration reduction performance under varied vibration spectra and pilot configurations. Full-Scale closed-loop control experiments have been completed. An Ulmholtz-Dickie mechanical shaker with 10,000lbs(f) drive capability was used to provide simulated representative helicopter vibration profiles from the base of the seat. Experimental results showed that significant vibration reduction has been achieved. As shown in Figure 3, the 2/rev, 4/rev and 8/rev harmonic peak responses at the helmet location, including the front-back and vertical directions, were reduced simultaneously; and the low-frequency amplification phenomenon was also mitigated effectively. The experiment

not only verified the effectiveness of the adaptive hybrid helicopter seat system, but also demonstrated the technical readiness for further flight tests on the aircraft.

6928-24, Session 5

Active constrained layer damping treatment of vibrating rotor blade for turbomachinery applications

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The critical structural element of a typical gas turbine engine is the compressor or turbine disk carrying several blades around its circumference. Most of the failures reported have been due to vibration induced fatigue of blade disk units due to operation in high cycle speed and high cycle temperature. The analysis is complicated by the various geometric features of the bladed disk unit. The blades are pre-twisted and attached at a stagger angle to the disk, from aerodynamic considerations and are considerably shorter than helicopter rotors. Owing to this, coupled bending modes and coupled bending and torsional modes occur. The blade width being comparable to its length, plate or shell theories will be required for accurate modeling. The present work is an effort at active constrained layer damping treatment of vibrating blade for turbo machinery applications. The constraining layer of ACLD treatment is a piezoelectric actuator layer and viscoelastic layer acts as constrained layer. A laminated shell element has been used for their modeling. The root of the blade is assumed to be fixed on disk. The blade geometry is modeled as cantilever shell. The laminated substrate shell made of a number of orthotropic layers. The geometry of the blade is discretized by eight noded, isoparametric quadrilateral shell element. The Cartesian coordinates of any point in this element are expressed in terms of standard shape functions and nodal coordinates and thickness variation of element is incorporated. To implement the selective integration rule for avoiding the shear locking, the state of strain at a point in the overall shell is represented by the two vectors of in-plane strains and transverse strains. Similarly, the state of stress is also represented by two vectors of in-plane stress and transverse stress. Upon deriving potential energy and kinetic energy for an element, method of virtual work is employed to obtain the elemental governing equations. At this stage the rotational degrees of freedoms are condensed to obtain a single elemental governing equation. The elemental equations of motion can be assembled to form the global equations of motion in such a manner that each patch can be activated separately. Recalling that the elemental stiffness matrix for an element augmented with the ACLD treatment are complex, one can realize that the global stiffness matrix is a complex matrix and its imaginary part is responsible for contribution to the dissipation of energy. Hence, when the piezoelectric constraining layer is not subjected to any voltage, the equation of motion given represents the modeling of the passive constrained layer damping of the substrate plates. In order to supply the control voltage for activating the patches of the ACLD treatment, a simple velocity feedback control law has been employed. According to this law, the control voltage for each patch can be expressed in terms of the derivatives of the global nodal degrees of freedom. In order to verify the validity of the present finite element model, first the natural frequencies of the substrates integrated with the inactivated patches of ACLD treatment of negligible thickness are computed and subsequently compared with the existing analytical results of uniform cross-section plate substrates without integrated with the patches. Frequency plot illustrates that the vibration of blade is a complex one with bending, twisting and coupled modes of vibration. It is observed from the frequency plot that the active patch significantly improves the damping characteristics of the blade for some modes over the passive damping. However, other modes are not controlled as other piezoelectric coefficients are not considered in the present analysis. To investigate the effectiveness of the actuator in damping first two vibration modes discrete patches of actuators are used. Five patch combinations are tested and shown through frequency plots. First patch combination contains one patch only which covers full upper surface of the blade. It can easily be observed from the frequency plot that some modes are damped to some extent but other modes are not damped. Second Patch combination contains one full patch with two holes (no patches) placed symmetrically over the surface of the blade passing through the midpoint of the blade surface. Each hole covers a surface area equivalent to four element areas. This patch combination is good for some lower as well as some higher mode damping.

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6928-25, Session 5

Application of orthogonal eigenstructure control in vehicles

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The orthogonal eigenstructure control was recently developed by the authors. The orthogonal eigenstructure control is an output feedback control that uses Singular Value Decomposition (SVD) to find the matrix that spans the null space of the closed-loop eigenvectors. This method regenerates the open-loop system while simultaneously determines a set of eigenvectors that are orthogonal to the open-loop eigenvectors. This results in significant reduction of the modal energies of the targeted modes. This method does not attempt to place the eigenvalues of the closed-loop system, nor does it require defining a set of closed-loop eigenvectors. The closed-loop eigenvectors will be within the admissible eigenvectors set and the closed-loop poles will be consistent with them. As a result, no extra constraints have been imposed to the system for placing the closed-loop poles at certain locations. This prevents the excessive actuators forces. As some examples, the application of the orthogonal eigenstructure control on an aircraft flight control and an automotive active suspension are presented.

Generally, eigenstructure assignment methods require to define a target eigenvector set for the closed-loop system. Moreover, the location of the closed-loop poles must be identified in order to reach the desirable specifications. But, there is no guaranty that the desired eigenvectors lie within the admissible eigenvectors set; since the admissible eigenvectors are consistent with the closed-loop poles. The difference between the desired and achievable eigenvectors implies an inaccurate control law. However, orthogonal eigenstructure control decouples the modes of the system by finding a control gain that generates a closed-loop system with orthogonal eigenvectors to the open-loop eigenvectors. The closed-loop poles are also consistent with the eigenvectors and the excessive controlling forces are prevented.

Since usually there are some limitations on the location of the actuators and sensors, collocation of actuators and sensors are not always possible. Also some systems might not have equal numbers of actuators and sensors. In this paper, the application of the orthogonal eigenstructure control is extended to systems with non-collocated actuators and sensors as well as the systems with different number of actuators and sensors. This generalization makes the orthogonal eigenstructure control enable to be applied to any linear system for control purposes as well. Considering the difficulty of defining the desired eigenvectors and efforts for predicting the appropriate locations for the closed-loop systems, it can be seen that orthogonal eigenstructure control is fairly straightforward.

As some examples, the application of the orthogonal eigenstructure control on an aircraft flight control and an automotive active suspension are presented. A controller is designed for lateral stability augmentation system of the linear model of an aircraft. This controller provides a yaw pointing and lateral translation control law that decouples the lateral and directional flight path response while both are decoupled from roll rate and bank angle. Also, the application of this method for suppressing the vibration is discussed in the active control of an automotive suspension. It is shown that how the orthogonal eigenstructure assignment reduces the effect of disturbances on a linear half car model.

6928-26, Session 5

Geometric optimization of controllable magnetorheological shock absorbers for commercial passenger vehicle

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This paper presents optimal design of controllable magnetorheological (MR) shock absorbers constrained in geometric parameters of commercial shock absorbers. In order to achieve this goal, two flow mode MR shock absorbers (one for front suspension; one for rear suspension) are designed using an optimization methodology based on design specifications for a commercial passenger vehicle. The optimization problem is to find optimal geometric dimensions of the magnetic parts for the front and

rear MR shock absorbers in order to improve the performance such as damping force as an objective function. A local quadratic fitting technique using commercial finite element method (FEM) software is adopted for the constrained optimization algorithm. After manufacturing the proposed MR shock absorbers, their field-dependent damping forces are experimentally evaluated and compared with those of conventional shock absorbers. Time responses and power consumptions are further demonstrated with respect to the applied current. In addition, vibration control performances of the quarter-vehicle installed with the proposed MR shock absorbers are evaluated under bump and random road conditions, and presented in both time and frequency domains.

6928-27, Session 5

Power harvesting for railroad track health monitoring using piezoelectric and inductive devices

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The growing availability of low power sensors, microprocessors, and transmitters makes it increasingly attractive to use distributed sensor networks for applications such as railroad track-health monitoring. However, the most limiting factor for these sensor networks is the lack of a long-term, low-maintenance power supply. Most existing systems still require a change of battery, and remoteness of location and low frequency of maintenance can limit their practical deployment. While earlier generations of devices such as strain gauges, temperature sensors and accelerometers required power on the order of hundreds of milliwatts, new devices exist that can support multiple types of sensors and serve as wireless transmitters while only requiring power on the order of a few mW. These advances in sensing technologies make it possible to consider converting from conventional battery power to energy harvesting techniques that do not disrupt normal operations and that can provide a minimal maintenance, long-term energy source for structural monitoring sensors. Here we describe an investigation of two principal methods for harvesting mechanical power from passing railcars in order to supply electrical power to remote networks of sensors. We first consider an inductive voice coil device directly driven by vertical rail displacement. We then consider a piezoelectric device that is attached to the bottom of the rail and is driven by the longitudinal strain produced by rail bending due to passing railcars.

Theoretical models of the behavior of inductive and piezoelectric devices were integrated with an analytical model of rail track deflection to perform numerical simulations of both of these power scavenging techniques. The simulations were conducted using MATLAB to predict electrical output levels as a function of resistive load and input mechanical conditions. Under the assumptions of a loaded coal train traveling at 13 mph, the voice coil simulation predicted an average power output of 0.16 mW, with peak values near 0.6 mW, into a 7.5 Ω matched resistive load. The piezoelectric device simulation predicted an average power output of 1.1 mW into a matched load resistor of 350 k Ω .

Lab and field tests were performed to validate the simulation results. Under low-amplitude 10-Hz sinusoidal excitation (similar to simulated train conditions), the voice coil system produced an average power of 0.146 mW into a matched resistive load. In a test involving unloaded (~65 kips) coal cars of standard size traveling from 10 to 15 mph, peak average power of approximately 0.053 mW was obtained with a load resistance of 387 k Ω . Scaling this result for loaded trains yields an expected average power output of 1.1 mW, in excellent agreement with the numerical simulations.

The results of this study suggest that simple inductive and piezoelectric devices can be used to power distributed networks of railroad track-health monitoring sensors. Increased power output levels can be achieved by device scaling or other techniques such as mechanical amplification of device displacement. Ongoing work includes prototype development and further investigation of increased power scavenging levels.

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6928-28, Session 6

A smart compliant mechanism made of SMA actuators utilizing shape memory and superelastic effects

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Compliant mechanisms are becoming more popular especially as MEMS devices. They are basically motion, force, or energy transferring devices like classical rigid-link mechanisms. However, some or all of their mobility is obtained from the deflection of its flexible members rather than joints. One-piece construction or with very few parts and joints, enhanced precision and availability, reduced wear, backlash, weight, and assembly time etc. are the major advantages that could be derived from compliant mechanisms. They are generally classified into fully or partially compliant devices. The former one has no traditional joints or links and the later one contains one or more conventional kinematic pairs in addition to compliant members. Compliant mechanisms, actuated by SMA have already been documented well in the literatures as planar and spatial manipulators. Oscillatory propulsion systems, robotic eye prosthesis, bistable mechanisms, endoscopic tip etc., are falls within the planar category and nitinol actuated stewart platforms, light weight compliant parallel manipulators etc., belongs to spatial type. In our earlier work a miniaturized parallel manipulator, made out of single piece of Beryllium-Copper (UNSC17300) and actuated by three SMA wires was presented. Preliminary investigation of its displacement analysis revealed that a maximum displacement of 1 mm could be obtained with the allowable deformation (Yield strength / Young's modulus) of 0.86 %. In all of these mechanisms, the compliant part is made of aluminium, plastic, spring or some kind of elastic material with suitable stiffness to impart the necessary compliance. Hence these mechanisms pose limitations in terms of size, displacements, maneuverability, and stiffness.

If a mechanism has to be designed as a mere compliant device, maximum flexibility can be chosen as an important parameter. Whereas, for the case of a compliant smart structure, stiffness also to be considered in addition to its flexibility. In order to overcome these difficulties, A mechanism made of superelastic nitinol as its structural member is proposed here. This manipulator is a fully compliant mechanism which is a new of its kind and possesses the advantages of a compliant device, parallel manipulator and smart structure. It is made of a superelastic nitinol thin walled tube as its central column and actuated by three numbers of identical and symmetrically connected SMA wires (six numbers in future). This novel mechanism exploits both shape memory effect (SME) and superelasticity (SE) of SMA. It also has the allowable deformation of 0.83 %, which is nearer to the corresponding value of Be-Cu and capable of exhibiting large displacements. Different actuation cases are possible, based on the number of wires being powered at a time. The buckling effect of the central column is more predominant when all the three wires are actuated at a time. Hence a set of large deflection equations have been formulated considering one-wire and two-wire actuation cases using elastica approach.

However, these expressions are only valid as long as the slope of the pillar is monotonic. The standard approach of coupling the effect of SMA actuation using the much complicated constitutive model together with transformation kinetics has been avoided here by using force sensors. However, solution for the static large displacement elastica expressions is obtained by coupling the SMA actuation force and strain induced using its geometric nonlinearities. The solution obtained using elliptical integration is compared with the results obtained by implementing line models and superelastic models in ANSYS. Based on the analytical results and simulation results, the dimensions of the manipulator have been revised downwards and fabricated for further experimental work with the consideration of increasing its actuation frequency. The in-plane translational and rotational flexibility expressions and force-displacement equations in 3D form were also obtained using vector approach for 'n' number of SMA wires. The speed of SMA actuation is generally in the range of 2 Hz or less if the wire is in still air with natural convective cooling. The performance of the manipulator is investigated further by immersing in various mediums for fast cooling for achieving higher actuation frequencies. The proposed manipulator can be used as an endoscopic tip, micro mirror and antenna positioning mechanisms, eye prosthesis etc.

Our ongoing research efforts are in the direction of trajectory generation and manipulation in multi stages with miniaturized prototypes.

6928-29, Session 6

Multifunctional SMA-based smart inhaler system for improved aerosol drug delivery: design and fabrication

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This paper documents the design and fabrication of a novel patented SMA-based smart aerosol drug inhaler system. Unlike conventional inhalers, delivering a fully dispersed air/aerosol mixture into the mouth, the smart inhaler system uses an additional nozzle to release the aerosol drug only from a strongly localized position within the mouth inlet. Kleinstreuer and Zhang [1,2] have found that such a controlled release in the mouth inlet greatly increases drug delivery efficiency and, depending on the release position, allows targeting of specific sites within an individual lobe of the lung. The methodology has been validated numerically and experimentally and shows promise to enable novel methods of chemotherapy with reduced side effects for the patient.

While the above-mentioned proof-of-concept had been performed with a number of fixed nozzles, the eventual system will feature an adaptive nozzle which can be positioned depending on a specific patient's requirements. Of all possible actuation mechanisms, micro-scale SMA wires combine low weight, low cost, low power requirements, and minimal obstruction of the airflow through the inhaler in an optimal way. The dual actuator/sensor nature of the SMA wires (via resistance measurement) further simplifies the design and allows for an extremely compact system design.

This paper presents and discusses the particular issues arising from the choice of the above SMA-based solution. It highlights the design, analysis, and fabrication process of a system that has to account for the integration of multi-functional SMA wires including mechanical, thermal, and electrical aspects as well as assembly considerations. SMA wire actuator characteristics such as achievable stroke and their effect on kinematic design are highlighted along with the consideration of actuator force requirement. Rapid prototyping technology is used for the fabrication of the Smart Inhaler device, and the problems posed by combining electrically heated SMA wires and wax-based polymer material are reported with innovative solutions. Finally, the implementation of a combined power supply/resistance measurement instrument is presented, enabling the efficient multi-functional use of actuator/sensor wires. Details of an extensive study of the electro-thermo-mechanical behavior of the commercially available Flexinol wires are used for the system is given in another paper submitted by the authors for consideration to this conference.

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6928-30, Session 6

Dynamics and control of buckling type devices using SMA wire integrated beam

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An analysis and design study using Shape Memory Alloy (SMA) wire integrated beam and its buckling shape control are reported. The dynamical system performance is analyzed with a mathematical set-up involving nonlocal and rate sensitive kinetics of phase transformation in the SMA wire. A standard material model reported by Brinson (1993) is modified by considering consistency condition in the material property tensors and by eliminating spurious singularity. A heat transfer model is employed to simulate the thermoelectric heating-cooling process. Considering this spatio-temporal variation in the temperature, we develop a state-space model of the integrated system (nonlinear beam and the SMA wire). Here, we restrict our analysis to designing an optimal state estimator and adaptive stabilization of the system plant to stay at a predefined coordinate in the

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transformation phase-space. Consequently, we also analyze branching in the control-system phase-plane trajectories.

Experiments using a thin aluminum beam with an SMA wire attached to its ends are studied. Results on the effects of the initial states (prestress and temperature) are reported.

6928-31, Session 6

Chaotic and random vibrations of a SMA passive vibration isolation and damping device

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The hysteretic behavior of pseudoelastic shape memory alloys (SMAs) results in a high dissipation capacity that can be used to attenuate undesired vibrations of a mechanical system or structures. Even though SMAs' evolving thermomechanical properties and high dissipation capacity are very interesting characteristics to be explored in passive vibration isolation systems, they can also lead to complex dynamical responses, in some cases leading to chaotic responses. Therefore, it is of fundamental importance to study the nonlinear dynamical response of SMA systems.

This work investigates the nonlinear dynamics of a SMA Passive Vibration Isolation and Damping (PVID) device through experimental tests and numerical simulations. The SMA PVID device was composed of a mass connected to a frame by two pre-strained pseudoelastic SMA wires of equal length. The device was subjected to two different vibration tests, single-frequency (dwell) excitation and random excitations, for selected values of the amplitude and frequency of excitation. The temperature value of the SMA wires was also measured during the vibrations tests.

Numerical simulations of a one-degree of freedom (1-DOF) SMA oscillator were also conducted to corroborate the experimental results. The oscillator had the same configuration of the SMA PVID device: a mass balance by two pseudoelastic SMA elements. The behavior of the SMA elements was modeled by a rate-independent constitutive model. The model is a modification of earlier work by Boyd and Lagoudas (1996) and it allows smooth transitions between the martensitic and austenitic phases. Moreover, the model is capable of simulating the thermomechanical coupling existent on SMAs. The numerical simulations of the SMA oscillator used as input the same values of amplitude and frequency of excitation used in the experimental tests, for the cases of isothermal and non-isothermal heat conditions.

Nonlinear analysis tools such as Phase Space Plots, Poincaré Maps, and Bifurcation Diagrams, and Lyapunov exponents were used to classify the type of dynamical response of the SMA oscillator motion. A procedure to determine the Lyapunov exponents from an experimental time series was used to classify the dynamical response of the SMA PVID device during the experimental vibration tests. Experimental and numerical results have shown that, in fact, the dynamic of SMA systems is quite complex, and that chaotic responses can occur for certain values of amplitude and frequency of excitation.

6928-34, Session 7

Experimental investigation and numerical evaluation of an innovative shape-memory alloy damper

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Superelastic shape memory alloy (SMA) is a potential candidate for use in structure damping devices due to its large recoverable strain range, high damping capacity, extraordinary fatigue resistance, and excellent corrosion resistance. Some SMA-based dampers have been developed, which either provides a good energy dissipation associated with a large residual deflection, or goes back to the initial state after excitation but with a small energy dissipation. In the performance-based seismic design and assessment approach, the residual deformation is emphasized as a fundamental complementary parameter in the evaluation of structural or

non-structural damage. Thus, it is necessary to advance an innovative SMA damper, combining re-centering and good energy dissipation, to satisfy the performance-based seismic design of structures. First, cyclic loading tests of superelastic SMA wires are conducted. The Lagoudas' simplified model is set up according to the hysteresis of the stress-strain curve. Second, an innovative SMA damper is designed. The device is configured simply, comprising four steel plates and two functional groups of SMA strands, such as the dissipating wires and the re-centering wires. Plate 1, 2, 3 and 4 are arranged in sequence. Plate 1 and 4 are fixed to the struts, and plate 2 and 3 are fixed to the center rod, sliding on the guides provided by the struts. The pre-tensioned dissipating wires are arranged like in a double counteracting system of springs, i.e., one strands couple the plate 1 to the plate 3, the other couple the plate 2 to the plate 4. The re-centering wires are located symmetrically, one being attached to the plates 1 and 2, and the other to the plates 3 and 4. As the center rod moving, one-sided dissipating wires are stretched, while the other are shortened, generating a full hysteresis with a large energy dissipation; simultaneously, one-sided re-centering wires elongate, associated with the other-sided wires buckling, leading to a hysteresis passing to initial point. Third, the mechanical behaviors of the innovative SMA damper are tested on MTS machine, considering the influence of cycles, loading frequency and displacement amplitude on the damper's hysteresis. The damper's mechanical parameters, such as the secant stiffness, the dissipated energy per cycle and the equivalent damping, are analyzed emphatically. Fourth, the mechanical model of the innovative SMA damper is set up to simulate the hysteretic behavior, its feasible predictions being validated by the experimental results. Finally, nonlinear time history analyses of a SDOF system are performed, and the results show that the innovative damper not only can decrease the vibration of the system under excitation, but also can mitigate the system's residual displacement after excitation.

6928-35, Session 7

Characterization of NiTiPdPt HTSMA springs and their potential applications in aeronautics (future of SMA)

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Shape memory alloys (SMAs) have been used as actuators in many different industries since the discovery of the shape memory effect. These include, but are not limited to, applications in the automobile industry, medical devices, commercial plumbing, and robotics. The use of SMAs as actuation devices in aeronautics has been limited due to the temperature constraints of commercially available materials. Consequently, work is being done at NASA's Glenn Research Center to develop new SMAs capable of being used in high temperature environments. One such material is Ni_{19.5}Ti_{50.5}Pd₂₅Pt₅. Recent work has shown that this material is capable of being used in operating environments of up to 250°C. This material has also been shown to have very useful actuation capabilities, demonstrating repeatable strain recoveries up to 2.5% under load. Based on these findings, further work has been initiated to explore potential applications and alternative forms of this alloy such as springs. Characterization of Ni_{19.5}Ti_{50.5}Pd₂₅Pt₅ springs, including their stroke capabilities, load carrying capabilities, and work outputs as a function of wire diameter and wire diameter-to-coil diameter ratio are discussed. The effects of loading history, or training, on spring properties were also investigated. Comparison of the springs to axially loaded wire actuators of the same wire diameter indicated that the stroke capability could be increased by orders of magnitude in exchange for a decrease in load carrying capacity, when converting an SMA wire into spring form. Volumetric requirement comparisons for housing the two actuator forms are also reviewed. These findings are then used to discuss the design of a flow-control mechanism for use in the centrifugal compressor of a helicopter engine. Finally, the paper concludes with a general view of SMA springs for use in latching mechanisms and large-stroke linear actuators for other potential aerospace applications including active jet engine structures and debrisless separation mechanisms for satellites.

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6928-36, Session 7

Testing of SMA-enabled active chevron prototypes under representative flow conditions (future of SMA)

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Reduction of jet engine noise in the vicinity of airports continues to be of paramount importance. Recent research has shown that chevrons applied to the exhaust nozzle can reduce jet noise by as much as 2-3 dB (EPN). Parametric effects are not well understood so even greater reductions may be possible. Fixed chevrons are now being installed on some production aircraft to realize this noise improvement. However, it has also been shown that the presence of fixed chevrons induces a thrust loss of approximately 0.25% at cruise. The concept of deployable or active chevrons has been proposed to minimize the thrust penalty. Recently, controllable or variable geometry chevrons have been installed on an experimental high bypass turbofan engine to test the capability of moving the chevrons under flight conditions. However, all model scale noise reduction studies to date have been performed using fixed chevron technology, where the geometry and resulting flow immersion is predetermined and invariant. Performing parametric studies by such methods is cost prohibitive. Parametric investigation by numerical means is tractable, but is of limited value because of insufficient fidelity in the noise predictions.

NASA Langley has conducted a multi-year effort to develop a model scale active chevron system for use in the jet engine simulator of the Low Speed Aeroacoustic Wind Tunnel. The ultimate goal of the project is to enable optimal control of far-field noise under realistic operating conditions by independent control of an array of active chevrons, i.e., optimal immersion amplitude and distribution with airframe integration effects and variable operating conditions. The active chevron concept employed in this project consists of a laminated composite structure with embedded shape memory alloy (SMA) actuators, termed a SMA hybrid composite (SMAHC). SMA actuators are embedded on one side of the bending axis of the structure such that thermal excitation generates a moment and deflects the structure. This development effort has previously demonstrated a capability to fabricate and test chevron prototypes in a bench top test system. Two curved active chevron concepts were demonstrated; one that was powered to immerse and one that was powered to retract. The present work has extended this development by testing the two chevron prototypes in a representative flow environment. Results from this testing will be presented along with rationale for down-selecting to one of the chevron prototypes for further development. Results from refinement of the fabrication approach and instrumentation of the chevrons for closed-loop immersion control will also be presented.

6928-37, Session 7

Parameter identification of piezoelectric bimorphs for dynamic applications considering strain and velocity dependent effects

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Piezoelectric bimorph elements are commonly used in a wide area of applications, among them various actuator applications in textile machines, applications in sensing like medical tissue identification, or the use in energy harvesting systems. Especially the last field may create a mass market for piezoelectric elements. Due to their easy use and low resonance frequency bimorphs seem to fit energy harvesting demands quite well. To get the best possible power output the element has to be designed as good as possible to fit the environmental excitation characteristics as excitation frequency and amplitude. Due to the need of a good understanding of the resulting system, a model based approach is desirable for the design of the used bimorphs. This is the case not only in Energy Harvesting systems but in most of mentioned applications.

A typical modeling technique is the utilization of modal models using electro-mechanical analogies. The needed parameters can either be easily identified by measurements of the piezoelectric system or they can be calculated using a more complex dynamic mechanical model.

This kind of modeling is well known for a good approximation of the

behavior of piezoelectric transducers - as long they are driven in the linear range. Unlike most Langevin transducers, piezoelectric bimorph elements show a smaller range of linearity in experimental investigations. Obviously, the bimorph elements have a strong shift of the resonance frequency and a considerable increase of the damping with increasing excitation. The change in frequency and damping leads to complications in system design. For example, Energy Harvesting Systems are commonly designed on one excitation frequency.

It is hypothesized that this nonlinear behavior mainly depends on the strain level of the bending element. Considering that strain is proportional to the velocity of the free end of the bimorph around the first mode, experimental results with constant strain level are performed. Experiments verify the relationship between the appearing nonlinearities and strain as well as velocity of the bending element.

Furthermore, measurement results of electrical excited bimorphs with different constant strain levels are used to identify parameter sets for different piezoelectric elements and excitations. Gained data allows the phenomenological definition of the behavior of the modal model parameters according to excitation levels. This enables the derivation of strain dependent parameter sets for specific materials.

The measurement data are also used to enhance the well known lumped parameter model for piezoelectric systems to handle the nonlinear behavior using the strain dependent parameter sets. The enhancement of the model allows the correct description and simulation of piezoelectric bending elements like bimorphs for different mechanic as well as electric excitation levels. This leads to a suitable design procedure to shorten development efforts.

6928-38, Session 8

Optimization and implementation of the smart joint actuator

J. E. Manzo, E. Garcia, Cornell Univ.

A new actuator system is being developed at the Cornell Laboratory of Intelligent Material Systems to address the problems of morphing shape change in flight. This low profile actuator, known as the 'smart joint', is capable of maintaining rigidity in its nominal configuration, but can be actively strained to induce rotation at flexure joints of a skeleton mechanism. In this way, the joint is energetically efficient, only requiring power consumption during active, discrete morphing maneuvers used to move between flight regimes at different points within a mission.

The composite beam mechanism uses shape memory alloy (SMA) for strain actuation, with shape memory polymer (SMP) providing actively tailored rigidity due to its thermally varying properties. The first phase of the actuator development was modeling of the generic composite structure, proving analytically and computationally that the joint can produce useful work. The next phase will focus on optimization of this joint structure and usage, including ideal layering configurations and thicknesses in order to maximize work density for a particular application. As well, prospective actuator placement locations within an airframe, their effect on the aerodynamics, and the ability to withstand realistic loading scenarios will all be investigated. Heuristic optimization methods will be employed to best determine the structure of the joint at various scaling ratios and potentially with varying aerodynamic loading taken into account. The results will be compared to finite element models and, ultimately, to dynamic actuator testing. With the ultimate goal of using this joint to morph a bat-like membranous aircraft wing, wind tunnel testing of active camber wing segments will be presented if available.

6928-39, Session 8

Topology optimization of a plate coupled with acoustic cavity

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This paper presents the development of topology optimization of plates coupled with acoustic cavities in an attempt to minimize the vibration of the plates and the sound radiation into the acoustic cavities. The developed topology optimization procedure aims at selecting the optimal material distribution over the plate surface in such a way that minimizes

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the structure-fluid coupling between the plate and the acoustic cavity.

A finite element model is developed to describe the structure fluid-interaction between the plate and the cavity. The model is integrated with the topology optimization algorithm to iteratively generate the optimal plate shape.

Prototypes of the topology optimized plates are manufactured using stereolithography techniques. These plates are coupled with an acoustic cavity that has five rigid sides. The plates are then excited using an electro-mechanical speaker. The vibration of the topology optimized plates and the sound pressure level inside the cavities are recorded and compared with the corresponding values when using plain plates of equal mass. The obtained result demonstrates the effectiveness of the topology optimization in minimizing the vibration of the plates and the sound radiation into the acoustic cavities.

The presented theoretical and experimental procedure can be easily extended to more complex structures such as shells where the attenuation of the vibration and sound radiation is critical to their effective operation. [Work is funded by ONR]

6928-40, Session 8

Turbomachinery blades damping by optimized shunted piezoelectric circuits

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Dynamics of gas-turbine blades are particularly aero-elastic coupling sensitive. These aerodynamic limits can be pushed away by adding extra damping to the structure in order to reach even better compressor performance.

As in many fields active control would solve easily this kind of instability. But the difficulty remains in the needed energy supply for actuators whereas these components are aimed to be bonded on rotating structures. The capacity of different auto-supplied devices using shunted piezoelectric circuits had been studied here to prevent turbomachine blades from fluttering.

Before realizing the study on complex turbomachine geometries, the presented technique uses a numerical development thanks to a 1D Euler-Bernoulli beam model combining both mechanical and electrical coupling parameters. A second development thanks to a 3D model had been made using a commercial tool, Comsol software. These approximate models are used to optimize electrically the shunted piezoelectric element and its localization. The results, verified experimentally, let suppose that vibrations can be reduced significantly when shunted piezoelectric circuits are mounted on a real structure.

6928-41, Session 9

Active optimal control of SSI system based on the finite element model of SSI system and shaking table test study

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In this study, first, a linear quadratic Gaussian (LQG) controller based on the finite element model of SSI system is constructed to optimally control the responses of SSI system. Substructure (Superelement) analysis is used to reduce the system matrices to a smaller set of DOFs, because number of states of the finite element model is very large and some states are not accessible for measurement or are difficult to measure. The DOFs reduced order system is used to design the active controller which includes the influence of the soil boundary conditions and the depth of the soil layer. Second, the influence of the boundaries on control effectiveness is investigated using the proposed method. The results show that the control effectiveness under three kinds of boundary conditions is almost same and better than that of lumped-parameter models. While 7DOFs reduced order system and 5DOFs reduced order system are compared, it can be seen that there isn't any difference in peak displacement, peak velocity and peak acceleration. Moreover, the influence of the depth of soil layer is studied. From the result it can be noticed that the depth of soil layer of the controller designed model will change the control effectiveness. Finally,

the standard two-floor shearing structure with SSI effects is used as the model, and AMD controller strategy depending the proposed method is adapted and a series of benchmark earthquake waves were input onto the specimen by the shaking table, and the test results show that the proposed method can effectively control the responses of SSI system.

6928-42, Session 9

Applicability of AMD controller based on the fixed-base structure to control SSI system

F. Wang, J. Ou, Harbin Institute of Technology (China)

For the practical AMD control systems, the AMD controllers designed on the fixed-base structure are applied to control the real structure standing on the soil. The whole system is that the controlled object is SSI system and the control strategy optimized object is the fixed-base structure. The two systems are different. This will make the anticipative control effectiveness change.

First, the essence of AMD controller based on the fixed-base structure to control SSI system is interpreted. The control force applied to the SSI system obtained by the same control gain G with the fixed-base structure, is not the optimization control force for SSI system.

Second, the applicability of AMD controller based on fixed-base structure to control SSI system is studied through simulation analysis using LQR algorithm, and compared with AMD controller designed on SSI system. The regulation of the control effectiveness varies with $\dot{\omega}_s/\dot{\omega}_r$ ($\dot{\omega}_s$ is frequency of SSI system, and $\dot{\omega}_r$ is frequency of fixed-base system) is investigated. The results show that the AMD controller designed for the fixed-base structure can control SSI system effectively when the ratio of the frequencies of the SSI system and the fixed-base structure $\dot{\omega}_s/\dot{\omega}_r$ is larger than 0.9. However, when $\dot{\omega}_s/\dot{\omega}_r$ is smaller than 0.4 this kind controller is not suitable to control SSI system.

Finally, the shaking table tests about AMD control SSI system built on three kinds of soil parameters are carried out using four kinds AMD controllers. The control effectiveness of the first two controllers to fixed-base system and SSI system is studied. The results show that the AMD controllers can control the responses of the SSI system, the control effectiveness decreases compared to the control for the fixed-base structure. In addition, the uncontrolled the peak values of the displacements for the SSI system and the fixed-base structure are different; the values of SSI system are lower than those of the fixed-base structure system, obviously. It shows that SSI effects can reduce the responses of system. A trend can be found that the decrease value of the control effectiveness increases with the increase of earthquake intensity. This phenomenon is attributing to the soil nonlinearity property. The properties of the soil changes with the increase of the earthquake intensity, and the soil gradually changes soft, lead to the decrease of the control effectiveness of AMD designed by the fixed-base structure. It shows that when the soil is rigid the AMD designed by the fixed-base structure can get the anticipation control goal, but the control effectiveness will lose with the soil changing soft, gradually. Tests results demonstrate that while the soil is stiff enough the controllers work very effectively, but the controllers can't control the response of SSI system with soft soil, even make larger deformation and acceleration of the structure. The results further validate the conclusion of simulation analysis.

6928-43, Session 9

Controllable elastic couplings of a composite multilayered beam

A. Marques, F. Gandhi, The Pennsylvania State Univ.

This paper describes the controllable elastic couplings of a composite multi-layered beam. In a recent paper in the Smart Materials and Structures Journal (Beams with Controllable Flexural Stiffness, 16 No. 4 August 2007), a concept for stiffness variation of a multi-layer beam was presented. In that study, the multi-layer beam comprised of an aluminum base beam with polymer sheets attached to the upper and lower surfaces and aluminum cover sheets. By heating the polymer layers through glass transition, the cover sheets were decoupled from the base beam resulting in a decrease in flexural bending stiffness. If the aluminum base beam and cover layers are replaced by orthotropic plies at different ply angles, it is

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possible to similarly change the elastic coupling of the composite beam by heating the intermediate polymer layers.

The multi-layered beam consists of a base layer of a two-ply Graphite-Epoxy laminate. Polymer layers are present on the upper and lower surfaces of the base layer and act as an intermediate layer. Another single ply Graphite epoxy laminate exists on the top and bottom respectively of the polymer layer. In effect, the base beam has polymer layers on the upper and lower surfaces sandwiched between two cover layers. When the polymer layer is stiff, the cover layers are strongly coupled to the base beam. Application of an extensional load results in the tip-twist of the multi-layered beam as an integral structure dominated by all four plies. However, if the shear modulus of the polymer layer is reduced, the cover layers are largely decoupled from the base layers and the tip-twist produced due to an extensional load is dominated by the two plies in the base layer.

In this paper, the extension-twist and the bending-twist coupling of the beam was observed due to the application of extension and bending loads respectively. At low temperatures, the polymer layer is in a glassy state and the application of an extensional load produces counter-clockwise tip twist in the beam. Using a thin electric heating pad embedded in the polymer layers, the temperature and hence the stiffness of the polymer layer can be controlled. By increasing the temperature, the shear modulus of the polymer layer decreases and at high temperatures, it is in a rubbery state. At this state, the base beam is decoupled from the cover layers and a clockwise-twist is produced dominated by the base beam layer. Analysis of various laminates and ply orientations indicate a significant difference in twist for an applied extensional load between the coupled and decoupled beam. Analysis is also performed using a bending load to observe bending-twist coupling effects. Again the difference in the tip twist is significant between the coupled and decoupled beam under bending loads and is maximum for a 45 degree ply orientation.

Current research involves experimental procedures to verify theoretical predictions in tip-twist measurements. A high strength adhesive is used to join the various layers of the beam which will be subjected to 1000kN extensional and bending loads and the deflections will be measured using high precision measuring devices. The heating pads along with a thermocouple and a temperature controller will be used to modulate the polymer layer temperature.

6928-44, Session 9

Piezo-shunt power-flow optimization for composite beam stabilization

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Numerical and technological tools have been developed for complete electromechanical integration of innovative shunting damping strategies for piezoelectric composite beam stabilization to realize a new type of hybrid piezocomposite smart structures.

The approach enhances the performance of fully passive configurations to control mechanical power flow in a beam by using negative capacitance elements. In contrast to passive shunted components that target discrete modes, negative capacitance shunted piezoelectric transducers offer the potential for broadband control from the low Hertz into the kilohertz range.

This paper presents an original approach to tune vibration power flow dispersion in a piezocomposite beam to obtain total wave absorption by only optimizing the electrical circuit configuration shunting a single piezopatch. The numerical study considers the power flow efficiency of the strategy and the stability and robustness difficulties observed when a single device is considered.

The simplicity of the proposed electromechanical controlling devices affords the possibility to define and realize distributed configurations and also lends itself to integrated distributed smart composite structures.

6928-45, Session 9

Two-step recursive fourth-order accuracy method for dynamic response computation based on principle of minimum transformed energy

D. Li, Beijing Jiaotong Univ. (China); T. Liu, Shenyang Jianzhu Univ. (China)

A fourth-order accurate method is presented for the computation of dynamic response in the field of structural vibration. Based on Benthien_Gurtin's principle of minimum transformed energy in linear elastodynamics in Laplace space, functional in the form of single convolution integral is obtained by restoring the functional in the Laplace space back into the original space. Based on the functional after spatial discretization, five-order Hermite interpolation functions are adopted to approximate the nodal displacement in local time domain. A unconditionally stable two-step recursive method is presented after the variational operation. The optimum value of parameter is selected according to the unconditionally stable analysis. Accuracy analyses and examples show that the algorithm is a fourth-order accurate method. The method provided a useful tool with simple code and easy implementation for the investigations of dynamic response computations in practical engineering.

6928-46, Session 9

Vibration damping of aircraft wing structure using active constrained layer damping patches

N. Mallik, Univ. of Cincinnati

Although the static airloads on the wing are always less than its structural strength, once the wing begins to twist and bend in a periodic manner, under certain conditions the dynamic airloads may begin feeding the elastic motion of the wing, causing its amplitude to grow, which in turn causes increased airloads that eventually exceed the structural strength. Such a catastrophic dynamic coupling between elastic motion and the unsteady aerodynamic loading is called flutter. The wings are tapered in all three directions and having cavities inside containing oil. Cross sectional asymmetry causes coupling of bending and torsional modes. Moreover, the wing width being comparable to its length, plate or shell theories will be required for accurate modeling. The present work is an effort at active constrained layer damping treatment of vibrating aircraft wing. The constraining layer of ACLD treatment is a piezoelectric actuator layer and viscoelastic layer acts as constrained layer. A laminated shell element has been used for their modeling. The root of the wing is assumed to be fixed on aircraft. The wing geometry is modeled as cantilever shell. The laminated substrate shell is made of a number of orthotropic layers. The geometry of the wing is discretized by eight noded, isoparametric quadrilateral shell element. The Cartesian coordinates of any point in this element are expressed in terms of standard shape functions and nodal coordinates and thickness variation of element is incorporated. To implement the selective integration rule for avoiding the shear locking, the state of strain at a point in the overall shell is represented by the two vectors of in-plane strains and transverse strains. Similarly, the state of stress is also represented by two vectors of in-plane stress and transverse stress. Upon deriving potential energy and kinetic energy for an element, method of virtual work is employed to obtain the elemental governing equations. At this stage the rotational degrees of freedoms are condensed to obtain a single elemental governing equation. The elemental equations of motion can be assembled to form the global equations of motion in such a manner that each patch can be activated separately. Recalling that the elemental stiffness matrix for an element augmented with the ACLD treatment are complex, one can realize that the global stiffness matrix is a complex matrix and its imaginary part is responsible for contribution to the dissipation of energy. Hence, when the piezoelectric constraining layer is not subjected to any voltage, the equation of motion given represents the modeling of the passive constrained layer damping of the substrate plates. In order to supply the control voltage for activating the patches of the ACLD treatment, a simple velocity feedback control law has been employed. According to this law, the control voltage for each patch can be expressed in terms of the derivatives of the global nodal degrees of

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freedom. In order to verify the validity of the present finite element model, first the natural frequencies of the substrates integrated with the inactivated patches of ACLD treatment of negligible thickness are computed and subsequently compared with the existing analytical results of uniform cross-section plate substrates without integrated with the patches. To investigate the effectiveness of the actuator in damping first two vibration modes discrete patches of actuators are used. Six patch combinations are tested and shown through frequency plots. First patch combination contains one patch only which covers full upper surface of the wing. Frequency response of this patch along with the wing demonstrates that second mode is damped to some extent but first mode damping is very little. Second Patch combination contains one full patch with two holes (no patches) placed symmetrically over the surface of the wing passing through the midpoint of the wing surface. Each hole covers a surface area equivalent to four element areas. Third Patch combination contains one patch with two holes placed symmetrically along a diagonal at two corners over the surface of the wing. Each hole covers a surface area equivalent to four element areas. Fourth Patch combination contains one patch with a hole placed exactly at the center over the surface of the wing. The hole covers a surface area equivalent to four element areas. Second, third and fourth patch combinations are good at first mode damping and effective to some extent for second mode damping. Also the effectiveness of second patch combination is better than third and fourth patch combinations in attenuating first mode of vibration.

6928-58, Poster Session

BATMAV: a biologically-inspired micro-air vehicle for flapping flight: kinematics and actuation

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The main objective of the BATMAV project is the development of a biologically inspired bat-like Micro-Aerial Vehicle with flexible and foldable wings, capable of flapping flight. This phase of the project focuses particularly on the kinematical analysis of the wing motion and the design of a smart material (shape memory alloy) driven actuator system mimicking the functionality of the bat's relevant muscle groups.

In the past decade Micro-Aerial Vehicles (MAV's) have drawn a great interest to military operations, search and rescue, surveillance technologies and aerospace engineering in general. Traditionally these devices use fixed or rotary wings actuated with electric DC motor-transmission, with consequential weight and stability disadvantages. SMA-wire-actuated flexible wings for flapping flight are promising due to increased energy density while decreasing weight, increased maneuverability and obstacle avoidance, easier navigation in small spaces and better wind gust stability. While flapping flight in MAV has been previously studied and a number of models were realized using light nature-inspired rigid wings, this paper presents a platform that features bat-inspired wings with flexible joints and muscle-wire actuation to allow mimicking the kinematics of the real flyer.

The bat was chosen after an extensive analysis of the flight physics of birds, bats and large insects. Typical engineering parameters such as wing loading, wing beat frequency etc. were studied and it was concluded that bats are a suitable platform that can be actuated efficiently using micro-scale Flexinol muscle wires. Also, due to their wing camber variation, they can operate effectively at a large range of speeds and allow remarkably maneuverable flight, avoiding obstacles while flying in small spaces (i.e. search and rescue missions).

In order to understand how to implement SMA 'mechanical muscles' on a bat-like platform, the analysis was followed by a study of bat flight kinematics. Due to their complexity, from the engineering point of view, only a limited number of muscles were selected to actuate the flexible wing. A computer model of BATMAV platform incorporating SMA wires, wings and platform body, was created using SolidWorks software. The skeleton was subsequently fabricated using rapid prototyping technologies, and a novel joint technology was introduced which, replaces the complicated morphology of the natural flyers by a combination of superelastic SMA wires as flexible hinges. An extended analysis of flight styles in bats coordinated with image processing and inverse kinematics theory for robotic manipulators resulted in a collection of data for joint angles variation of the wing bone structure. These data implemented into

the direct kinematics of the 'robotic-like wing arm' helped to mimic the wingbeat cycle of the natural flyer. In order to investigate the extent of SMA actuation capability, a computer-assisted tensile test setup was designed to study the mechanical properties of SMA micro-scale wires. The results of the investigation are used to optimize the lengths and the attachment locations of the wires such that enough lift, thrust and wing stroke are obtained.

6928-102, Poster Session

Analysis of the dynamics of the vibratory tabular valve

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Construction of a novel tabular vibratory valve and its design optimization is presented in the paper. Coupling of the dynamic properties of a vibrating tube with the dynamic behavior of a steel ball inside that tube can help producing a new type of smart doser of liquid material which can be effectively controlled by piezoelectric actuators. The unique feature of the tabular vibratory valve consists in the fact that the sealing surface of the seat is facing towards the intake duct and is located in the node of the second natural mode of transverse vibration of the elastic pipe. Theoretical analysis of the stability of this non-linear system is coupled together with the experimental study of an operating valve. Laser holographic interferometry is used for the identification and optimization of working regimes of the this system.

6928-103, Poster Session

Analysis dynamics of piezoelectric optical scanner with periodical microstructure

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Piezoelectric optical scanner is developed for multi-coordinate control of optical laser beam by excitation of microstructures. The manufactured microstructure is the periodical structure which was implemented in piezoelectric optical scanner design. Such type of opto-micro-mechanical systems can be used for accurate angular or linear deflection of optical elements in various optomechanical and optoelectronic systems. The operating principle of these devices is based on piezoelectric effect and on conversion of high-frequency multi-dimensional mechanical oscillations of piezoelectric vibration transducers into directional multi-coordinate motion of the optical elements in the measurement chain. The main distinctive feature of such optical piezoelectric scanners is the combination of high micrometer range resolution with a wide range of angular deflections of the scanning elements. The manufacturing process and visualization of the microstructure were presented. The device consists of piezoelectric cylinder and a scanning element with three degrees of freedom. The control model of this device was derived using simulation results of optical scanner by COMSOL Multiphysics software. ESPI digital holographic PRISMA system was used to validate the result of simulation of piezoelectric optical scanner and to test the functionality of piezoelectric optical scanner with implemented microstructures.

6928-104, Poster Session

Limit of feedback gains of collocated sensor and actuator pairs for beams

Y. Lee, Univ. of Incheon (South Korea)

This paper presents the availability of piezoelectric actuators with finite lengths bonded on beams to actively control their motion. It is well known that direct velocity feedback (DVFB) control could be useful when a sensor and actuator pair is collocated on structures for the suppression of vibration. It is considered that three different collocated pairs of piezoelectric actuators (20, 50 and 100 mm) and accelerometers installed on three identical clamped-clamped beams (300 * 20 * 1 mm) with DVFB strategy. The response of each sensor-actuator pair requires strictly positive real (SPR) property to apply a high feedback gain. However the length of the piezoelectric actuator could affect SPR property of the sensor-actuator response. Intensive simulation and experiment shows the

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effect of the actuator length variation is strongly related with the frequency range of SPR property. A shorter actuator gave a wider SPR frequency range as a longer one had a narrower SPR range. The shorter actuator showed limited control performance in spite of a higher gain was applied because the actuation force was relatively small.

Thus an optimal length ratio (actuator length/beam length) was suggested to obtain relevant performance with good stability with the control strategy.

The result of this investigation could give important information in the design of active control system to suppress unwanted vibration of smart structures with piezoelectric actuators and accelerometers.

6928-105, Poster Session

A new optimal vibration control system for two connection structures

J. Zhang, Xiamen Univ. (China)

Building structures which are resistant to earthquake and wind excitation has been a challenging job for more than a century. In recent years, considerable attention has been paid to research and development of structural control devices, with particular emphasis on alleviation of wind and seismic response of buildings and bridges. Many innovative structural control devices have been applied to the full scale structures. The two-structure connection control system is a new vibration control system, which is composed of two adjacent parallel structures connected by active or passive control devices. In comparison with the conventional building structures, this new vibration control system depends on the dynamic interaction of the two adjacent parallel structures connected by control devices to reduce the effects of earthquake excitation, so that the respective dynamic characteristics of the two adjacent parallel structures and the vibration absorption capacity of the control devices may be utilized reasonably. In this paper, we venture to propose a new optimal vibration control system which composed of two adjacent parallel structures connected by passive control devices. This optimal design work involves two aspects: parametric optimization and number and placement optimization. The optimal parameters of passive control devices can be obtained by using the equivalent optimal control method based on the stochastic vibration theory. A new performance index of passive control devices based on the dynamic responses of the control system in frequency domain is also proposed. According to this performance index, the optimal number and placement of passive control devices can be obtained. Numerical results illustrate that the optimal design method proposed in this paper is effective and flexible. It may properly utilize the interaction between two structures and the control devices to reduce the response of buildings.

6928-106, Poster Session

Flexible multisensors for robotics

M. Santoro, ENEA (Italy)

A Pressure Pad based on a foam material, whereby light introduced to the foam is scattered in a manner dependent on the force applied to the surface of the foam, is our pressure detecting device. 60 pressure sensors are spaced evenly throughout the area of the touchpad. Each individual pressure sensing element consists of a tiny light source and a tiny detector imbedded in a thin cellular elastomer. As pressure is applied to the elastomer in the region of the sensor, the cell size distribution is altered along with the bulk optical scattering properties of the material in that area. The light detector measures the change in scattered light intensity at the sensor, and interprets this as a change in pressure. Optical fibers laminated into the structure are used as the "nervous system", to deliver transmitted light to the location of the sensors, and to deliver received light back from the sensor. In order to improve the quality of information available from the device, others sensors are added to the pad: Resistance Temperature Detectors, Silicon PIN Photodiodes, three-axis inertial sensors. This data set classified by an SVM (Support Vector Machine) algorithm.

6928-107, Poster Session

Design and evaluation of a passive damper by using pseudoelasticity NiTi wires

Q. Pan, C. Cho, Inha Univ. (South Korea)

Shape memory alloys (SMAs) are well known as their distinct behaviors such as shape memory effect (SME), pseudoelasticity effect (PE, also known as superelasticity effect). Furthermore, some Shape memory alloys like NiTi alloy exhibit noticeable high damping property on account of these two effects. Ascribing to their large recoverable deformation ability and high damping capacity as well, however, those shape memory alloys are commonly used for active and passive damping applications.

In this paper, one passive damping device employing pseudoelasticity NiTi wires for energy dissipation is presented. The main components of this damper can be categorized as two parts according to their functions, one is NiTi wire and the other one is the spring. NiTi wire is utilized to dissipate the mechanical energy via energy conversion, associated with the phase transformation of wires from austenite to martensite during loading-unloading process. The spring, however, owns large stiffness to stretch the NiTi wires and generate the recover force after deformation. The detailed explanation on the whole structure of the damper, as well as the establishment of its mechanical model and functional principle, is given in the text of this paper.

Moreover, the mechanical behavior of pseudoelasticity NiTi wires subjected to certain environment condition is observed. In terms of those experimental data, a numerical evaluation on the damping property of the model, involving dissipated energy and loss factor, in quasi-static state is accomplished. The consequent results reveal this damping device is able to dissipate plenty of mechanical energy, associated with the phase transformation of NiTi wires in pseudoelastic behavior range.

The maximum load of this damper may range from several kilogram to decades of tons by choosing different number of NiTi wires, in accordance with different requirement. The stroke, however, is determined by length of NiTi wires, i.e. the length of the designed SMA damper. Due to its mechanical behaviors, this damper is expected to be utilized as an effective vibration reduction device for structure protection or low frequency mechanical system.

6928-108, Poster Session

Experimental evaluation of a flapping-wing aerodynamic model for MAV applications

J. Lee, D. Kim, J. Lee, J. Han, Korea Advanced Institute of Science and Technology (South Korea)

Flapping-wing aerodynamics has drawn attentions of worldwide researchers in the fields of aerospace engineering, biology, and zoology. As well as the natural flapping flyers, the flapping-wing MAVs experiences complex unsteady aerodynamics in low Reynolds number regime. Recent bio-inspired flapping-wing MAVs are being developed for the purpose of reconnaissance in confined spaces, for example, inside buildings, and tunnels. It is also known that they are highly potential alternatives of exploring flying robot in the future space mission. In order to realize practical flapping-wing MAVs, some technical challenges should be resolved. The constituting components such as batteries, actuators and sensors, and control units should be further miniaturized. In addition, the understanding on the complex unsteady aerodynamics should be enhanced, and based on these understanding, the overall platform design can be further improved for highly maneuverable and stable low-speed flight.

CFD-based calculations for flapping wings have been performed with restrained conditions; In spite of their high potential, it is inefficient to apply CFD in the design stage or parameter studies because of high computational costs. Therefore, there is a strong need to develop the sufficiently efficient aerodynamic model of flapping-wing. There have been proposed a few simple flapping-wing aerodynamic models; however those models are not sufficiently validated because of limited availability of precise experimental data.

We developed an efficient flapping-wing aerodynamic model based on the modified strip theory. In the present aerodynamic model, high relative angle of attack can be considered and a new delayed stall model is

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proposed. This aerodynamic model can be used for design and controls of flapping wing MAVs, such as wing structure optimization and flight controller development. In addition, the present aerodynamic model was fully evaluated by the comparison with the aerodynamic data of flapping models. We manufactured a precise experimental device to measure the aerodynamic loads of flat-plate wings under plunging and pitching motions at low Reynolds numbers. The plunging and pitching motion generators make sinusoidal harmonic motions with adjustable amplitudes and frequencies. The experimental device has five embedded sensors to measure lift and thrust forces (2 load cell, KTOYO-651AQ), plunging and pitching motions (2 laser sensors, LB-301/LB-1201), and to compensate the inertia force of vertical direction (1 accelerometer, PCB352C66). These signals are managed by DSP board (dSPACE, DS-1103). This experimental device is installed in a low speed wind-tunnel with the test section of 300 x 300 mm squares and 1000mm length, and the free stream velocity is varied from 1m/s to 15m/s.

In summary, we developed and evaluated an efficient flapping-wing aerodynamic model which can be used as effective tools for the platform design and the implementation of autonomous flight. The present experimental aerodynamic data are also valuable for the evaluation of other flapping aerodynamic models.

6928-109, Poster Session

Experimental and analytical investigation on innovative compound shape memory alloys dampers for structure control

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Energy dissipation technique, relying on the absorption and dissipation of big amount of energy by devices, provides a very effective passive method of protecting structures from the hazard of earthquakes. An innovative compound damper combining friction device with superelastic shape memory alloy (SMA) wires was proposed. The most important property of the damper is integration with stable energy dissipation capacity mostly provided by the friction device and re-centring feature profited from the superelastic pre-tensioned SMA wires.

To investigate the mechanical behaviors as a function of pre-displacement, displacement amplitude and loading frequency, cyclic tensile tests on a scale model under various loading conditions were conducted. The effectiveness of SMA damper to reduce the seismic vulnerability of structures is assessed through shaking table tests on a structure. The Experimental and Analytical results show that the compound SMA damper has both the stable energy dissipating and recentering features with the hysteretic loop under cyclic loading-unloading, and it is effective in reducing the seismic response of structures.

6928-110, Poster Session

Self optimizing piezoelectric damper

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Passive viscoelastic vibration dampers require no electronics or power to operate but require their size to be comparable to the wavelength of the vibration that they are trying damp. For low vibrational frequencies this means that they are unavoidably bulky. In addition, their damping factors generally demonstrate significant temperature dependence. Traditional active vibration cancellation systems can be less bulky and temperature dependant but require complex electronics and can have significant power demands.

Passive (open loop) damping using piezoelectrics was demonstrated more than 15 years ago and offers a compromise between the passive viscoelastic and active damping systems. In these systems, mechanical deformations of the structure are transferred to an attached piezoelectric element which converts the mechanical energy into electrical energy. This electrical energy can then be dissipated via the use of various electrical networks. Resonant networks are generally used as they maximise the effect the damper has on the mode to which it is tuned, however, any change in the modal frequencies due to changes in the structure or loading will reduce the effect of the passive (open loop) piezoelectric damper.

To overcome this drawback, this paper describes a hybrid damping

technique that actively tuned the electrical shunt circuit in a passive piezoelectric damping system to optimise the damping characteristics. Synthetic inductors were used to produce the large inductance values required to produce the low-frequency electrical resonance with the small inherent capacitance of the piezoelectric, offering considerable space and weight savings over a comparable traditional wound inductor. The closed loop system comprised a strain gauge sensor bonded to the structure under evaluation and a low power, low cost, microcontroller based control system. The control system was able to alter the inductance and resistance of the electrical network within a prescribed range to produce optimal structural damping at all times.

The system was tested using piezoelectric fibre composites bonded to both sides of a glass fibre composite beam. A shaker was used to subject the beam to 'white noise' excitation and the dynamic response of the beam was measured by analysing the output of an accelerometer. It showed that a modest amount (~1.3 % by volume) of piezoelectric material added to the composite structure, along with appropriate circuitry, could give rise to an increase in the loss factor of the structure by a factor of 10. The control system performed well, repeatedly settling on electrical network values within a few percent of those identified by hand.

Different control strategies are discussed and the performance of the system with temperature is detailed.

6928-111, Poster Session

Cost-effective piezoelectric micro energy harvesting system

H. Kim, V. Bedekar, The Univ. of Texas at Arlington; R. Mahanjan, Virginia Polytechnic Institute and State Univ.; W. H. Lee, S. Priya, The Univ. of Texas at Arlington

The demand for the self-powered wireless sensor is growing for various applications including structural health monitoring of aircraft and civil structures. One of the ways to achieve the self-powering of the microsensors is by scavenging energy from the wasted mechanical vibration energy in the environment. In some specific cases, this mechanical to electric conversion is attractive and practical solution. In this presentation we present the results on the piezoelectric microharvester fabricated through two different methods. The first method utilizes the conventional MEMS process. Piezoelectric thin films were synthesized using sol-gel method and deposited by spin-coating. The cantilever structure was patterned using photolithography and RIE (Reactive Ion Etching). The second method utilizes the assembly of the laser micro-machined PZT on a silicon die. The fabricated devices were tested using the mechanical shaker to characterize the variation of the output voltage and power as a function of frequency and acceleration. Further, a comparative analysis is presented for both these methods to quantify the cost-effectiveness (i.e. generated power per dollar).

6928-112, Poster Session

Design and Characterisation of Micro-Diaphragm for Low Power Drug Delivery Applications

D. W. Dissanayake, The Univ. of Adelaide (Australia)

No abstract available

6928-47, Session 10

Sensitivity enhancement for damage detection in linear systems using optimal feedback auxiliary signals and system augmentation

K. X. D'Souza, B. I. Epureanu, Univ. of Michigan

A considerable amount of research has been focused on sensitivity enhancement for damage detection in linear systems. Sensitivity enhancement can be obtained using a control based eigenstructure assignment technique to place the frequencies and eigenvectors of the system. For instance, for single degree of freedom systems it is known

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that: decreasing the natural frequency enhances its sensitivity to stiffness changes, while increasing the natural frequency enhances its sensitivity towards mass changes. Extending the sensitivity enhancement idea to multi-degree of freedom systems is more complicated. The sensitivity of the frequencies of the system to mass/stiffness changes is given by a function that includes the closed loop eigenvalues and their right/left eigenvectors and the mass, damping, and stiffness matrices and their derivatives. Due to complexity of the function, optimization algorithms are often employed to determine the control gains that result in the optimal placement of the system eigenvalues and eigenvectors. Recently, sensitivity enhancement for damage detection using eigenstructure assignment has been extended to nonlinear systems. The nonlinearity in the system was accounted for by forming augmented linear system models (of higher dimension). These augmented systems are designed such that they follow a single trajectory of the corresponding nonlinear system, and are characterized by a specific forcing that ensures it follows the nonlinear trajectory if projected onto the original (physical) space. Due to the specialized forcing in the augmented degrees of freedom, the modal analysis technique used to extract modal properties must be an input/output approach as opposed to an output-only approach. This is especially well suited for sensitivity enhancing feedback control since the input excitation is readily available (as the controller output is easily measured). The use of system augmentation for damage detection has several benefits outside of its ability to handle nonlinearities. For example, sensitivity enhancement can be increased because the stability constraint must be applied only to the linearized system, while the augmented linear system does not have to be stable. In this work, the various benefits of system augmentation will be explored for damage detection in linear systems. In order to use system augmentation in a linear system a nonlinear controller must be designed to add the nonlinearities necessary for system augmentation. In addition to the increased sensitivity enhancement, fewer controller actuator points are required due to the added augmented equations. Numerical simulations for a linear mass-spring-damper system will be used to validate the technique and the effects of noise will be discussed.

6928-49, Session 10

Sensitivity-based performance evaluation and reliability assessment of adaptive systems

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The reliability assessment of complex active systems requires simulation methods, which reproduce complex system performance and also account for failure and fatigue scenarios. More and more, test methods traditionally carried out experimentally are replaced by computational or 'virtual' methods. Reliability of these complex adaptive systems is hard to estimate for several reasons. A priori undetermined interaction between various influencing parameters, unknown fatigue properties of the multifunctional materials employed in sensors and actuators and very complex system performance requirements make it difficult to predict under which circumstances the system may fail. Sensitivity Analysis (SA) of the comprehensive adaptive system model has proven to be a valuable tool for the identification and assessment of scenarios that are relevant for system reliability. For the example of an active oil pan, which is equipped with piezoelectric sensors and actuators to suppress structural vibrations, the method is outlined. Sound radiated from the oil pan is one of the main contributions to the noise emission of combustion engines in cars and dominates the noise contribution in most urban traffic scenarios. For several technical reasons, passive solutions for the reduction of noise emission are not feasible. Therefore, active noise suppression systems are designed, comprising piezoelectric actuators and sensors, which are subject to more or less severe degradation and other failure modes, depending on operating conditions, applied control algorithm and load-time history. The performance of the active system, characterized by a defined reduction of noise emission in a particular frequency range, is simulated in different failure and fatigue scenarios. These include sensor and actuator degradation, debonding or position tolerances (misplacement) and malfunction.

6928-50, Session 11

Temperature sensitive stability of feedback controllers for MR dampers

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Smart fluid dampers can undergo large temperature changes due to the heating associated with energy dissipation. Such heating will alter the fluid's properties and could degrade control system performance. For example, previous work by the authors has shown that the stability of an MR damper under feedback control is dependant on the fluid's compressibility and viscosity parameters [1]. In this study, a temperature dependent model of an MR damper is developed from experimental data, and it is shown that the fluid's yield stress, viscosity and compressibility vary widely. An experimental and numerical control study is then performed to investigate the resulting effects of temperature on the stability of two feedback controllers - a PID controller, and a proportional controller. Experimental results indicate that both controllers can exhibit a reduction in stability with increasing temperature, particularly if the controller gains are not suitably chosen. The temperature dependant MR damper model predicts this behaviour well, and it is shown that the change in viscosity has the most notable effect on stability. Future work could focus on the resulting effect on a complete vibration system, devices with different modes of operation, and alternative controllers.

[1] Sims, N D (2006), "Limit cycle behaviour of smart fluid dampers under closed-loop control", *Journal of Vibration and Acoustics*, 128, 413-428.

6928-51, Session 11

Design, modeling, and manufacturing of a mixed mode magnetorheological mount

T. Nguyen, M. H. Elahinia, Univ. of Toledo; C. Ciocanel, Northern Arizona Univ.

Noise and vibration have always affected not only the operation of various devices but also people's comfort. These issues are highly present in currently emerging technologies like hydraulic launch assist vehicles. While the switching mechanisms in hydraulic hybrid vehicles enhance fuel efficiency, they cause complicated patterns of noise and vibration. This, combined with a wider range of frequencies excited by this mechanism requires advanced vibrations isolators that can provide variable damping and stiffness. A solution to this problem can be provided by MR mounts.

An MR mount is capable of changing its stiffness and damping characteristics appropriately depending on the input excitation amplitude and frequency. This paper presents simulated and experimental results for a mixed mode magnetorheological (MR) fluid mount. If the MR mount is only working in one mode, either flow mode or squeeze mode, the range of isolation force provided by the damping and spring rate of the mount is constrained by the geometry of each mode. However, when the mount design can facilitate both working modes, the effect is combined to accommodate a wider range of amplitudes and frequencies of excitation.

The mathematical governing equations of the mount are derived to account for both flow and squeeze mode in operation. These equations implemented in MATLAB/Simulink(c) with a specific set of parameters. The simulated results indicate that the combination of modes is beneficial for the mount performance in certain conditions.

The parameters used in simulation are evaluated through experiments carried on two MR mount prototypes, a flow mode and a squeeze mode. The flow mode prototype allows for changes in the inertia track geometry, while the squeeze mode prototype permits changes in the gap size between the two squeezing plates. In the end of the paper, the predicted results are compared with the experimental results acquired on the prototypes.

6928-52, Session 11

Performance of a magnetorheological fluid-elastomer (MRF-E) vibration isolator in a single degree-of-freedom system

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In this work, theoretical and experimental studies are carried out to

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investigate the performance of the MRF-E vibration isolator in a single degree-of-freedom (SDOF) system. Theoretically, the equation-of-motion, utilizing the proposed dynamic model, is derived in order to provide behavioral predictions on the effectiveness of the semi-active device at suppressing unwanted vibrations. Experimentally, a SDOF system, constrained to rectilinear motion, composed of a mass, four linear springs, and the MRF-E vibration isolator is designed and fabricated. The ratio of the payload acceleration to the base input acceleration is measured for different input conditions. These data are compared to the theoretical prediction of the system performance given by the derived equation-of-motion. This comparison validates the proposed model's prediction of the MRF-E vibration isolator's behavior in a SDOF system.

6928-53, Session 11

Semi-active control of building torsion using multiple MR dampers

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The mitigation of torsional responses in a full-scale three-story structure is pursued in the current study using an array of semi-active devices. A total of four magnetorheological (MR) dampers are employed for real-time control of the response of the structure to an extensive set of earthquake excitations. Intelligent management of MR damper resistance levels is incorporated through a global fuzzy logic controller (FLC). The FLC is generated using a controlled-elitist genetic algorithm (GA). The search process for optimal FLCs is expedited by a discrete search space of fuzzy logic membership functions. In addition, uncontrolled experimental tests are used to collect training data from the benchmark structure that has no MR dampers installed.

For robust control a special training excitation record is obtained from seismic software that is named RSPMatch. RSPMatch modifies historic ground records in the time-domain by wavelet operations.

Both numerical and large-scale experimental efforts are undertaken to validate the proposed control system. Six degrees of freedom are used to model the structure. Results show the GA-optimized FLC's perform superior to passive cases.

6928-54, Session 11

Experimental study of pounding reduction of highway bridge with MR dampers

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Pounding between the adjacent segments of the highway bridge is one of the important factors that induce the damage of the bridges under earthquake ground motion, due to the difference in dynamic characteristics of the adjacent structures and the spatial variation of the earthquake ground motion.

Changing the gap size of the expansion joints is the natural way to mitigate the collisions of the bridges. However, the expansion joints with small gap size between the adjacent superstructure segments will affect the function of the expansion joints for accommodating the length changes of the superstructure due to thermal effect, and enlarging the gap size will disturb traffic on the deck. To prevent deck joints from separating and unseating in seismic events, both cable restrainers and pipe restrainers were suggested to be installed in the bridge superstructures following the 1971 San Fernando earthquake in USA. However, the restrainers can only be used to prevent the unseating of the bridge decks, and the collision of the adjacent segments can not be eliminated with the installation of those devices. With the development of the structural control technology, the possibility of using structural control devices, such as viscous damper, crushable device, shock transmission device and variable damper, to reduce the seismic pounding of the highway bridges have been investigated by some researchers.

This study experimentally investigates the effectiveness of MR dampers to mitigate the pounding damage of highway bridges under seismic excitation. A 1:20 scaled base-isolated bridge model is manufactured by using linear rubber bearings. Shaking table tests of the uncontrolled bridge model are firstly conducted for the cases of structure without and with pounding effects. A semi-active control algorithm for reducing the pounding effects

of the highway bridges is developed, and shaking table tests are also conducted for structure with the semi-active control system. Experimental results show that the pounding between the adjacent segment of the bridge with significantly increases the acceleration responses, and the semi-active control system can effectively reduce the pounding effect with the developed semi-active control algorithm.

6928-91, Session 11

Hybrid assistive knee braces with smart actuators

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In this paper, a new leg exoskeleton is developed utilizing an MR actuator. The idea is to use the MR actuator to provide controllable assistive torque to the knee joint and thus make the knee brace adaptable to the person while interacting with environment. The MR device can function as a clutch or a brake while the motor will be turned on when needed. The main parts of the system include: braces, MR fluid actuator, sensors. The braces include upper brace and lower brace. The upper brace is bound to the upper leg and the lower brace is bound to the lower leg. The lower brace is connected to the foot, and the upper brace is connected to the waist. The braces transfer the assistive torque generated by the actuator to the lower limb. An elastic element is attached to the bottom of the shoe to absorb shock, thus provides protection to the system. The sensors are used to detect the user's walking condition and estimate the needed assistive torque. Two force sensors are mounted on the front and rear sole of the foot to measure the reaction force from the floor. Two strain gages are mounted on the aft and fore of the lower brace to measure the force acting on the actuator. The torque produced by the actuator can be measured using these strain gages. An angular sensor is to measure the knee joint angle. The knee angular velocity can also be derived by differentiation of the angle signal. MR fluids are used in shear mode to produce or transfer torque. The outer cylinder is connected to the upper leg, the shaft is connected to the motor, and the motor is mounted on the lower brace. The shaft can be locked to the lower brace. For this actuator, there are three working conditions:

- 1) The shaft is locked to the lower brace and the magnetic field is on. The MR device acts as a brake, which can provide controllable passive torque.
- 2) The magnetic field is off. The MR device doesn't work and the knee joint can rotate freely.
- 3) The shaft is unlocked to the lower brace and the magnetic field is on, while the motor is working. As the shaft is unlocked to the lower brace, the shaft can rotate relatively to the lower leg, thus the MR device acts as a clutch to transfer the torque from the motor to the upper leg.

The main functional components are the alternately placed outer disks (or stators) and inner disks (or rotors). The outer disks are mounted to the outer cylinder by splines. The inner disks are connected to the shaft by inner splines, which can rotate relatively to the outer disks as the shaft rotates. MR fluids are filled in the gaps between outer disks and the inner disks. As the shaft rotates and the magnetic field is on, the torque due to shear effect will be generated between the outer and inner disks. This torque is controlled by the applied magnetic field.

6928-55, Session 12

Application of macrofiber composite in actuating a tail of biomimetic fish

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Abstract: Macro fiber composite (MFC) is a promising smart material that offers high flexibility, which can be used for actuator in a cost-competitive device. Its applications include vibration damping, dynamic structural morphing, micro-positioning, structural health monitoring, force-sensing and energy harvesting. The MFC is a layered, planar device that employs rectangular cross-section, unidirectional piezoceramic fibers embedded in a thermosetting polymer matrix. This active, fiber reinforced layer is then sandwiched between copper-clad Kapton film layers that have an etched interdigitated electrode pattern. The actuators of active fiber composite provide not only the required durability and flexibility, but

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also higher electro-mechanical constants by capitalizing on the stronger longitudinal d33 interdigitated by using interdigitated electrodes. Comparing with traditional piezoelectric materials, MFC possesses a better electromechanical couple characteristic. In the paper, an application of MFC in actuating a tail of biomimetic fish is discussed. By utilizing the d33 effect, a piece of plastic film with a certain thickness is stucked onto the MFC in order to make the structures besides PZT fibers dissymmetrical. When applying a voltage on the MFC, the structure will perform a certain bending angle which offers swinging power for the tail of biomimetic fish. There are two steps in the design of the biomimetic tail. Firstly, a fundamental model of tail is designed. And the feasibility of driving fish tail by MFC, the proper swinging frequency of the tail and the best driving method for it are obtained by the test of driving a model of ship by it. Then, the ideal driving effect has been got with the limited driving force via the study of material property, material thickness, shape and size of the metal piece connected to the MFC, method of connection, the shape of the under water part of the fish and so on. Meanwhile, the paper also studies a dynamic response of the tail against a viscous resistance from water. The reasonable shape and swinging method for biomimetic tail is designed based on the observation of the motion of alive fish and the study of bionics. In the experiment, the grating sticking method which significantly reduce the work of radial force is utilized to obtain an ideal bending effect for the tail. By this method, the curvature of biomimetic fish tail increases by 30%, namely 6 degree. The driving force approaches 1 N. The range of the available frequency is around 2Hz. In contrast to the traditional biomimetic fish actuated by motor, the tail actuated by MFC presents the advances including small volume, low noise, simple structure and easy electrical control in speed and deformation. The excellent performances of actuator made of MFC implies an emerging application in future. In addition, the limitation of actuating force and the relatively high inputting voltage for MFC need to be solved in further work.

6928-56, Session 12

Insect inspired wing actuation structures based on ring-type resonators

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In this paper, we illustrate and study the opportunities of resonant ring type structures as wing actuation mechanisms for a small-scale Flapping Wing Micro Air Vehicle (FMAV). Various design alternatives are presented and studied based on computational and physical models.

Insects provide an excellent source of inspiration for the development of the wing actuation mechanisms for FMAVs. The insect thorax is a structure which in essence provides a mechanism to couple the wing muscles to the wings while also being targeted for weight reduction through application of a resonant structure, using tailored elasticity. The resonant properties of the thorax are a very effective way to reducing the inertial cost of wing movement. The wing movement itself is fairly complex and is guided by a set of control muscles and thoracic structures which are present in proximity of the wing root. This last part is very hard to reproduce technically due to large complexity so another method of control over the aerodynamic forces has to be found.

The development of FMAVs at a small scale requires a move away from classical structures and actuators. The use of gears and rotational electric motors is hard to be justified at the small scale. Resonant structures provide a large design freedom whilst also providing various options for actuation and control. The move away from deterministic mechanisms offers possibilities for mass reduction.

The challenges that lie in the development of a FMAV wing actuation mechanisms are myriad. First, the type of structure aimed for. The mechanism should be able to provide a hovering state and control around this state. The type of structure is a major design consideration. Second, control mechanisms have to be built in from the beginning, since the goal is to have a truly insect inspired design without additional control surfaces, for example a tail section for control. And at last, the type of actuator has to be chosen. This last choice is highly interwoven with the first and second points.

The focus in this paper is on the use ring-type structures to act as a basis for a number of different designs. Starting from very simple structures there is an expansion towards structures which allow for control of the

resonant state. A ordering on functionality is introduced to classify the design alternatives. Covered are structures which vary in coupling to the wing as well as degree of control of the wing movement. Control is implemented by perturbing the resonant state of the structures. This type of control leads to a reduction of complexity in the structure. These structures are mostly compliant in origin but also apply elastic hinges. The structures are tested in a laboratory setup to judge performance, using integrated electromagnetic actuators or by the use of an external electromagnetic shaker.

6928-57, Session 12

The characteristics of LIPCA and its application for mimicking insect flapping

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Insect flight has a lot of amazing performances such as rapid flight maneuver, long-time hovering, low wing loading and high lift-generation at low Reynolds number. It is fantastic to watch but difficult to mimic them. Thus, mimicking insect flight is one of challenges for engineers and scientists over the world during the past decades. Recently, many significant results about mimicking the flapping motion of insect flight were reported. A first tiny robot modeled on a fly took off successfully, which was reported by Robert Wood et al. In these researches, besides using motor as an effective actuator for most systems, a flapping-wing device using Lightweight Piezo-Composite Actuator (LIPCA) was also introduced by Park et al. In this flapping-system, the actuator displacement of the LIPCA was amplified and transmitted to flapping motion of wings through a four-bar linkages system. The best operation frequency for this flapper was around 10 Hz. In this system, a passive wing rotation was implemented so that the flapping device could produce positive force even during upstrokes. Due to a large passive rotation, the flapping device could not properly create flapping motion at a higher excitation frequency.

In the real world, wing-beat frequency of insects is populated from a few Hz, such as large butterfly, to over 1000 wing-beats per second such as tiny gnat like midge. In addition, at the end of each stroke the wings are rotated to change the angle of attack. In an effort to make the flapper closely to a beetle, this paper studied natural frequency of the LIPCA actuator by experiment and finite element analysis. By changing the loading, which is against the actuation force, on the LIPCA and measuring the displacement at the resonant frequency respectively then we get the relationship between the actuation displacement and the actuation force at the natural frequency for each load case. The results showed that the natural frequency of the LIPCA with simply supported condition was around 85 Hz. Using Matlab simulink tools, we simulated the mechanism as a dynamic system to determine a compatible amplify coefficient for the linkages system to design the other flapping mechanism. In this device, the connections between the wing roots and the output linkages were modified such that wings were active rotated at the end of each stroke. The aerodynamic force generated by this device was also evaluated from the total generation force and the inertial force, which were measured by experiment. The smoke wire test was also performed to visualize the vortices around the wings. The detailed results will be reported in the final manuscript.

6928-59, Session 12

Passive self repairing and active self sensing in multifunctional polymer composites

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The goal of the research since the early 1990s has been to develop self-repairing and self sensing composites. Our revolutionary approach involves the autonomous release of repair chemicals from within the composite matrix itself and the active sensing to assess that action utilizing the same tube structure. The repair agents are contained in hollow, structural fibers that are embedded within the matrix. Under stress, the composite senses external environmental factors and reacts by releasing the repair agents from within the hollow vessels. This passive autonomous response occurs wherever and whenever cracking, debonding or other matrix damage transpires. Superior performance over the life of the composite is achieved through this self-repairing mechanism.

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The active sensing of volume of voided repair chemical and location of voiding reveals the location and amount of damage to the laminate. This health monitoring of composites is important for their widespread use in life safety applications such as aerospace structures. The focus of the research being the implementation of active sensors and passive actuators which by using the same structure of glass tubes provide large area coverage without adding much parasitic weight. The development is a novel, voiding based sensor for damage detection with composite structures. This consists of an inspection guide produced from glass reinforcing fibers which release repair chemical when damaged.. The sensor was shown to be sensitive to very low impact energies, but also capable of revealing more extensive damage caused by high energy impacts.

This unique combination of active sensing and passive repair serves as an example of combination for autonomous systems that can consist of various approaches in one integrated system.

6928-60, Session 13

Seismic retrofitting of bridge columns using shape memory alloys

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This analytical work focuses on enhancing the seismic performance of reinforced concrete (RC) bridge piers by using innovative active confinement technique. Steel jackets and fiber composite wraps are currently being used to provide extra passive confinement for RC bridge columns in order to enhance their ductility and shear capacities. Although the passive confinement approach has been widely accepted and used, research has shown that better results could be obtained by applying external confining pressure on the concrete element; a technique that has been widely known as active confinement. Previous attempts to apply active confinement on bridge piers using steel and composite materials had all failed due to several problems related to the method of applying the confining pressure. The approach proposed in this paper focuses on exploring the concept of using belts (straps) made of Shape Memory Alloys (SMAs) in providing active confinement for RC bridge piers. The shape recovery phenomenon of SMAs will be utilized to apply the external confining pressure without the need for excessive hardware or labor. This will provide an easy and reliable solution for the problems encountered when using steel and composite materials. A multiple-frame bridge model is developed and analyzed using the finite element program OpenSees. The bridge model is subjected to a suite of ground motion records with different characteristics. The bridge columns are subjected different levels of active confining pressure at the plastic hinge locations. The results obtained using the proposed approach is compared with the case of using Carbon Fiber Reinforced Polymer (CFRP) wraps for passive confinement. A simplified constitutive relationship is utilized to describe the behavior of the confined columns. The results show a significant improvement in the ductility and shear capacities of the columns in the case of using the proposed SMA belts compared to the conventional CFRP wraps.

6928-61, Session 13

Vibration isolation of multistory building by genetic algorithm

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Many engineering structures and applications contain vibrating machineries in which reduction of the vibration level to conform with performance objectives is a necessity. It is desirable to minimize the transfer of such vibrations to the structure.

In this paper the base sinusoidal vibration along with nonlinear instruments characteristics is studied. Passive vibration isolation system is created as optimized components of internal part of structure to minimize the transfer of energy to the structure.

The system consist of three mass which connected by nonlinear spring and damper. The external force is sinusoidal were exerted to lower mass. In order to minimize the transfer of energy from lower mass to upper mass the harmonic balance method was used to achieve the dynamic properties of systems. In this study the effect of the nonlinearity in the springs were considered. The optimization approach is carried out by

Genetic Algorithm. The parameters were desirable to optimize are the properties of springs and dampers. The external force could represent the effect of the earthquake.

6928-64, Session 14

Flapping performance and simulation of an insect-mimicking flapper actuated by a compressed unimorph piezoelectric composite actuator

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Flying insects are marvelous micro-machines that provide source of inspiration for the realization of intelligent micro-robots capable of autonomous flight. They can be used for various purposes from detecting environmental hazards to security. Flying insects also have many desirable features of vision, flight characteristics and maneuverable abilities such as long-time hovering, quick maneuver, effectively discontinuous changes of direction, etc., which make the insect an ideal prototype for tiny micro air vehicles (MAVs). In the viewpoint of aerodynamics, flying insects can fly in the low Reynolds number regime with non-steady state aerodynamics and produce relatively high lift and thrust compared to the conventional aerodynamics. Therefore, scientists from around the world are reverse-engineering and doing many research to reveal the secrets of insect flight. In engineering, if we are able to mimic flying insects, we will be able to innovatively improve the performance of flying vehicles.

Recently, many researchers have been successfully used piezoelectric actuators for mimicking the thorax of flying insects. One of the recent works introduced by Park et al (2007) is full three dimensional prototype of flapping wing device actuated by a Lightweight Piezoelectric Composite Actuator (LIPCA). They successfully demonstrated their flapping device in aspects of force and vortex generation. However, this device still needs improvement due to the limited actuation displacement of the LIPCA actuator. The LIPCA actuator has been proven to show better performance when it is under compressive stress than the original one in terms of actuation displacement and force. If we simple replace the actuation part in the flapping device with a compressed LIPCA, we expect the modified flapping device can show better flapping performance.

We have analyzed and experimentally examined the flapping performances in terms of aerodynamic force generation, flapping frequency and flapping angle of the two flappers actuated by the original LIPCA and the compressed LIPCA, respectively. The flapping tests were conducted at various flapping frequencies to search for the optimum flapping frequency at which the maximum aerodynamic force was achieved. To measure the inertia force, we conducted the flapping tests in a vacuum chamber; then the aerodynamic forces were calculated by subtracting the inertia forces from the total forces measured in the air. For the CFD simulation, we established the corresponding kinematical equations of the wing by examining the high-speed camera images taken from front and top at the same time. The experimental results showed we could improve the flapping angle 22 % and the average vertical aerodynamic force 20 % by using the compressed LIPCA. Finally, the Particle Image Velocity (PIV) test in a wind tunnel was also carried out to capture the vortices generated by the flapping device during operation to ensure that the flapping device can produce lift and thrust.

6928-65, Session 14

An aeroelastic analysis of a flexible flapping wing using modified strip theory

D. Kim, J. Lee, J. Lee, J. Han, Korea Advanced Institute of Science and Technology (South Korea)

In past few decades, flapping flight of birds, bats and insects has fascinated many researchers in various fields such as biology, aeromechanics and engineering because of highly efficient maneuverability and aerodynamic benefits especially in a low Reynolds number flight regime. Numerous efforts have been made to make flapping-wing vehicles such as ornithopters or flapping micro air vehicles, and many analytical and experimental studies on flapping wings have also been performed to understand the aerodynamic characteristics and flight mechanisms of the

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wings. However, these studies have been mostly conducted by using rigid wing models.

Actually, the biological flyers have spanwise-chordwise anisotropic flexible wings, and use complicated wing motions such as flapping, twisting, folding, or rotating motions. The artificial flyers also have very thin and flexible wings structurally similar to those of the nature's flyers, but they use mainly the flapping and passive motions generated by the wing flexibility. However, the deformation of these flapping wings is strongly coupled with aerodynamic forces generated by the wing motion. In order to consider this complicated fluid-structure interaction, aerodynamic and structural analysis technologies such as CFD and FEM must be applied simultaneously. However, it needs very expensive computational cost and is still extremely difficult to analyze accurately the fluid-structure interaction of the biological or artificial flexible flapping wings. Therefore, for the realization of optimal flapping-wing design and real-time control, an applicable aerodynamic model of flapping wings is indispensable, and an aeroelastic analysis method should be developed.

In the present study, an aeroelastic analysis method for flexible flapping wing flight is proposed and this approach is verified with experimental data. First, a numerical aerodynamic model based on the modified strip theory is suggested not only for the performance prediction but also for preliminary design and control of flexible flapping wings. The structural dynamic model of a flexible flapping wing is established using multi-body dynamics to analyze the flapping-wing motion with large displacement and deformation. The aeroelastic analysis method is developed by coupling these aerodynamic and structural modules. Second, a flexible flapping wing is manufactured using composite frames and a flexible PVC film skin. The wing is a rectangular flexible wing with the aspect ratio of $AR = 5.6$ and the chord length of $c = 9.7$ mm. To measure the aerodynamic forces (lift and thrust), static and dynamic tests are performed in a low speed wind-tunnel with the flapping pitch angle of, the flapping frequency of, and the airspeed of. Finally, the aerodynamic forces predicted by the aeroelastic analysis method are compared with the experimental data of the rectangular flapping wing. The results show the good agreement between the predicted and measured data. Moreover, the chordwise and spanwise flexibility effects on the aerodynamic performance of the flexible flapping wing are investigated from additional aeroelastic analyses. We expect that this aeroelastic approach proposed in this study will be usefully applied to optimal flapping-wing design and flapping-wing flight control.

6928-66, Session 14

Numerical analyses of stabilization and control for flapping-wing flight

J. Lee, D. Kim, J. Lee, J. Han, Korea Advanced Institute of Science and Technology (South Korea)

The maneuverability and the stability of birds and insects have attracted biologists and engineers to discover their flight mechanisms and develop bio-inspired flying vehicles. There have been numerous attempts to develop flapping-wing vehicles which are capable of flying with flapping wings similar to the nature's flyers. However, most have been based on intuitive design of observation and trial-and-error approach to mimic a certain type of the creatures. In order to develop more systematic design and control processes and to improve the performance of the flapping-wing vehicle, it is necessary to establish an effective and reliable aerodynamic model. Computational fluid dynamics requires too much calculation time and cost, thus they are not suitable for controlling time-varying systems such as a flapping-wing air vehicle. Basically, the stability stands for tendency of an air vehicle to return to its equilibrium position after it has been disturbed. Since the flapping-wing flight inherently produces time-varying motions and it is a very unstable system, the control inputs of stabilizers such as a tail wing should be reorganized according to each phase of flapping cycle. It means that in order to maintain the trim condition of the flapping-wing vehicle, it is necessary to control the pitching moment by adjusting the pitch or yaw angle of the tail wing instantaneously.

This research aims at stabilization and path-following control of the flapping-wing flight by controlling the tail-wing's pitch and yaw angles. First, we have formulated an aerodynamic model for calculating the aerodynamic forces and moment acting on a flapping-wing vehicle. The aerodynamic model is based on the modified strip theory, which is improved for high relative angle of attack and post stall condition. The

instantaneous flight characteristics can be predicted when the kinematic parameters such as flight speed, flapping frequency, stroke angle and mean angle of attack are initially given. Second, three kinds of flight modes are numerically controlled. In these simulations, the object of the flight simulation has 30cm wing span, and the lift, thrust and moment acting on the flapping-wing flight are assumed to be bilateral symmetric, which are predicted by the aerodynamic model. If the resultant performance does not fulfill stable level flight then the kinematic parameters are reorganized by feedback control to modify the next wing-beat to fulfill the longitudinal stabilization.

For the first step, we simulated the level flight only depending on tail-wing pitch angle in a constant flight speed and unchanging main wing motion. After the longitudinal stability is managed, lateral stability is adjusted with yaw-angle control of the tail wing. As the second step, the aerodynamic forces are asymmetrically applied to adjust its stability then it is again controlled by adjusting the pitch and yaw angles. As the final step, based on these strategies we can simulate the flight to sustain a certain trajectory such as circulating on the same altitude with different flapping frequency or flight speed. The flight control algorithms for flapping-wing vehicles proposed in this study can be useful for the real-time control and system design of optimal flapping-wing vehicles.

6928-68, Session 14

Bio-inspired shape memory actuated hexapod robot

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Nickel-titanium based alloys, commonly known as shape memory alloys, have proven highly useful for their property of contracting up to 8 percent when heated by an electrical current and returning to their original length when cooled. This work utilizes the shape memory property to provide actuation for a six legged walking robot. Many hexapod robots have been developed for university research or for commercial availability to hobbyists. The vast majority of these hexapods are actuated by servo motors which are large, loud, and create jerky motions. Robots that do use shape memory alloy for actuation are generally only a few inches in length, have a limited range of limb motion, and must be tethered to a power source. The robot presented in this research is approximately a foot long, carries an onboard power source, and possesses three degrees of freedom per leg. The research focuses on using this robot to demonstrate the potential of shape memory wires as robotic actuators and on developing a framework in which the actuators can be used to their greatest potential in terms of system flexibility and minimization of power requirements.

A geometrical analysis of the robot frame revealed that wires exceeding two robot body lengths would be required to actuate desired gaits. To provide antagonistic pairs of wires for each degree of freedom and to satisfy the required wire lengths, a unique system of coiling the wires into actuator cells was created. The compact structure of the actuator cells allows for more wires, and for wires of greater length, to be carried on the legs. The result is an actuator system which can provide much higher forces and can actuate the robot legs through the large angles required. The cells can be activated individually, or in conjunction with other actuator cells to provide increased forces. Additionally, the self contained structure of the cells allows for the easy exchange or addition of actuators and for locomotion to continue despite the failure of individual cells.

The robot itself is bio-inspired in the design of the limbs, which are individually specialized in their segment lengths and joint torque production abilities. The actuation system forms an integral part of each limb structure and allows for flexibility in actuator cell activation as required by the desired gait or terrain difficulty. The human body recruits muscles in a similar manner, signaling contraction in multiple muscle fibers or groups in order to produce a desired force. The robot is also able to selectively activate wires of different diameters in order to perform movements at a faster or slower rate, similar to the division of skeletal muscle into fast and slow twitch fibers. On a flat, even surface the robot walks using a minimal number of cells and the shortest possible actuation distances. However, when rough terrain or obstacles are encountered, the robot is able to adapt its gait by increasing actuation distances and the number of activated cells.

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6928-69, Session 15

Recent studies of electrostatic variable area actuation of membrane reflectors for beam guidance

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Project Location: SDSM&T

This paper reports on recent research on the dynamic behavior of small deformable mirrors based on thin, metallized membranes. Such mirrors represent a low-cost compromise between commercial fast steering mirrors, used mainly for beam steering (e.g., [1], [2]), and deformable mirrors with over hundreds of actuators used in adaptive optics systems for astronomical observations. The main focus of this study is on providing a predetermined focus/defocus correction to a laser beam, as well as producing specified angular deflections of the beam in the vertical and horizontal planes. Additional performance goals also include, meeting required bandwidth specifications and performing the tasks with minimum jitter. Electrostatic actuation is used for this task; current designs are comprised of 3 actuator pads fabricated on a fiber reinforced plastic substrate that drive a metallized kapton membrane, which is separated from the substrate by spacers providing a known air gap.

The current experimental setup uses a class 3b laser, an array of photodiodes known as a quad cell, a deformable metallized kapton mirror with actuation pads as described above, as well as control circuitry. The laser is aimed at the mirror, and the beam is then reflected to the target, in this case an array of photodiodes known as a quad cell. Signals from the quad cell are then feed to the control circuitry which has a maximum operating frequency of 500 Hz, and a 300 VDC signal is then sent to various sections of the pads to keep the beam in the center of the quad cell.

In a previous paper [3] we reported on the control system for a variable area actuation strategy, which restricted the allowable membrane deflection to 1/3 of the available gap size in order to avoid the potential instability caused by "snap down." Here we address the difficult problem of extending the control strategy into the deflection regime where the full nonlinear model must be used for the actuation force. The solution to this problem is an extended controller that can handle the full deflection range of the 40 μ m air gap between the charged electrodes on the fixed substrate and the movable metallized reflective membrane.

The observer for the control system operates in continuous time mode. Current tests are focused on observer implementation, and these results will be included in the full paper. Although the discrete area approximation is also shown alongside, only the continuous-area approximation is studied here. It is easily seen that the open loop system would be unstable, while the closed loop system closely follows the desired reference specification (maximum deflection approaching 40 μ m, and bandwidth approaching 500 Hz).

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6928-70, Session 15

Integration, control, and applications of multifunctional smart struts

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The development of smart structure technology and advanced mechatronic

systems requires active struts with super-precision, large stroke, and simultaneous precision positioning and vibration suppression capabilities over a wide frequency range of interest. However, current commercially available linear actuators are either not precise enough in accuracy, or not large enough in stroke, or not wide enough in frequency range, and hence they cannot meet some strict application requirements. This paper mainly focuses on the development of such linear actuators.

The integration, analysis, control, and application of a linear actuator are investigated. The linear actuator has super-precision, large stroke, and simultaneous precision positioning and vibration suppression capabilities. It is an integration of advanced electro-mechanical technology, smart materials technology, sensing technology, and control technology. Based on the electro-mechanical technology, a DC-motor driven leading screw ensures the large stroke of motion and coarse positioning. The smart piezoelectric technology makes the fine positioning and vibration suppression over a wide frequency range possible. The advanced control strategy greatly compensates the hysteresis characteristics such as backlash and/or dead-zone, and enables the excellent performance of the actuator. Several sensors such as load cells and displacement sensors are also integrated. Finite element analysis, controller design, and testing of this linear actuator are also conducted. The applications include flexible manipulator control, modified Steward platform for thrust vector control of satellites, and so on. This paper starts with the configuration of the linear actuator. Then, the finite element analysis and dynamic testing are performed. Followed the control strategy, the application examples and the results are presented. The paper ends with conclusions and future work.

6928-71, Session 15

Robust vibration suppression of an adaptive circular composite plate for satellite thrust vector control

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Adaptive composite panels have great potentials to be used as common structures in various industrial fields as well as the main components of future spacecrafts. As a novel application of adaptive composite structures, a smart composite platform with simultaneous precision positioning and vibration suppression capabilities for the Thrust Vector Control (TVC) of satellites is being developed at the Intelligent and Composite Materials Laboratory of the University of Hawaii at Manoa (UHM). The device plate of the UHM platform is an adaptive composite circular plate (ACCP) that utilizes integrated sensors/actuators and controllers to suppress low frequency vibrations during the thruster firing as well as to potentially isolate dynamic responses from the satellite structure bus.

Since the disturbance due to the satellite thruster firing can be estimated, a combined strategy of the disturbance observer (DOB) and feed-forward control is proposed for vibration suppression of the ACCP with multi-inputs and multi-outputs in this paper. In addition, it is discovered that the cut-off frequency and the relative degree of the low-pass filter are the two major tuning knobs for the DOB performance. Simulations and experimental results show that higher relative degree of the low pass Q-filter with the required cut-off frequency will enhance the DOB performance for the high-order system control. Further, although the increase of the Q-filter cut-off frequency will guarantee a sufficient stability margin, it may cause an undesirable increase of the control bandwidth. The effectiveness of the proposed control strategy is verified through simulations and experiments using the ACCP system.

6928-72, Session 16

An investigation into active piezoelectric nanocomposites for distributed energy harvesting

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The use of monolithic piezoceramic materials in sensing and actuation applications has become quite common over the past decade. However, these materials have several properties that limit their application in practical systems. These materials are very brittle due to the ceramic nature

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of the monolithic material, making them vulnerable to accidental breakage during handling and bonding procedures. In addition, they have very poor ability to conform to curved surfaces and result in large add-on mass associated with using a typically lead-based ceramic. These limitations have motivated the development of alternative methods of applying the piezoceramic material, including piezoceramic fiber composites (PFCs), and piezoelectric paints. Piezoelectric paint is desirable because it can be sprayed or painted on and can be used with abnormal surfaces. The ease at which the active composite can be applied allows for far larger surfaces to be used for energy harvesting than can be achieved with typical materials. Developments in piezoelectric nanocomposites for energy harvesting will also allow for the development of compliant materials with electromechanical coupling greater than available through existing piezoelectric polymers such as polyvinylidene fluoride (PVDF). Furthermore, the application of PVDF is limited to thin films due to the straining process required to obtain piezoelectric phase of the material. However, active nanocomposites be molded into geometries that couldn't be obtained using currently available materials. The present study will characterize a variety of piezoelectric nanocomposite materials to determine how the properties polymer matrix and the piezoelectric inclusion affect the energy harvesting performance. The resulting active nanocomposites will be compared to existing piezo-polymers for power harvesting.

6928-73, Session 16

Rectifier-less piezoelectric micro power generator

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A novel thin film lead zirconate titanate $Pb(Zr,Ti)O_3$ (PZT), energy harvesting MEMS device which always has tensile strain is designed to eliminate the use of rectifying circuit for each vibrating beam. It is designed to harvest energy from parasitic vibrational energy sources and convert it to electrical energy via the piezoelectric effect. By harvesting parasitic energy from the vortex-induced vibration of the oil pipelines, we envision a massive number of microsensors be deployed along the hundreds miles of pipeline in a very cold and remote area.

The new pie-shaped design for the harvester (about a size of a nickel) has a radical departure from previous design concepts. This design always generates positive tension on the PZT layer and then positive charge throughout the vibration cycle. It produces a same polarity output charge without using any additional bridge rectifier, which will be a huge cost saving for commercial production. The new design avoids the high Q resonance, which is also a big advancement from previous designs. This will enable more robust power generation even if the frequency spectrum of the source vibration varies unexpectedly. Furthermore, the beam shape is optimized to achieve uniform allowable strain throughout the PZT layer.

The whole thickness of silicon wafer is used as the proof mass to increase the power in the new PMPG. The structural layer is a 10um thick layer of silicon oxide which is deposited by PECVD and post-annealed at 800C for 1 hour. Subsequently, a 0.5um thick layer of PZT is spin-coated on top of thin layers of ZrO_2 (100nm) acting as the diffusion barrier layer. The top interdigitated electrodes are patterned by e-beam deposition of Ti/Au (200A/2000A) and lift-off and the generated charge will be extracted from the electrodes exploiting the PZT d33 piezoelectric mode. The final device is released by reaction ion etching of the PZT and oxide layer and DRIE the silicon from the wafer's back. Currently, the first prototype is being fabricated at MIT's Micro Technology Laboratory. This energy harvester design will be the first self-rectifying piezoelectric power generator.

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6928-74, Session 16

Performance characteristics of a high-frequency jetting dispenser featuring piezoelectric actuator

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This paper presents a new type of jetting dispenser driven by a ring type piezoelectric actuator. By operating at very high frequencies, the dispenser is expected to provide very small dispensing dot size of low viscous adhesive, viscosity of 50cp, at high dispensing flow rate in semiconductor packaging processes. After describing the mechanism and operational principle of the dispenser, a mathematical model of the system is derived by considering behaviors of the piezostack, the dispensing needle and the adhesive fluid dynamics. In the modeling, a lumped parameter method is applied to model the adhesive whose rheological property is expressed by a Bingham model. The governing equation of the whole dispenser is then derived by integrating the structural model with the fluid model. Based on the proposed model, the dispenser is designed and manufactured. Subsequently, dispensing performances such as dot size and dispensing flow rate are investigated using the proposed model, which is then validated by experiment.

6928-75, Session 16

A blended polymer electret-based micro-electrostatic power generator

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Over the years, power harvesting technologies for low power electronic devices have attracted much interest. In this paper, the design and fabrication of a micro electrostatic power generator that is comprised of a stator with a self-made electret material to store charges and a rotor with inter-digital electrodes is presented. The newly developed electret material is made from a solution which ingeniously blends cycloolefin copolymer (COC) and polystyrene (PS) together. This unique solution can easily be integrated and adopted to a micro fabrication process. The charge storage ability of this new electret material was investigated and results showed that low concentrations of polystyrene (PS) in the blended material will be more stable than when there is pure cycloolefin copolymer (COC) or when there is a higher charge storage ability. Our newly developed blended electret material has excellent mechanical properties and is easy to use when compared to using teflon FEP or PP. A feasibility study of a micro electrostatic power generator based on our blended electret material was performed. Experimental results obtained demonstrate the feasibility and effectiveness of this new type of micro electrostatic power generator.

6928-76, Session 16

Piezoelectric control of nonlinear moal interaction in stiffened structures

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Control of static and dynamic instabilities of plates using piezo-electric patches is receiving increasing attention in industry and technical literature in recent times. In this paper relatively simple strategies are envisaged and investigated to effectively control the instabilities of stiffened plates.

Optimally designed stiffened plates subject to compression tend to fail by an interaction of overall and local buckling, and are imperfection-sensitive. In the case of stiffened shells, the local buckling can be unstable and the interaction with the overall mode can be even more destabilizing in nature. For these structures, the load corresponding to dynamic instability can be significantly less than that which would cause collapse under static conditions.

As a first step in unraveling the issues involved in the piezo-electric control of the structures afflicted by nonlinearities, the problem of a simply supported axially compressed column on elastic foundation is studied. Here the significant nonlinearity arises from the softening foundation. The column is so designed as to have coincident critical load for the first two modes of buckling. Imperfections are assumed to be proportional to half-wave length of buckling. Self-sensing piezo-electric actuators

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are deemed to be attached to the top and bottom faces of the column. These can be continuous with facility of variable voltage or discrete with each patch actuated by an appropriate independently varying but distinct voltage. It is shown that buckling capacity of the column can be increased by a feedback voltage proportional to the strain at the top/bottom faces (or curvature) of the column. However to sustain the column at a load significantly higher than static buckling load (P_s) there is a premium price to pay in terms of energy that must continue to be supplied.

The column is compressed up to a value which is close to P_s without any exercise of control. At this point it is disturbed by a sudden application of a uniform lateral load which is of the order of 1% of its buckling capacity. Now the column vibrations are controlled by voltages proportional to the strain rates sensed at the top/bottom faces of the column. The column settles to its underlying static equilibrium configuration. The optimality of the 'velocity control' is studied by appropriately varying the feedback gain. In most of the calculations three patches of self-sensing piezo-actuators are used, and some cases of continuous patches with spatially varying voltages are considered for comparison.

The problem of stiffened panels with coincident local and overall critical loads is next considered. Imperfections are assumed in both the modes. The analysis of the stiffened plate is carried out a special technique in which the local buckling deformation is embedded into the plate elements representing the plate and stiffener elements.

Without any control, the stiffened plate loses a great deal of its initial stiffness at 60% of the critical load and becomes completely unstable at 78% of the critical load, with deflections increasing without limit. It is shown that effective control which stabilizes the structure up to the critical axial compression (P_{cr}), can be achieved by appropriate piezo-electric self-sensing actuators attached to the tips of the stiffener. Beyond P_{cr} , control is still possible but at the cost of an abrupt increase in the quantum of energy supplied. The dynamic response of the column carrying various levels of axial compression is triggered by applying a uniformly distributed lateral load of 1% of the critical load. The control of the vibrations is achieved by negative feedback voltages proportional to the strain rates sensed at the top and bottom of the stiffener. Local mode deflections were successfully controlled using an actuator in the form of a longitudinal piezo-electric patch attached to middle of the plate element. The relative merits and practicality of these strategies of control are discussed in the paper.

6928-78, Session 17

Experimental assessment of negative impedance shunts for vibration suppression on a beam

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Negative impedance shunts have been used with piezoelectric materials for the purposes of vibration suppression. Details of the shunt design may be determined using different performance objectives such as maximum dissipation or minimization of reactive input power. Experimentally optimized shunts are applied to a composite piezoelectric aluminum beam subjected to a broadband disturbance. Performance measures of interest includes an overall power balance for the system, as well as tip vibration suppression and spatial average vibration suppression. The resulting measures are compared to the maximum damping and reactive tuning suppression theories.

6928-79, Session 17

Structural vibration control with semi-active variable stiffness TLCD

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Tuned Liquid Column Dampers (TLCD) is an effective control device developed from Tuned Liquid Dampers (TLD), which increases structural damping through the vibration of liquid in the U-shaped container to suppress the structural dynamical response. The potential advantages of liquid vibration absorbers include: low manufacturing and installation costs; the ability of the absorbers to be incorporated during the design stage of a structure, or to be retrofitted to serve as a remedial role;

relatively low maintenance requirements; and the availability of the liquid to be used for emergency purposes, or for the everyday function of the structure if fresh water is used.

To improve the control performance of passive TLCD, semi-active TLCD systems have been proposed and investigated. To satisfy the requirements of optimal damping, semi-active TLCD can adjust the head loss coefficient by changing the orifice opening of TLCD according to the pre-designed control law. Theoretical and experimental results have shown that the semi-active TLCD can get better control performance than passive TLCD.

However, the frequency of TLCD is determined by the length of liquid column. It is difficult to adjust the frequency of TLCD to be same or similar as the one of the structure if the structure has high natural frequency, which affects the application TLCD. Adjustable frequency TLCD can solve this problem, where springs are added to the TLCD system. The vibration characteristics of adjustable frequency TLCD are determined by the length of liquid column and stiffness of springs.

The adjustable frequency TLCD is still a passive control device, where the stiffness of the spring is pre-determined and cannot change during the vibration control process. To improve the performance of passive adjustable frequency TLCD, Semi-active Variable Stiffness Tuned Liquid Column Damper (SAVS-TLCD) is presented, with the stiffness of additional spring online adjustable. The state of stiffness can be ON or OFF according to the requirements of control system during the vibration. The mechanical model of SAVS-TLCD is derived and the off-and-towards-equilibrium (OTE) strategy algorithm is used to adjust the state of stiffness. The results indicate that SAVS-TLCD has larger frequency width of reduction and can still be effectiveness if there is a little error between the frequency of TLCD and the structure.

6928-80, Session 17

Several topics from active vibration control technique using piezoelectric films

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Piezoelectric films are flexible, light weight, thin sheet-like elements and can be easily bonded on flexible structures as distributed sensors/actuators for active vibration control applications. Such flexible films possess huge variety of functionality of arbitrary shaping, fitting to curved surfaces, lamination, and so on. Therefore, with these elements combined with control circuits, smart flexible structures based on a new principle are expected to be realized. During the past two decade, a lot of researchers have treated this research topics.

However, conventional studies are limited to the control of relatively small (micron-order) displacements of thin flexible structures as well as numerical studies by handling controller design of software aspects. In order to obtain enough vibration control effect in the actual experiment, following problems must be overcome; i.e. compensation of electromagnetic noises, ability of obtaining high feedback gain and enough control power, and compensation of temperature for pyroelectric effect. Furthermore, in the vibration control of flexible curved structure, in-plane motion and bending motion are coupled, and in general strain distribution along the thickness direction is not symmetric. For that reason, in general, the system tends to be unstable when the distributed sensor and actuator are bonded on the opposite surfaces of the curved structure. Actually, even in the case of straight beam, it has been observed in the author's bending vibration control experiment of a flexible beam using rectangular-shaped piezoelectric film sensor/actuator pairs, that the system became unstable due to the effect of in-plane strain, which was not considered in theoretical model. In such case, if a self-sensing actuator bonded on one surface is used and one piezoelectric element act as the actuator and as the sensor simultaneously, the system may become stable in principle. But the difficulty in using a self-sensing actuator is that the stability of the system strongly depends on the balancing of the bridge circuit. To date, a lot of studies exist concerning the self-sensing actuator. In these studies, piezoceramic bimorph actuators were mainly treated, and effective methods for curved structure with piezofilms have not yet been developed.

One way to get rid of the above-mentioned problems is to introduce control theory and solve them from the software aspects by using computer powers. However, from the viewpoint of realization of smart structures,

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It is further important that simplification of hardware aspects of devices and to compose structural element, sensor, actuator, and controller in well balance such that the entire system can be simpler and smarter. From this standpoint, several fundamental active vibration control principles, which will be valid in actual implementation, of smart flexible structures using piezoelectric films as distributed sensor/actuator have been developed in the author's studies. Decentralized control methods using sensor/actuator pairs, effects of variations of the shape of distributed piezoelectric films on their functions as sensor/actuator for active vibration control, a self-sensing actuator using piezoelectric films with different thickness and area, a self-sensing actuator using laminated piezoelectric films for vibration control of curved or two-dimensional structures, and a quasi-wave-absorbing control method of a cantilever beam using piezoelectric films were developed with a few additional control methods, and investigated both theoretically and experimentally. By applying each of these methods, it was verified that the enough vibration control effects were actually obtained and the theory agrees well with the experiment.

It is concluded that from all the results of conventional studies including works by the author, vibration control effects by using conventional piezoelectric films are still limited to some extent. Therefore, new materials superior than conventional piezoelectric materials, in the sense of enough control power and shaping capability, should be developed toward the realization of the smart structures and obtaining large vibration suppression effects. In recent years, some novel piezoelectric high-polymers are beginning to be developed in the world, and it seems that new high-polymer material age and new flexible smart structure will be promised to arrive in the future.

6928-81, Session 17

Active damping control of micromachined devices in a low-atmospheric pressure environment

R. N. Dean, Jr., G. T. Flowers, C. Chen, S. J. Kim, Auburn Univ.

Some harsh environments, such as those encountered by missiles, rockets and various types of industrial machinery, contain high frequency/amplitude mechanical vibrations. Unfortunately, some very useful MEMS components are sensitive to these high frequency mechanical vibrations. Examples include MEMS gyroscopes and resonators, oscillators and some micro optics. Exposure of these components to the high frequency mechanical vibrations present in the operating environment can result in a variety of problems, ranging from an increased noise floor to component failure. Passive micromachined silicon lowpass filter structures (spring-mass-damper) for vibration isolation have been demonstrated in recent years. However, the performance of such filter structures is typically limited by low damping. This is especially true if operated in low pressure environments, which is often the optimal operating environment for the attached device requiring vibration isolation.

One solution is the implementation of active techniques using electrostatic actuators. These devices are utilized in many micromachined silicon devices to generate mechanical motion. They offer a number of advantages, including low power, fast response time, compatibility with silicon micromachining, capacitive position measurement and relative simplicity of fabrication. This paper demonstrates the application of active micromachined mechanical lowpass vibration isolation filters in a low atmospheric pressure environment, through integrating a parallel plate electrostatic actuator with the micromachined passive filter structure to realize an active mechanical lowpass filter. The electrostatic actuator structure is used both as the control loop actuator and as the direction of relative velocity sensor. When the relative velocity sensor detects that the micromachined structures are moving away from each other, it turns on the electrostatic parallel plate actuator to retard this motion, thereby draining kinetic energy from system. When the direction of relative velocity changes, the actuator is turned off. This process effectively increases the damping in the system. The sensor detection threshold or the actuator drive voltage can be adjusted to tune the system damping to the desired level. The physical size of these active filters is suitable for use in or as the packaging for sensitive electronic and MEMS devices, such as MEMS vibratory gyroscope chips. The resulting electromechanical system-in-a-package allows for optimum system performance through allowing the use of state of the art components in mechanically harsh environments.

6928-82, Session 17

Frequency response analysis of vibration system with parametric excitation of damping coefficient

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This paper proposes a method of frequency response analysis of a vibration system with parametric excitation of damping coefficient and external harmonic excitation. In general, the purpose of the application of the damping is to dissipate the vibration energy and to reduce the vibration amplitude of the system as soon as possible. Recently, some variable dampers that the damping coefficient can be changed easily have developed, i.e. Magneto-Rheological (MR) damper, Electro-Rheological (ER) damper. Many researchers have applied the variable damper for a semi-active control to reduce the amplitude of the vibrating system. However we have proposed quite opposite method to use the variable damping in previous study. Our purpose of the use of the damping is not decrease but increase of the vibration amplitude of the system, and it is similar to resonance of the vibrating system. One of the applications of the proposed system is a dynamic absorber. The dynamic absorber takes advantage of resonance phenomenon, and the passive type and/or the active type are of use in a whole range of fields. However, there is no example to apply semi-active control to the dynamic absorber. There is a possibility in the future that motion of the dynamic absorber is controlled, because resonance is generated by a variable damper driven by the proposed method

In this paper, a simple vibration system, i.e. a mass is supported by a spring and a variable damper these are placed in parallel, is considered. The coefficient of the variable damper is changed like sine wave, i.e. artificial damping parametric excitation which of frequency can be chosen. The damping force generated by the variable damper is equivalent to a product at the damping coefficient and the relative velocity between the base and the mass. By multiplying the input sine wave from the base excitation by the frequency controllable sine wave of the variable damper, new vibration that has another frequency besides the input frequency arises. Therefore, when the system is excited by the base excitation in a frequency that is faster than that of the natural frequency of the vibrating system, the changing of the damping coefficient in a suitable frequency can generate new vibration that has same frequency as the natural frequency. As a result, the vibration amplitude increases because of a phenomenon that is similar resonance. By the artificial parametric excitation of variable damping, the resonance can be occurred in anywhere more than the natural frequency. In this paper, first, we carried out theoretical analysis, and obtain frequency response of the proposed system. Finally, we confirm the effectiveness of the proposed analysis method by comparing the analysis result with the previous simulation results.

6928-83, Session 17

Recent studies of electronic tuning of out of plane stiffness and dissipation of piezoelectric polymer membranes

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Project Location: SDSM&T

Lightweight flexible structural elements would benefit greatly from an ability to tune the dissipation and stiffness of the structural element. This would provide a compromise between large passive systems, and complex, real-time, active control implementations. Different elements of a structure could be altered based on the loads that they experience. This could be implemented by either varying the effective stiffness to shift a particular resonance out of a chosen frequency range, or by increasing the structural damping over different parts of the operating frequency spectrum at different times.

This study will focus on thin piezoelectric film strips connected in parallel with an electronic circuit which provides a "negative capacitance," [1], [2], [3], and an electrical load consisting of a resistor and a capacitor. Due to the inverse piezoelectric effect, each film forms an electromechanical system in conjunction with the parallel circuit. The overall impedance of this system can be controlled by correctly varying gain parameters within the circuit.

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This work models the PVDF strips of non-vanishing thickness and stretched under a constant, boundary applied tension. Both flexural stiffness and in-plane tension are accounted for in setting up the partial differential equation of motion. Forced response calculations were carried out over a range of frequencies with the circuit tuned to provide the best dampening at chosen frequencies.

The negative capacitance circuit was built using standard components including a Fairchild 351 operational amplifier. Harmonic excitation was provided with an acoustic speaker driven by a wave form generator. Tests were carried out over a frequency range with the circuit tuned to provide the critical circuit gain at three representative frequencies: 200, 600, and 1200 Hz. Measurements of out-of-plane deflection at a chosen point were taken using an LED/photodiode pair, which was calibrated experimentally. The voltage developed between the electrodes was also measured. Tests were conducted without the negative capacitance circuit in parallel and then with, and both deflection and voltage amplitudes were compared for the two cases. Theoretical and experimental results were analyzed and compared.

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6928-84, Session 17

A variable bending stiffness sandwich structure using fluidic flexible matrix composites (F2MC)

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Adaptive structures with variable stiffness are useful in many applications, such as morphing vehicles, soft robotics, and semi-active isolation mounts. In a recent study [Shan et al., 2007], a fluidic flexible matrix composites (F2MC) tube element concept was introduced and analyzed. It was shown that F2MC tubes are capable of providing variable axial stiffness with a high/low moduli ratio of more than an order of magnitude. Such variations come from the anisotropic material properties of the F2MC tube and the high bulk modulus of the working fluid confined in the tube. With such promising results, the next step is to expand the investigation to the design of such F2MC tube elements into structures that can resist loading from various directions with variable stiffness.

:Presented in this paper is a variable bending stiffness honeycomb sandwich panel, building upon the concept of F2MC sheets. In this structure, the traditional sandwich face sheets are replaced by composite F2MC tube layers. The variable tube stiffness, combined with the anisotropic honeycomb core material properties, would give the new sandwich structure variable bending stiffness properties against transverse loading. In this research, an analytical model is developed based on Lekhnitskii's solution and Timoshenko beam theory. A segmented multiple-F2MC-tube configuration is synthesized to increase the variable bending stiffness range. The analysis shows that the new honeycomb sandwich structure using F2MC tubes of 10 segments could provide a high/low bending stiffness ratio of order 102. Segmentation and stiffness control can be realized by an embedded valve network, thus granting a fast response

time. The experimental effort to verify the acclaimed analysis results are on going and will be addressed in detail in the finished paper.

6928-85, Session 18

Investigation of an energy harvesting small unmanned air vehicle

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In this project the addition of energy harvesting is investigated to determine the benefits of integrating it into a small unmanned air vehicle (UAV). Specifically, solar and piezoelectric energy harvesting techniques were selected and their basic functions analyzed. The initial investigation involved using a fundamental law of thermodynamics, entropy generation, to analyze both the small UAV with and without energy harvesting. A notional mission was developed for the comparison that involved each aircraft performing a reconnaissance mission. This analysis showed that while the UAV with energy harvesting generated less entropy, the UAV without energy harvesting outperformed the other UAV in total flight time at the target. The analysis further looked at future energy harvesting technologies and their effect on the energy harvesting UAV to conduct the mission. The results of the mission using the advanced technology showed that the energy harvesting would increase the effectiveness of the energy harvesting vehicle and making it possible to outperform the UAV without energy harvesting. Additionally, both the solar and piezoelectric technologies were characterized experimentally and analytically. With this information, designs for integrating energy harvesting into the small UAV system were developed and tests were conducted to show how the energy harvesting designs would perform. It was demonstrated that the addition of the solar and piezoelectric devices would supply usable power for charging batteries and sensors and that it would be advantageous to implement them into a small UAV.

6928-86, Session 18

Vibration energy harvesting for micro air vehicle sensors

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The development of unmanned aerial vehicles (UAVs) has been of interest for military applications for several decades. Most recently, focus has been placed on creating small UAVs termed micro air vehicles (MAVs), which can be small enough to be carried and deployed by soldiers in the field. These vehicles are primarily used for surveillance and reconnaissance, however, they can be designed to perform other tasks as well. One limitation of currently available MAVs is their endurance or maximum flight time. MAVs are small and lightweight, therefore, they cannot carry large fuel payloads. Specifically in electric powered MAVs, the rechargeable batteries used to power the aircraft often compose a large amount of the overall aircraft mass, so increasing the battery size to improve endurance is not practical. In an effort to improve the endurance of MAVs without adding a significant amount of weight, the concept of vibration energy harvesting is considered. Vibration energy harvesting is the idea of converting mechanical vibration energy into electrical energy through the use of smart materials. In the case of MAVs, it is proposed that piezoelectric harvesters be incorporated into the design of the aircraft in order to actively harvest vibration energy both in flight and while at rest. This research will focus on quantifying the energy available for harvesting from wing deflections as well as rigid body motion of the aircraft. By surface mounting piezoelectric patches at the root of the wings, energy can be harvested from the strain in the wings as they deflect from wind gusts and maneuvering. Additionally, by placing a cantilever beam inside the fuselage of the aircraft, energy can be harvested from the rigid body motion of the aircraft. Both wing mounted and cantilevered patches will be able to harvest energy not only during flight but also if the aircraft is perched on a vibrating structure such as an air conditioning unit on top of a building. The goal of this research is to harvest an adequate amount of energy to power an MAV sensor such as a camera. By powering a sensor from harvested energy, there will be less load on the rechargeable battery that powers the aircraft resulting in an increased endurance.

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6928-87, Session 18

Analysis of membrane wing for micro air vehicles

E. A. Leylek, J. E. Manzo, E. Garcia, Cornell Univ.

Bats are remarkably nimble flyers, and they can fly with such agility by using their ability to vary the camber of their wings. Inspired by these creatures, we are developing a membrane wing capable of morphing. The wing consists of skeletal support structures with embedded "smart" joints for actuation, covered by a membrane. The joints actively change the twist and the camber of the wing, similar to leading edge and trailing edge flaps, but the wing remains continuous. To design the cross-section of the wing supports and to study the effect of changing camber on parameters such as lift coefficient, drag coefficient, and lift-to-drag ratio, XFOIL is used to systematically compare airfoils of various thicknesses and various cambers at a Reynolds number of 100,000. NACA 4-digit airfoils with the point of maximum camber at 30% of the chord were studied in a range of maximum thickness from 3-10% and variations in maximum camber of 0 to 9% for each thickness. Results suggest that very thin airfoils yield the largest lift-to-drag ratios but have smaller maximum lift coefficients. Moderately thin airfoils (~6%) yield a favorable combination of high lift-to-drag ratios and high maximum lift coefficients. Lift-to-drag ratios as high as 63, along with the ability to morph to a camber that would provide the best lift-to-drag ratio or lift coefficient, suggest that such a wing would be extremely effective and efficient, as well as a great improvement over current aircraft.

Morphological aspects from bats, pterosaurs, and other gliders with membranous wings that provide them with unique flying characteristics are combined to create a full wing that is tested quasi-statically in the wind tunnel. The wing consists of interchangeable parts to test the effects of different geometric parameters on lift, drag, and moment coefficients, along with the overall effect on vehicle stability and performance. Data is taken with a load cell for the wings at different angles of attack through stall, and flow visualization with neutrally buoyant helium bubbles is used to capture the flow patterns around the wing. Sail theory in conjunction with a lifting-line method is used in an iterative process to computationally predict the flight characteristics of certain 3D wings. Such a wing would provide unique flight capabilities through morphing for use in micro-air vehicles to create a single aircraft for use in multiple mission objectives.

6928-89, Session 19

Behavior of thin lightweight structures under propagating waves

E. A. Petersen, Univ. of Nebraska/Lincoln and South Dakota School of Mines and Technology; U. A. Korde, South Dakota School of Mines and Technology

The ability to automate the detection and repair of small defects in materials is of great importance when it is difficult to physically access the structure housing them, as is the case with vehicles in space. Systems with this ability are known as Integrated Vehicle Health Monitoring Systems (IVHS), and are being implemented more and more [1] on helicopter rotors, aircraft wings, etc. [2] The purpose of this research is to investigate the possibility of using distributed piezoelectric transducers to accomplish structural integrity

testing of thin structures in space. In order to realize this goal, we must have a thorough understanding of the structure's vibration/wave response-one must be able to distinguish between healthy and damaged samples. In our previous paper, [3] we reported on the in-plane vibration response of membrane strips and sheets using in-plane actuation and sensing with piezoelectric transducers. Hall et al. [4] have also studied the dynamics of membrane strips. Once defect detection is accomplished, the detectors are to become the healers. Time-reversal of applied signals [5] would allow acoustic focusing at the defect [6] and could facilitate healing, either via a pre-applied filler or an energetic fusing of the edges at the crack.

Experimentally differentiating between cracked and uncracked membrane strips and sheets has thus far proven difficult [3]. In this study, we continue our analysis of membrane sheet vibrations and also examine crack detection in single-crystal silicon wafers, where more wave types are present. Experimental work has been conducted with piezoelectric PZT stacks being used as actuators and receivers on single crystal silicon

wafers and a steel sheet.

Wave solutions to the equation of motion are obtained for three cases, (i) a rectangular membrane made of Kapton, (ii) a single-crystal Silicon thin plate, and (iii) a rectangular sheet of 22 gauge steel. Theoretical and experimental results for the natural frequencies of the steel sheet in flexural mode agree reasonably well. The paper discusses these results and the implementation of time reversed acoustics for crack detection.

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6928-90, Session 19

Experimental studies of using wireless energy transmission for powering SHM sensor nodes

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In this paper, we present our experimental investigation of using wireless energy transmission systems to operate SHM sensor nodes. The goal of this study is to develop SHM sensing systems which can be permanently embedded in the host structure and do not require an on-board power sources. With this approach, the required energy will be periodically delivered as needed to operate the sensor node, as opposed to being harvested as in the conventional approaches. The wirelessly transmitted microwave energy is captured by a microstrip patch antenna, and then transformed into DC power by a rectifying circuit and stored in a storage medium to provide the required energy to the sensor and transmitter. The method of increasing the efficiency, energy storage medium, target applications, and the integrated use with traditional energy harvesting sources will also be discussed. This paper summarizes considerations needed to design such energy delivery systems, experimental procedures and results, and additional issues that can be used as guidelines for future investigations.

6928-92, Session 19

Design of dual-stage actuation system for high-precision optical manufacturing

J. Tang, Univ. of Connecticut

Currently in optical machining systems, the voice coil actuator is being implemented for servo control. Although exhibiting improved features over previous servo motor, voice coil still has noticeable bandwidth limitation and positioning resolution limitation (>0.1 μm). It has been recognized that these inherent limitations essentially hinder the further improvement of lens surfacing performance. Lens surfacing requires fast tracking and

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very high accuracy of the cutter motion for high throughput. In current systems, when the frequency of the cutter tracking motion increases to a certain level, there exists significant tracking error in both magnitude and phase. Besides, in general the current lens surface roughness is at 0.2 μm level, primarily due to the limitation in positioning resolution.

In order to fundamentally solve these issues, in this research we develop a new type of dual-stage servo actuation system, where a voice coil covers the long-range motion of the cutter during the coarse positioning stage (with displacement range at multiple inches and motion frequency below 150Hz), and a piezo stack induces the fine motion of the cutter during micro-surfacing (with virtually unlimited bandwidth and sub-nanometer positioning resolution). One critical step in this research is a proper mechatronics-based design of integration/mounting of the piezo stack to the voice coil. In order to take full advantage of the piezo stack actuator's bandwidth, the mounting should be well-aligned, have smooth connection relative to the coil with minimized friction/backlash, and lead to minimized loss of displacement stroke and maintain excellent rigidity to reduce vibration within the operating frequency range. Our approach is to develop a flexure mechanism to accomplish the seamless connection between the voice coil and the piezo stack. In this flexure mechanism, properly distributed hinges will guarantee the perfect alignment of the piezo actuation in the moving direction without twisting. The hinge profiles (that are directly related to the axial stiffness, torsional stiffness, and bending stiffness of the actuation system) and the necessary clamping enforcement is optimally designed with dynamic/static analysis, so the natural frequencies of the entire actuation system are adjusted higher enough to avoid vibration, and the piezo stack displacement can be transmitted.

We first carry out correlated finite element analysis and experimental study to identify hinge configuration and profile that can yield optimized overall bending and torsion stiffness (to yield sufficiently high natural frequencies), while minimizing the actuation stroke loss. Sensitivity analysis is performed, to investigate the influence of parametric change on system robustness, such as dynamic loading sustainability and cutter alignment. After the dual-stage actuator is prototyped, extensive testing and analysis are performed for the purpose of system identification and dynamic modeling. The identification consists of two phases: the identification of a lumped-parameter mechanistic model to be used in control synthesis, and the identification of the system electro-mechanical property. The equivalent mass, stiffness, and damping coefficients of the voice coil, the piezo stack, and the connection mechanism are identified via a series of experimental modal analyses on separate components and on the coupled integral system. The bandwidth of the actuators is also identified. We apply wide-band excitation signals to the voice coil and the piezo stack, and measure the corresponding outputs to get the Bode plots. The actuation characteristics are evaluated from the corresponding Bode plots, which give the bandwidth information of the respective actuators. In order to fully characterize the actuation properties, open-loop testing is performed using the prototype. Sample command signals for both the coarse and fine motions are applied to the actuator/cutter that is installed on the lens surfacing machine, to set up the un-controlled baseline. With these design and analysis as basis, a variety of control algorithms will then be tested, which include simple PID control, repetitive learning control, and sliding mode control.

6928-93, Session 20

Active wing design with integrated flight control

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Previous investigations into Small Unmanned Aerial Vehicle (SUAV) technology have focused on the development of wing designs with very low stiffnesses and high flexibility. This approach results in the realization of adaptive wing designs which can only be utilized in low speed aerodynamic environments. The current project investigates the design of active wings for the use in higher wind speed environments. In the current work an active wing was developed utilizing PZT actuators for active roll control of a SUAV during flight.

The goal of the current work was to design an adaptive composite wing with a very thin profile with integrated active roll control capabilities. First, the feasibility and potential of this concept was investigated using Finite

Element Analysis (FEA) and Computational Fluid Dynamics (CFD) analysis. The Jedelsky profile was chosen for the wing design and modeled in ANSYS Version 11 using solid and solid-shell elements. Active elements were defined in the model and the piezoelectric actuators were modeled using the thermal expansion analogy. Coupling between the structural and fluid environments was accomplished with sequential coupled analysis to establish the effect of structural actuation on the forces produced by wind pressure forces.

Optimization loops were performed for achieving a large ratio between passive stiffness and actuator efficiency under given boundary conditions (e.g. laminate failure criteria, allowable actuator deformations) by modifying the actuator position as well as the laminate stacking sequence.

A prototype of the active wing design was manufactured using glass and carbon fiber reinforced plastic laminates, PCV-foam and Macro Fiber Composite (MFC) actuators.

Validation of the coupled ANSYS model was accomplished via quasi-static actuation and preliminary wind tunnel tests. The design parameters of 2 kg lift forces with a wind speed of 10 m/s were realized, showing good correlation with the numerical model predictions. Displacement measurements of the active wing under quasi-static loading and wind tunnel conditions verified the performance ability of the current wing design.

6928-94, Session 20

Bistable mechanisms for morphing rotors

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In this paper we explore the use of bistable mechanisms for rotor morphing, specifically, blade tip twist. The optimal blade twist distributions for hover and high-speed forward flight are very different, and the ability of the rotor to change effective twist is expected to be advantageous. Bistable or "snap through" mechanisms have multiple stable equilibrium states and are a novel way to achieve large actuation output stroke at relatively modest effort for gross rotor morphing applications. This is because in addition to the large actuation stroke associated with the snap-through (relative to conventional actuator/ amplification systems) coming at relatively low actuation effort, no locking is required in either equilibrium state (since they are both stable).

We analyze a bistable twisting mechanism using finite element analysis and predict the bistable behavior. The analysis is then used to predict the effect of centrifugal and aerodynamic loads on the bistability and morphing performance for a rotor tip twist application.

6928-95, Session 20

Shape control of a morphing structure (rotor blade) using a shape memory alloy actuator system, future of SMA

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Development and test results of a rotor blade twist control system that utilizes a thermo-mechanical shape memory alloy (SMA) are presented. The actuation system must control the blade shape during flight operations allowing the blade to be configured for greater lift during takeoff and landing. This system must also allow for thrust optimization during forward flight conditions to meet alternate objectives such as fuel efficiency or noise. The requirements for the actuator design include: extreme ruggedness, sizing small enough to fit within the blade yet strong enough to twist it, low mass to meet centrifugal structural constraints, and the ability to transition all blades from one specified shape to another in a synchronous manner as to minimize asymmetrical rotor loading. Conventional actuator techniques proved to be unfeasible due to their size, weight, and lack of robustness. However, SMA actuators provided an excellent solution because of their very high torque output to weight ratio and suitability to the dynamic environment of a rotorblade.

The SMA actuators presented other challenges related to the behavior of the SMA material, and these are addressed herein. For example, the response of the SMA tube is dependent on its temperature, but the temperature is not homogenous due to thermal gradients created when the tubes are heated or cooled. Additionally, due to design constraints, only a few local temperatures were available for feedback in the controller.

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The SMA material is also an energy storage element resulting in response lag, and this is undesirable particularly with respect to the need for fast synchronized motion. Furthermore, the SMA position response to temperature is severely hysteretic in nature making it nearly impossible to recover properly when the position overshoots a desired set point.

The shape controller developed to overcome the challenges identified above is presented herein. Thermoelectric modules (TEM's) are used to actively transfer heat between SMA tubes and other heat conductor and radiator components. An energy transfer mechanism stabilizes the blade configuration into two discrete positions, and it is activated using the SMA tube actuators. SMA actuator angular positions and system temperatures are measured and used for feedback. Modeling and system identification techniques are used to establish parameters used in a temperature rate estimator residing in the controller. The estimator was developed to make the controller robust to variances in convection resulting from changes in the ambient air temperature. Implementation of a non-trivial solution to nonlinear and coupled thermal response equations was also required to insure effective use of the TEM's. These methods and response test results are presented herein.

6928-96, Session 20

Prediction of aircraft dynamics and control with shape changing wings

E. A. Cuji, E. Garcia, Cornell Univ.

This paper will present a prediction of the vehicle dynamics and control of an aircraft with shape changing wings. The aerodynamic forces will be calculated using a 3D aerodynamic model developed that utilizes a modern adaptation of Prandtl's lifting-line method, which is based on a fully three-dimensional vortex lifting law. This method is able to analyze the aerodynamic properties of wings of arbitrary camber, sweep and dihedral. The method will be applied to analyze the dynamics of different out-of-plane wing configuration of interest for morphing aircraft application. Using the aerodynamic properties calculated, we want to study the effects on the aircraft dynamics of a morph wing configuration. We want to investigate the effects that specific configurations will have on stability and control of the aircraft. But, most importantly, we want to see how we can take advantage of these properties by utilizing shape change in the wing to perform maneuvers that conventional aircraft cannot do.

One particular wing configuration of interest is the wing configuration that has two sections, an out-of-plane dihedral section and a horizontal configuration, like a V shape wing configuration. An investigation as to how the dihedral part will affect the dynamics and control of the vehicle will be performed. For this wing, since some of the lift force at each dihedral part will have a horizontal component, this could provide yaw control. An analysis of symmetric and asymmetric V shape wing will be performed. Also we want to see what it will be the effect of having flaps on the dihedral part of the wing and see how we can use this effect to perform different maneuvers.

6928-97, Session 20

Shape control of a piezo-activated beam model with application to a class of morphing air vehicles

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Recently, Macro Fiber Composite (MFC) PZT actuators were successfully demonstrated as an effective aircraft control mechanism. Knowledge gained from the initial aircraft design, accessibility to an array of potential design materials, and recent advances in solid state electrical components have demonstrated the need for a more detailed design. This research investigates the design, simulation, and development of piezo-embedded spars which control the camber distribution along the span of a small scale air vehicle.

Currently, there are four materials being considered for manufacturing aircraft structural components: EPP foam, EPS Foam, fiberglass, and SLS rapid prototyping material. Each has advantageous characteristics with respect to small aircraft design. For example, the fiberglass lay-up process is very inconsistent; material parameters can vary drastically between sets of wings making control design and implementation very

difficult. At half the density, the SLS material seems to have comparable stiffness properties for identical thicknesses. Moreover, the manufacturing process is highly accurate thus leading to a more consistent, light weight design. Characterizing these materials is essential for both the design and manufacturing of various components integrated onto the aircraft. More specifically, a material analysis will aid in optimization of the maximum variation of the shape shifting spar actuator thus increasing control effectiveness.

Actuator limitations and technological maturity of existing power electronic components hinder determination of the electronic actuator topology that provides maximum shape change while consuming the least amount of energy. Currently, there is a myriad of possible configurations consisting of combinations of both unimorph and bimorph configurations for various operating voltages and hybrid switching systems. We aim to classify the set of available high voltage actuator topologies intended for use on small scale, camber morphing aircraft with piezoelectric embedded devices.

The output of the material and actuator/electronics analysis leads to the design of an active spar for use as a control effector on the aircraft. Potential on board sensor technologies are being investigated for feedback in the control system design. These consist of collocated sensors embedded in MFC, conventional strain gauges, and optical strain gauges. The bulk of this paper details design, model development, shape control synthesis, and simulation of the active spar configuration. Moreover, experimental results are provided to compliment the simulated. The paper concludes with a comparison, conclusions, and future work.

6928-98, Session 21

Vibration suppression of a flexible manipulator using self-tuning optimal control and LIPCA actuator

V. P. Phan, H. C. Park, N. S. Goo, Konkuk Univ. (South Korea)

Active vibration suppression of a flexible manipulator plays an important role in many engineering applications such as robot manipulator and high-speed flexible mechanism. The control performances of light-weight and flexible manipulator can be enhanced when we apply variable control parameters rather than fixed control parameters. With this concept in mind, we have developed a self-tuning optimal control method of a flexible manipulator, which tunes itself to the optimal parameters, based on the initial maximum responses of the controlled system and a genetic algorithm. GA is used to search optimal PPF parameters such that the objective functions determined from the initial maximum responses can be minimized. Then we made a lookup table which had optimal PPF parameters as a function of the initial maximum responses and the lookup table can be used in the real-time control algorithm.

6928-99, Session 21

Numerical analysis of deformation of a beam with thin piezoelectric actuators partially debonded and buckling

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Piezoelectric materials are thin and have good efficiency and response speed of transformation between electrical energy and mechanical energy, so that studies on application of the piezoelectric materials to active and passive structural controls have been carried out for about two decades. In the applications, piezoelectric ceramics fibers sandwiched between adhesives and electroded plastic films or thin piezoelectric ceramics plates are often bonded on host structures. In their experimental and theoretical studies it is usually assumed that the piezoelectric actuators and sensors are perfectly bonded to the host structure.

However, the debonding may take place due to manufacturing imperfection and/or impact of foreign objects, and the debonded region may also extend due to a subsequent repeated deformation. Furthermore, when the sandwiched piezoelectric ceramics fibers or the thin piezoelectric ceramics plates are used as actuators, they may buckle when they bend or extend the structure. In such a case static and dynamic performances of the structure would be degraded.

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Therefore, investigation and understanding of the degradation of the performances due to the debonding and buckling are important for designing a structure with piezoelectric actuators and sensors and redesigning a control law of the structure after the debonding takes place. However, few analyses of the structures with actuators and sensors debonded and buckling are published. Therefore, in this paper a linear mathematical model for analyzing deformation of a beam with thin piezoelectric actuators partially debonded and buckling is proposed based on Timoshenko beam theory, and passive and active extension and bending performances of the beam are further investigated.

The bonded region is modeled as a single beam element, while the debonded region is modeled as beam elements of debonded piezoelectric actuators and a host structure. Effect of buckling of the actuators is considered by applying a force equal to the buckling load to the ends of the debonded region as an external force.

When the actuators are debonded from their edges, only the bonded regions contribute to the deformation of the beam structure but the debonded regions do not contribute at all, that is, the performances become the same as those for a beam with bonded actuators shortened by the debonded region. When the actuators are debonded from within them, both the ends of which are still bonded, their performances are almost the same as those for the perfectly bonded actuators independently of length and location of the debonded region, before the debonded regions buckle. However, after they buckle, the performances drop depending on the length and location of the debonded region.

6928-100, Session 21

Shape memory alloy wire actuated robot squid with flexible fins

Z. Wang, G. Hang, Y. Wang, L. Jian, Harbin Institute of Technology (China)

A robot squid with flexible fins actuated by shape memory alloy (SMA) wire is presented. Most underwater robots are driven by propellers. The problems of propellers are noise, disturbance the shallow waters ecosystem, the possibility to strike marine animals, and so on. Natural swimming movement could be the solutions of the above problems. So many robot fish have been developed. But robot fish actuated by motors still have noise at swimming. This paper developed a robot squid capable of noiseless swimming with good maneuverability.

The swimming movements of both short-fin and long-fin squid are investigated and modeled at first. Short-fin squid usually swim in an oscillating way, while long-fin squid in an undulating way. Simplifications are adopted as the flexible fins are very difficult to be modeled. The flexible fin is divided into many segments just like fin rays of fish and the movement of a segment is flexible bending to both sides. The whole fin can be simulated by several fin segments connected with a flexible membrane.

Squid fin is made up of muscular hydrostat, which can support the body and generate movements and forces without bony skeleton support. The three kinds of muscles are transverse muscles, longitudinal muscles and dorsoventral muscles, which mainly control the width, length and thickness, respectively. The skin, muscle fibers and connective tissue fibers can store elastic energy during bending and when the fin segment returns to the straight status, the elastic energy can be released. This is known as elastic energy storage and exchange mechanism, which can optimize the energy efficiency. During fin segment bending, longitudinal muscles and dorsoventral muscles can be ignored because the fin segment is very short.

Then the fin segment is modeled. By comparing several actuators, SMA wires are found to be the most suitable actuators to act as the transverse muscle fibers to actuate the artificial fin segment, which is called biomimetic fin. The biomimetic fin consists of SMA wires, elastic substrate and artificial skin. Skins are adhered on both sides of elastic substrate and SMA wires are embedded in the skin adjacent to both sides of the elastic substrate. Both elastic substrate and skin can store and release elastic energy during bending and returning.

Bending experiments of biomimetic fin were done to verify the concept. The results show that the biomimetic fin can bend flexibly to both sides. Thermal analysis of SMA wires is done to find proper control strategy. In

order to achieve the frequency similar to squid fin, high electric current with short pulse width and proper cool conditions can be applied.

The robot squid consists of 2 fins, remote control module, pulse generator module and batteries. Each fin is consists of 5 biomimetic fins and a membrane. The robot squid weights 532 g. Experimental results of oscillating swimming show it can swim forward or backward and rotate. The average swimming speed and the rotary speed reached about 8 mm/s and 12 °/s, respectively.

6928-101, Session 21

An improved robotic fish actuated by piezoceramic actuators

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Underwater environment may provide a lot of potential benefits for human life but the place is inconvenient for human activity. Therefore, robotic fish is one of the most popular robots to access to underwater. For small underwater vehicles driven by propellers, their efficiency is usually no more than 40 percent. The main cause is power consumption to produce vortices, which is perpendicular to the direction of motion and do not produce thrust. Whereas, fish has caught interest of vehicle designers because they can cruise a great distance and maneuver in a tight space. Especially, their fast swimming is efficient and their propulsion is silent. A lot of models of the robotic fish have been proposed. The most famous one is MIT's motor-actuated RoboTuna, which was used to study fish propulsion mechanisms. Draper Lab's hydraulic-actuated Vorticity Control Unmanned Undersea Vehicle (VCUUV) and UC Berkeley's Calibot are other examples of robotic fish. Besides using electric motor for an actuator, smart materials are employed by a few researchers as actuator of fish-mimicking swimming vehicles. Piezoelectric actuator (THUNDER) was used to build a miniature swimming vehicle by Borgen, et al.. Shape memory alloy (SMA) was employed to produce undulating motion of a lamprey robot by Ayers, et al.. A fish microrobot was developed by Guo, et al. using ICPF actuator.

In recent years, we have been developing a robotic fish actuated by Lightweight Piezo-Composite Curved Actuator (LIPCA), which produces reasonable actuation force and displacement. In this work, a new actuation mechanism is proposed for improved as thrust and swimming speed. The new model has three main parts: power supply, actuation and linkage system. The power supply includes an 11.1 V battery and Miniaturized Piezoelectric Actuator Driver (MIPAD) which can amplify a low voltage of battery into a high voltage. The actuation system is composed of 4 LIPCAs and the actuators are excited at 300 V peak-to-peaks (Vpp). The linkage system comprises two main components, which are a gear system and a bar system. In comparison with the previous robotic fish model, driving system (actuation system plus linkage system) of the present robotic fish is placed in the vertical direction. So that, cross section of the robot body can look like that of real fish. The fully-assembled robotic fish is 28 cm long, 12 cm high and 7 cm wide.

For purpose of achieving large thrust force, body and/or caudal fin (BCF) movement is mimicked. Experiments have been conducted with a thunniform fin. In this study, the tail beat angle of the robotic fish is estimated by the vector calculus and compared the measured tail beat angle in the air. When the LIPCA is excited by 300 V at 3.1 Hz, the tail beat angle is 115 degree in the air. Besides, the tail beat angle is also measured and compared that of the previous robotic fish in the water. The tail beat angle was increased about 60 percent.

As the LIPCAs are excited at different frequency from 0.6 Hz to 3 Hz, effect of frequency as well as size of caudal fin on thrust force was investigated. The highest average thrust force was 0.01 N at 1.5Hz frequency. Thrust performance is examined by calculating Strouhal number, Froude number and Reynolds number.

The experimental results indicate that, the thrust force of the present robotic fish has been improved and swimming speed is also increased.

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6929-01, Session 1

A study exploring the feasibility of designing an integrated actuator and performance monitoring system using piezoelectric diaphragms

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There are several piezoelectric devices that are used as both actuators and sensors. These include the split-electrode unimorph (Murata) the piezoelectric transformer (Morgan Matroc and APC) and the MFC-S1 (Smart Material). In the current study, a pre-stressed piezoelectric composite diaphragm has been modified to integrate actuation and sensing into a single device for an active flow control synthetic jet application. A PZT wafer is used as an active element of the composite and a PVDF film is used as a sensor. As the diaphragm oscillates forming a pulsating jet, dynamic strain is transferred to the PVDF film. These vibrations create a voltage which can be stored and used to power other small devices and also in monitoring the actions of the active diaphragm. This study is aimed at examining the feasibility of correlating the generated voltage to changes in cavity pressure and jet velocity with the goal of creating an integrated performance monitoring system.

6929-02, Session 1

Extended life PZT stack test fixture

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Piezoelectric stacks are being sought as actuators for precision positioning and deployment of mechanisms in future planetary missions. In addition in some applications the working environment is considered harsh compared to normal terrestrial conditions. These environmental conditions include low and high temperatures in the range of $\pm 200^\circ\text{C}$ and vacuum or high pressure. Additionally, the stacks are subjected to high stress and in some applications a long lifetime expectancy is required. Many of these requirements are beyond the current industry design margins for nominal terrestrial applications. In order to investigate some of the properties and limitations we have developed a new type of test fixture that can be easily integrated in various test chambers for simulating environmental conditions, can provide access for multiple measurements while being exposed to adjustable stress levels. The fixture can be adjusted for testing different dimensions stacks and can be easily used in small or large numbers. The tests that were planned using this fixture include impedance, capacitance, dielectric loss factor, leakage current, displacement, breakdown voltage, and lifetime performance. The fixture characteristics and test capabilities are presented in this paper.

6929-03, Session 1

Determination of effective piezoelectric coefficients of PZT thin films on a substrate

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In microelectromechanical systems (MEMS), a piezoelectric thin film is deposited on a substrate (e.g. silicon). For proper use of the device the material behaviour such as the piezoelectric coefficients has to be known. Because of the clamping of the substrate, the piezoelectric film behaves differently from the pure material. Experiments can determine the piezoelectric coefficient in poling direction very accurately by means of e.g. double beam laser interferometric measurements, but the behaviour in transversal direction is difficult to determine. A simple analytical model

taking into account a rigid wafer is, in the first step, a good approximation. Nevertheless, for the demanded high accuracy in practical use, it is not sufficient.

To improve this simple model, finite element analyses were performed to investigate the behaviour of piezoelectric thin films on a silicon wafer. First, the simple model was verified by means of FEA. After that, instead of a rigid wafer, an elastic one was taken into account. In a parametric study different material properties of the thin film and the substrate were investigated. The obtained results permitted to derive a more complex analytical model for a piezoelectric thin film on a substrate. The proposed model accounts for the elastic layer in order to determine the effective piezoelectric coefficients in any direction. Also, effects on the edges of the electrodes were investigated.

Note that the presented finite element model dealt with a piezoelectric thin film which is completely covered with an electrode. However, in practical use, only several electrode spots are used to apply a voltage to the layer. Therefore, finite element simulations for differently sized spot electrodes were also performed, and a comparison with the results with fully covered electrode was carried out.

6929-04, Session 1

A novel evaluation of piezoelectric coefficient of PZT thin film

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In this paper, we demonstrate a new method to evaluate the piezoelectric coefficient (d_{31}) of piezoelectric thin film. The sol-gel driven lead zirconate titanate (PZT) thin film with large crack-free area is obtained by using a modified conventional fabrication process. The polycrystalline film is spin-coated on Pt/Ti/SiO₂/Si substrate and has a preferential (111) orientation. The method to evaluate the piezoelectric coefficient (d_{31}) of the PZT thin film is based on thin film stress measurement technique. Tencor FLX-2320 film stress measurement system which is a very simple and cheap equipment is used to obtain the wafer curvature information when voltage is applied to PZT thin film on wafer. The stress in thin film is calculated by the obtained wafer curvature. By using the constitutive equation of polarized piezoelectric material, the d_{31} coefficient can be determined from calculated thin film stress and applied voltage.

6929-05, Session 1

The effect of environmental temperature on the performance of piezoelectric transformers

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Over the past few years, different types of piezoelectric transformers (PT) have been widely used in power inverters to drive cold cathode fluorescent lighting (CCFLs). As it stands now, both white light LEDs and CCFLs are perceived to be the two major backlight sources. It is well known that the display quality of flat display panels (FDP) such as LCD-TVs (liquid crystal display televisions) correlates closely with the performance of the backlight module. Since transformers play an important role in backlight module performance and LCD-TVs are sold all around the world, piezoelectric transformers are required to work under different environmental temperatures and conditions. As transformers themselves generate heat during operations, this heat along with the environmental conditions will influence the resonance frequency of piezoelectric transformers, and in turn may affect both the material properties and the overall system power efficiency. This paper examines the achievable power efficiency for Rosen-type, disk-type, center-driven dual-output piezoelectric transformers in detail. More specifically, the range of the resonance frequency shift with respect to temperature changes, which in turn change central driven frequency and the associated efficiency will all be studied. Finally, the relationship between the CCFL and temperatures was investigated with an attempt to explore future product application opportunities.

6929-06, Session 2

Compositional dependence of single-crystal PMN-xPT phase transformations

C. S. Lynch, K. Webber, Georgia Institute of Technology

In collaboration with NUWC, experimental data has been collected on compositions of single crystal PMN-xPT moving away from the morphotropic phase boundary. Experimental results show that there is a compositional dependence on the phase transformation behavior, in addition to the electromechanical coupling.

6929-07, Session 2

Experimental study of the electro-mechanical switching behavior of a piezoelectric stack actuator

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Piezoceramic materials provide excellent electromechanical properties such as high actuation speed, subnanometer resolution, and high forces, which make them very attractive for applications in electromechanics and electrostatic transducers. They are used widely in building smart structures, microelectronics and MEMS applications by utilizing the ceramics as both actuators and sensors. While mostly used as "linear" material there are a number of applications that make use of their non-linear range like nano-positioning translation stages. Most of these devices are driven by purely electrical loading and the performance is limited due to well known piezoceramic characteristics such as hysteresis, rate dependence, temperature dependence, and creep. Piezoelectric actuators are commonly coupled with a spring that introduces stress resulting in electro-mechanical coupling. In order to make more efficient use of piezoceramics, these undesirable characteristics need to be systematically studied and understood.

This paper provides a systematic study of the rate-dependent hysteresis behavior of a commercially available PZT stack actuator. Experiments covering full as well as minor loops are conducted at different loading rates with polarization and strain recorded. In addition, the creep behavior at different constant levels of the electric field is observed. Electro-mechanical behavior was observed while the actuator was spring-loaded under varying pre-stresses and with varying spring stiffness. One observation from these experiments shows that for identical loading paths, minor loop curves change dramatically with an increased loading rate. These rate-dependent observations provide evidence of kinetics being characterized by strongly varying relaxation times that can be associated with different switching mechanisms.

The domain switching process of piezoceramics is believed to result from two successive 90° switches rather than a single 180° switch even for electrically induced switching [1]. The Gibbs free energy will be used to illustrate switching criterion between the different crystal variant orientations. There are several mechanisms that contribute to the switching kinetics that can be seen in the Gibbs energy landscape. These mechanisms will be focused on and used to explain the different phenomenon observed in the experiments. This paper also proposes an electro-mechanically coupled free energy model based on the theory of thermal activation that is capable of representing the rate-dependent kinetics of the switching processes. The physics-based model uses parameters identified from the experimental data to effectively match the actuators characteristics.

1. S. C. Hwang, C. S. Lynch and R. M. McMeeking, Ferroelectric/ferroelastic interactions and a polarization switching model. *Acta Metallurgica et Materialia*, Volume 43, Issue 5, May 1995, Pages 2073-2084

6929-08, Session 2

Multilayer piezoelectric stack actuator characterization

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Future NASA missions are increasingly seeking to perform actuators at precision levels that are as fine as micro and even subnanometer levels.

For this purpose, multilayer piezoelectric stacks are being considered as actuators for driving these precision mechanisms. Sets of commercial PZT stack were tested in various AC and DC conditions at both nominal and extreme temperatures and voltages. AC signal testing included impedance, capacitance and dielectric loss factor of each actuator as a function of the small-signal driving sinusoidal frequency, the ambient temperature. DC signal testing includes leakage current and displacement as a function of the applied DC voltage. The applied DC voltage was increased gradually from zero to over eight times the producers' specifications to assess the correlation between leakage current and breakdown voltage. The extreme temperature testing was done in a thermal chamber at temperatures range of -180C to +200C that exceeds the producers' specifications. In order to study the lifetime performance of these stacks, five actuators were driven by a 60volt, 2kHz sine-wave for ten billion cycles. For this test, an automated data acquisition system was implemented to monitor the harmonic components of each stack's electrical current and voltage waveforms over the life of the test. Periodic spot checks of displacement, impedance, capacitance and leakage current over the life of the test were also performed to assess performance degradation. Analysis of the experimental results will be presented in this presentation.

6929-09, Session 2

Material parameter measurements for ferroelectrics using the partial unloading method

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Motivated by predicting the performance and reliability of piezoelectric devices, considerable research efforts have been made in recent years to mathematically describe the large-signal nonlinear behaviour of ferroelectric piezoceramics. The success of such modelling approach depends strongly on our knowledge of the loading history dependence of the material properties. In this experimental work, the nonlinear ferroelectric and ferroelastic behaviour was investigated in detail for a commercially available soft lead zirconate titanate (PZT) material under low-frequency electric voltage and compressive stress loading. It was found that the material's response was significantly loading rate dependent. The evolution of the dielectric, piezoelectric and elastic moduli was determined using a fast small electric field and stress partial unloading method, which was specially designed to minimize time-dependent effects as much as possible. The results were used to separate the reversible response from the irreversible remanent response due to domain switching.

6929-10, Session 2

Inhomogeneous creep fields in PZT: an experimental study

Q. Liu, Univ. of Cambridge (United Kingdom); J. E. Huber, Univ. of Oxford (United Kingdom)

The technique of birefringence imaging was exploited to observe the evolution of creeping fields (polarisation/strain) in transparent PLZT 8/65/35 samples. PLZT samples with partial surface electrodes were loaded with a constant voltage boundary condition, producing non-uniform electric field. The resulting birefringence contours evolve with time and can be related to charge and strain measurements. At low levels of polarisation (far from saturation) it was found that the principal strain difference has an approximately quadratic dependence on polarisation, and a linear dependence on birefringence magnitude. The patterns of evolving strain and polarisation were modelled using a power law creeping crystal plasticity model which is compared with the optical measurements. The results allow the boundary of the "switching" region to be mapped, and the local polarisation map near an electrode tip is constructed. A good agreement between model and experiment is found.

6929-11, Session 3

Reverse polarization switching in ferroelectric lead zirconate titanate (PZT) thin films

W. S. Oates, Florida State Univ.

The effective utilization ferroelectric thin films requires precise control of the polarization switching behavior. Reliability issues associated with substrate clamping are well known; however, top electrode constraints can have a dramatic effect on polarization retention. A two dimensional phase field model of a ferroelectric capacitor island was numerically implemented using finite elements to predict polarization switching when top and bottom electrode constraints were present. The model is used to show that there is a delicate balance between electrical energy from applied fields and mechanical energy from ferroelastic coupling and electrode residual stress which leads to reverse polarization switching. The phase field model predicts spontaneous reverse switching will occur when a top electrode is approximately the same thickness as the ferroelectric layer. The reverse switching behavior does not occur when the top electrode is infinitesimally thin.

6929-12, Session 3

Finite element simulation of ferroelectrics based on a micromechanical approach

M. Elhadrouz, Ecole Nationale Supérieure d'Arts et Métiers (France)

Ferroelasticity and ferroelectricity are the non linear behaviours exhibited by piezoceramics, especially in the case of high electric field or stress. A micromechanical approach has been adopted to capture domain switching leading to such non linearity. The work affects to the single crystal behaviour is followed by a finite element technique to get the macroscopic behaviour of polycrystalline piezoceramics. It can be achieved through a potential energy like the free energy accounting for the incompatibilities existing between domains and that are induced by the switching process. Thus, the origin of the energy is multiple: elastic, electric but also interfacial due to interactions between domains. In the considered case of a cubic-tetragonal transition through the Curie point, six domains "variants" are defined and connected to the six directions along which the spontaneous polarization may arise. A solid finite element has been developed in the software Abaqus®. It has eight nodes with the mechanical displacement and the electric potential as degree of freedom. Then, an electromechanical constitutive law can be implemented in the code. The influence of the grain properties and the interaction (between grains and domains) are discussed based on the numerical results of the finite element simulation.

6929-13, Session 3

Rate-dependent incremental variational formulation of ferroelectricity

D. Rosato, C. Miehe, Univ. Stuttgart (Germany)

The paper presents continuous and discrete variational formulations for the treatment of the non-linear response of piezoceramics under electrical loading. The point of departure is a general internal variable formulation that determines the hysteretic response of the material as a generalized standard medium in terms of an energy storage and a rate-dependent dissipation function. Consistent with this type of standard dissipative continua, we develop an incremental variational formulation of the coupled electromechanical boundary value problem. We specify the variational formulation for a setting based on a smooth rate-dependent dissipation function which governs the hysteretic response. Such a formulation allows us to reproduce the dielectric and butterfly hysteresis responses characteristic of the ferroelectric materials together with their rate-dependency and to account for macroscopically non-uniform distribution of the polarization in the specimen. An important aspect is the numerical implementation of the coupled problem. The discretization of the two-field problem appears, as a consequence of the proposed incremental variational principle, in a symmetric format. The performance of the proposed methods is demonstrated by means of a spectrum of benchmark problems.

6929-14, Session 3

Micromechanical model of nonlinear relaxor ferroelectric phase transformation

K. Webber, C. S. Lynch, Georgia Institute of Technology

The field driven phase transformation behavior of relaxor ferroelectric single crystals of PZN-xPT is step-like and displays a distinct forward and reverse threshold field whereas the same behavior in PMN-xPT, displays a transformation occurring over a range of field levels. Analogous to the diffuse Curie point in relaxor ferroelectrics being the result of compositional fluctuations at the nanometer length scale, the diffuse field driven transformations in PMN-xPT are modeled as a series of step-like transformation thresholds associated with compositional fluctuations. The results are in excellent agreement with experimental data and suggest an alternative mechanism to that of the transformation occurring by a continuous rotation through a monoclinic phase.

6929-15, Session 3

Oxygen vacancy diffusion, domain switching, and electromechanical behavior of ferroelectric perovskite

J. Li, Univ. of Washington

In this talk, we present our recent work on ferroelectric perovskites, where domain switching is coupled with oxygen vacancy diffusion, leading to profound influence on their macroscopic electromechanical properties. A thermodynamic framework is presented first that couples electro-elastic field with oxygen vacancy distribution, and phase-field simulation is then carried out to study the diffusion of oxygen vacancies and evolution of domain pattern, as well as the resulting electromechanical behaviors. The pinning of domain wall by the oxygen vacancies is observed, and ferroelectric shape memory effect due to the symmetry of oxygen vacancy distribution is simulated.

6929-16, Session 3

Prediction of effective properties of short piezoelectric fiber composites using Eshelby's models

N. Mallik, Univ. of Cincinnati

In this paper, author presents the equivalent inclusion approach to obtain the effective properties of piezoelectric composites viewed as an inclusion in matrix medium. As special case of short fiber, Eshelby's model is applied to continuous fiber composites and results are shown. The geometry of short fiber composite is a three dimensional one. It is assumed that the bond between the matrix and inclusion is perfect, the composite is homogeneous and the materials of matrix and inclusion are linearly elastic. The constant electric field is applied along one of the axes of the coordinate system. The inclusion problem considered consists of ellipsoidal domain of piezoelectric medium inside a composite medium. Piezoelectric domain is subjected to uniform eigenstrain. Matrix domain may be piezoelectric or may not be piezoelectric. The inclusion induces stress fields in both piezoelectric and matrix domains. This inhomogeneous inclusion problem can be considered as the summation of a homogeneous inclusion problem with applied stress and electric field at large distances from inclusion and only a matrix medium with same applied stress and electric field. Until now interaction of one inclusion is considered but for real composites there will be many fiber inclusions measured by fiber volume fraction. For such cases relations can be modified approximately by introducing average strain disturbance arising due to interactions of the different inclusions and which is related to average stress disturbance in the matrix medium. During the whole process only unknown parameter is eigenstrain. Once this parameter is obtained for a particular type of inclusion from Green function approach elastic strain energy of the composite can be obtained. Equating this relation with the similar equation obtained in terms of composite coefficients one can easily obtain composite elastic and piezoelectric coefficients. When one of the dimension of the inclusion become very long compared to other dimensions then the inclusion becomes a long fiber composite. For this case the Eshelby's tensor

becomes zero. The aspect ratio of the inclusion is defined by the ratio of longitudinal length to transverse length. When aspect ratio tends to infinity then the stiffness value of the composite predicts the Voigt upper bound value. It is also observed that this prediction does not depend on the shape and/or size of the transverse parameters of the inclusion. Variation of stiffness coefficient with fiber volume fraction for different finite values of the aspect ratio is also predicted. Those results are superimposed with the result obtained by method of cells approach. It can be observed that long continuous fiber inclusions predict more stiffness values than the flake composites i.e. penny shaped inclusion and spherical shaped inclusions. Lastly, variation of ratio of piezoelectric stress coefficient of the composite to the piezoelectric stress coefficient of the inclusion with fiber volume fraction is demonstrated for different kinds of inclusions. It is observed that the long continuous inclusions provide more values of piezoelectric stress coefficient than the flake type of inclusion like penny shaped inclusion. It is also observed for this case that prediction of the value of piezoelectric stress coefficient for long continuous inclusions does not depend on the cross sectional shape and size of the inclusion.

6929-18, Session 4

Design of a new structural-health monitoring based on piezoelectric sensors for detection of strains of various amplitudes

C. Wakabayashi, M. Taya, H. Sato, Univ. of Washington

Vehicle's components experience large strain during its operations. Monitoring a set of only large strains of the components is adequate under tight power budget for analysis of critical loading. For data of all strain history including smaller amplitudes as a function of time requires huge data storage system which in turn requires large power and communication equipment. Therefore, development of more energy efficient structural health monitoring (SHM) system is increasingly important for assessment of its long term reliability. SHM has two components, one is to record history of large straining during vehicle operation, and the other is to detect any larger damages hidden in a vehicle during or when it is at rest. This study is aimed at the first SHM issue.

The concept of this new SHM is to measure the fatigue properties of piezoelectric sensors that are subjected to a set of loading. In this research, we used cantilever beam made of aluminum (Al) plate on which piezoelectric thin plate is mounted. The Al cantilever beam is subjected to a set of known vibrations by electro-magnetic induction apparatus. Then we measured residual P-E curves of the piezo-sensor at a number of fatigue cycles. It is found that the residual P-E curves of fatigued piezo-sensor exhibit continuous reduction of P-E loops, which provide a useful data set to assess what level of loading that the cantilever beam has experienced.

6929-19, Session 4

Evaluation of the influence of initial residual microfield distributions on the ferroelectroelastic material behavior

A. C. Liskowsky, P. Neumeister, A. S. Semenov, H. Balke, Technische Univ. Dresden (Germany)

Components with nonlinear coupled electromechanical material properties are attaining increasing importance for actuator and sensor applications. For the simulation of the effective behavior of ferroelectroelastic materials, an algorithm based on a micromechanical approach taking into account residual microfields was developed and implemented into a three-dimensional finite element code. An electric vector potential was used in the finite element formulation in order to guarantee positive definite stiffness matrices.

The material model considers nonlinear effects that are rate-independent. Furthermore a tetragonal crystal structure is supposed, which evolves after cooling under the Curie temperature. For the finite element simulation of the polycrystal, each Gauss point represents one multi-domain single crystal. To each single crystal there are assigned the volume fractions of the six possible domains as internal variables as well as an initial lattice

orientation, distributed randomly over the representative volume element. The domain wall motion and therefore the change in the volume fractions are approximated by means of using a critical driving force for the switching. By shaping integral averages over all single crystals, the results are homogenized. In addition their statistic distribution is examined.

Under cooling during the preparation of ferroelectrics there emerge residual electromechanical microfields. They are obtained by direct simulation of the cooling process, where the coefficients of the spontaneous strain and spontaneous polarization are temperature-dependent. Thereafter the influence of the residual microfield distributions on the poling and following load cycles is studied with different types of boundary conditions and loading regimes.

6929-20, Session 4

Experiment investigation for a new type of piezoelectric friction damper

Z. Dahai, H. Li, Dalian Univ. of Technology (China)

A novel type of piezoelectric friction damper is proposed. It mainly includes preload bolt, piezoelectric actuator, load cell, friction sliding plate and a steel box. The force generation of the piezoelectric actuator is tested under different preload forces. Next, the force-deformation performance in passive state is tested on MTS under different frequencies and amplitudes. And then, the hysteresis characteristics are investigated under various frequencies and amplitudes when both linearly increasing voltage signal and preload force are applied on the piezoelectric friction damper. Experimental results indicated that the load-displacement loops of the damper in passive state are nearly rectangular and does not change significantly with the excitation frequencies. The hysteresis loops of the piezoelectric friction damper are stable when applied to the linearly increasing voltage signal, and the force generation of the piezoelectric actuator is fairly well.

6929-21, Session 5

Magnetic and electric-field alignment of cellulose chains for electro-active paper actuator

J. Kim, S. Yun, Y. Chen, S. Lee, H. S. Kim, Inha Univ. (South Korea)

Cellulose-based Electro-Active Paper (EAPap) has been discovered as a smart material for applications of sensors and actuators. EAPap has many advantages in terms of large displacement, low power consumption, light weight, biodegradability and low cost. Since understanding its actuating mechanism, piezoelectric property of EAPap has been investigated due to its structural crystallinity. We expect that alignment of cellulose chains can be an effective method to lead its outstanding piezoelectric property.

In this research, uniaxial alignment of cellulose chains will be investigated by applying magnetic field and electric field. As exposing different field to EAPap samples, the changed characteristics will be analyzed by X-Ray diffractometer, Scanning electron microscopy and Transmission electron microscopy. Finally, the piezoelectric properties of EAPap samples will be evaluated with comparing their piezoelectric charge constant.

6929-22, Session 5

Rotational isomeric state theory applied to the stiffness prediction of an anion polymer electrolyte membrane

F. Gao, L. M. Weiland, Univ. of Pittsburgh

While the acidic polymer electrolyte membrane (PEM) Nafion® has garnered considerable attention, the active response of basic PEMs offers another realm of potential applications. For instance, the basic PEM Selemion® is currently being considered in the development of a CO₂ separation prototype device to be employed in coal power plant flue gas. The mechanical integrity of this material and subsequent effects in active response in this harsh environment will become important in prototype development. A multiscale modeling approach based on rotational isomeric state theory in combination with a Monte Carlo methodology may

be employed to study mechanical integrity. The approach has the potential to be adapted to address property change of any PEM in the presence of foreign species (reinforcing or poisoning), as well as temperature and hydration variations. The conformational characteristics of the Selemion® polymer chain and the cluster morphology in the polymer matrix are considered in the prediction of the stiffness of Selemion® in specific states.

6929-23, Session 5

High-surface area electrodes in ionic polymer transducers: numerical and experimental investigations of the chemo-electric behavior

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Ionomeric polymer transducers have received considerable attention in the past decade due to their ability to generate large bending strain and moderate stress at low applied voltages. Ionic polymer transducers consist of an ionomer, usually Nafion, sandwiched between two electrically conductive electrodes. Recently, a novel fabrication technique denoted as the direct assembly process (DAP) enabled controlled electrode architecture in ionic polymer transducers. A DAP transducer consists of two high surface area electrodes made of uniform distributed particles sandwiching an ionomer membrane. Akle et al (2006) found a correlation between the amount of metal powder and strain response. This finding was supported by Wallmersperger et al (2007) with numerical simulations. Furthermore, it is known that chemo-electrical reactions are occurring at the electrode leading to flux of charges crossing the metal-ionomer interface. In this paper theoretical investigations as well as experimental verifications are performed. The model consists of a convection-diffusion equation describing the chemical field as well as a Poisson equation describing the electrical field. In this paper, the model is solved by applying the Newton-Raphson method using stabilized finite elements in space and time. Additionally, the model incorporates chemical reactions at the electrodes and flux across the metal conductor interface. Boundary conditions with different flux profiles such as constant flux or variable flux over time are attempted. Initial results demonstrate that adding the flux is leading to a change of the local charge distribution in the domain, i.e. especially the charge accumulation at the interface may be reduced. This result could be an explanation for the back relaxation observed in IPTs. Experimental results with several metal particles such as Gold, Platinum, Ruthenium Dioxide, and silver are provided. The electrode architecture is varied and the actuation performance is characterized and compared to the numerically obtained results.

6929-24, Session 5

Fabrication and characterization of piezo-paper made with cellulose

H. S. Kim, S. Yun, J. Kim, G. Y. Yun, J. Kim, Inha Univ. (South Korea)

Cellulose-based Electro-Active Paper (EAPap) has been discovered as a smart material that can be used as a sensor and actuator. Its advantages include low voltage operation, light weight, low power consumption, biodegradability and low cost. EAPap is made with cellulose paper coated with thin electrodes. EAPap shows a reversible and reproducible bending movement as well as longitudinal displacement under electric field. The out-of-plane bending deformation is useful for achieving flapping wings, micro-insect robots, and smart wall papers. On the other hand, in-plane strains, such as extension and contraction of EAPap materials are also promising for artificial muscle applications.

Piezoelectricity is one of major actuating mechanism of a cellulose-based EAPap. The performance of EAPap is sensitive to the fabrication process of cellulose film. Cellulose is a complex anisotropic material. Aligning cellulose fibers in the fabrication process is a critical parameter to improve mechanical and electromechanical properties of EAPap such as stiffness, strength, piezoelectricity and so on. Wet drawn stretching method will be introduced in the fabrication process of cellulose film to increase

piezoelectricity of EAPap and its mechanical and electromechanical properties will be investigated. The final paper will present the possibility of cellulose-based piezo-paper fabricated by wet drawn stretching method.

6929-25, Session 5

Failure characteristics of bilayer lipid membranes formed over hydrophilic and hydrophobic substrates

M. A. Creasy, D. P. Hopkinson, D. J. Leo, Virginia Polytechnic Institute and State Univ.

Phospholipid molecules are the fundamental building blocks of cell membranes in living organisms. These molecules are amphipathic with two hydrophobic fatty acid chains (tails) linked to a phosphate containing hydrophilic group (head) that spontaneously form a bilayer lipid membrane (BLM) with a 4-8 nm thickness in an aqueous solution. Recently, researchers at Virginia Tech have developed a biomimetic micro-hydraulic actuator that pumps fluid across a porous substrate that is coated with a planar BLM with inserted ion transporter proteins. The ion transporter proteins pump fluid through the BLM from a reservoir into a sealed chamber causing an internal pressure increase and chamber deformation. The performance of this actuator is believed to be limited by the strength of the BLM across the porous substrate

For this purpose, a custom test fixture was fabricated to measure the strength of a BLM over a porous substrate. The fixture consists of a stepper motor linear actuator that drives a piston in order to apply pressure to a BLM in very fine increments. The pressure, monitored with a pressure transducer, is observed to increase until the BLM reaches its failure pressure, and then drops. In a previous study 1-Stearoyl-2-Oleoyl-sn-Glycero-3-Phosphocholine (SOPC) phospholipids were used to form micro-BLMs over a commercially available track etched polycarbonate substrate containing an array of many pores with pore sizes ranging from 0.05 = 10 microns in diameter. Mixtures of SOPC and cholesterol were also tested because studies have shown that cholesterol increases the strength of BLMs. Additional studies have been performed where the track etched polycarbonate substrate has been masked except for a single pore. Pore sizes ranging from 5 - 20 microns in diameter were tested and a bilayer lipid membrane was formed over the single pore and pressurized using the aforementioned test apparatus. Also, for some experiments the phospholipid mixtures have been marked using a di-8-ANEPPS fluorescent dye. Using a fluorescence equipped microscope, it was possible to image the BLM before and after pressurization.

For the current study, BLMs were formed over polycarbonate substrates with and without a polyvinylpyrrolidone (PVP) surface treatment. PVP is a wetting agent that can make surfaces hydrophilic. It is believed that the surface properties of the substrate affects the strength of the BLM. Pore sizes ranging from 5 - 20 microns in diameter were tested for PVP and PVP-free substrates. The same test apparatus of the previous experiments were used for this study with SOPC and a mixture of SOPC and cholesterol. As before, for some of the experiments the phospholipid mixtures have been marked with the same fluorescent dye to image the BLM before and after pressurization.

6929-28, Session 6

Effective material properties of MWCNT-coated carbon-fiber composites

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In this work MWCNT coated carbon fiber composites are assessed for multi-functionality through the use of continuum based micromechanics modeling techniques. The MWCNT coated carbon fiber composites investigated in this work consist of carbon fiber/epoxy lamina with thin annular interphase regions surrounding the carbon fibers. The interphase regions consist of MWCNTs imbedded within the bulk matrix material. Effective mechanical (elastic), thermal and electrical properties of the bulk composite are evaluated using the Mori-Tanaka, composite cylinders and generalized self-consistent methods. The effect on bulk effective properties of MWCNT volume fraction, alignment direction and length within the interphase regions are investigated. Numerical results obtained from the micromechanical analysis indicate that interphase coatings can

provide considerable enhancements to the overall mechanical, thermal and electrical properties of the bulk composite at low MWCNT weight percents.

6929-29, Session 6

Self-sensing and self-actuating CFRP structure using partially flexible composites

K. Kumagai, A. Todoroki, R. Matsuzaki, Tokyo Institute of Technology (Japan)

For Unmanned Aerial Vehicles (UAV), a Morphing wing is desired to improve the maneuverability and reduce the total weight of structures. It enables the aircraft to change its standard performance. Our research group has developed a foldable composite structure for a morphing wing skin plate by using Carbon Fiber Reinforced Plastics (CFRP). Its material system employs two kinds of matrices; normal thermoset resin like epoxy for most of the structure and silicon rubber for the fold line. The material system is called Partially Flexible Composites (PFC). The PFC can be folded in a small load very easily. Since the carbon fibers are continuous throughout the structures, the PFC has perfect stiffness and strength except for the fold line. In this paper, a self-sensing system and a self-actuating system of the PFC are confirmed.

Firstly, a self-sensing system of the PFC is investigated. Since carbon fibers have electrical conductivity, damages of the PFC can be detected by monitoring electrical resistance changes of the PFC. This method has been proved by our research group, and it is called Electrical Resistance Changes Method (ERCM). An electrical resistance model of the PFC is built and a relationship of ratio of fiber fractures and electrical resistance changes is obtained. A property of this relationship is proved experimentally. Then, to investigate the performance of the PFC, cyclic-bending tests are conducted. In the experiment, two kinds of specimens with 2mm-long and 10mm-long flexible part are used. Damages of the PFC caused by cyclic-bending are detected by using ERCM. At the results of the experiment, the PFC with more than 10mm-long flexible part has almost no damage and it can maintain its stiffness and has the strength to apply actual structures.

Secondly, a self-actuating system of the PFC is confirmed. A McKibben pneumatic artificial muscles actuator is applied to an actuator of the PFC. This actuator generally consists of an inflatable internal bladder made of a rubber material and an exterior braided shell that is a flexible and non-extensible thread. These materials are attached at either end to fittings. When the high-pressure gas is passed into the internal bladder, it tends to increase its volume. Due to the external non-extensible thread, however, the actuator shortens according to its volume increase. Then the actuator produces tension, if it is coupled to a mechanical load. In this study, a silicon rubber is used as an inner material and a carbon fiber is used as an exterior material. These materials are the same as the materials of flexible part of the PFC. The actuator can be built into the flexible part of the PFC, and the PFC shape is deformed according to the tension produced by the actuator. Therefore, the flexible part of the PFC has functions as a fold line and as an actuator.

As the results of this study, it is confirmed that the PFC has functions as a self-sensing and a self-actuating system due to the carbon fiber's electrical conductivity and the material of flexible part.

6929-86, Session 6

Fatigue characteristics of carbon-nanotube blocks under compression

J. Suhr, Univ. of Nevada/Reno

Structural components subjected to cyclic stress can succumb to fatigue and fail at stress levels much lower than under static load. The fatigue behavior in CNT structures has never been reported, albeit its importance in devices incorporating CNT components. Here, this work report vertically aligned MWCNT under cyclic compressions, exhibit viscoelastic behavior similar to that observed in soft-tissue membranes. Under the compression, the mechanical response of the CNT arrays shows preconditioning, hysteresis, nonlinear elasticity and stress relaxation, and large deformations. Furthermore, no fatigue failure is observed even at high strain amplitudes up to half million cycles. The outstanding fatigue

resistance and extraordinary soft-tissue like behavior suggest properly engineered CNT structures could mimic artificial tissues, and their added high electrical conductivity could make them excellent candidates for use as multifunctional material systems.

6929-90, Session 6

Calculation of electromagnetic material parameters for uniaxial bianisotropic composite materials through numerical simulation

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Through the use of conductive straight wires or coils the electromagnetic properties of a composite material can be modified. The asymmetric geometry of the coils creates an overall chiral response. Therefore, the polarization vectors rotate as an electromagnetic wave travels through such a medium. We present some methods on how to eliminate the chirality effect. To calculate the chirality of a medium prior to its manufacturing, we developed a method to extract all the electromagnetic material parameters, including chirality, for a general uniaxial bianisotropic structure. Our method uses appropriate line and surface field averages for a single unit cell of the composite periodic structure, following the method proposed by Pendry. These overall field quantities have physical meaning only when the microscopic variation of the electromagnetic quantities in the scale of the unit cell is not important, that is when the wavelength of interest is significantly larger than the maximum linear dimension of the unit cell. The overall constitutive relations of the periodic structure can then be obtained from the relations among the average quantities. We have applied this method to a number of chiral and non-chiral structures, and established that the results are in close agreement with previous work.

6929-91, Session 6

Electric field-assisted processing of nanocomposites: a route toward developing multifunctional polymers

S. Banda, S. Kalidindi, Z. Ounaies, Texas A&M Univ.

Polymer-based materials are widely used in aerospace industry due to their many advantages such as low density coupled with relatively high specific strength and specific stiffness, and good manufacturability. This unique combination of characteristics motivated their use in military, commercial aircrafts and spacecrafts. Recent research is directed at improving their energy absorbing ability and their toughness, as well as increasing their electrical properties. One approach is to modify the composites through addition of nanoparticles; the performance of the resulting multiscale-reinforced composites is affected by dispersion and position of nanoparticles in the polymer matrix. This study demonstrates the possibility to spatially manipulate nanoparticles (single wall carbon nanotubes are used as model nanoparticles) using an electric field in two classes of polymers (photocurable and thermocurable matrix), and we assess the impact of orientation on electrical and mechanical properties. Ultimate goal is that optimization of mechanical and electrical contrast throughout the material will enhance the active response, hence imparting added functionalities to the composite.

We will accomplish this goal by focusing on four research tasks: 1. achieving efficient dispersion of SWNTs in liquid polymer solutions; 2. analyzing in-situ alignment of SWNTs in liquid polymers under electric field; 3. processing solid patterned nanocomposites; and 4. characterizing their electrical and mechanical properties. In both polymer systems, we use combination of ultrasonication and mechanical stirring to promote dispersion of SWNTs. Optical microscopy(OM) and scanning electron microscopy are used to assess the quality of dispersion and determine agglomerate sizes in polymers. In both cases, there is uniform dispersion of SWNT bundles, with most bundle sizes around $\sim 1\mu\text{m}$. In the next step, an electric field is applied to the SWNT-liquid polymer suspensions and the resulting microstructure is monitored by in-situ optical microscopy as a function of field frequency, magnitude and duration. Solution of 0.03wt% SWNT-urethane dimethacrylate liquid polymer is subjected to an external ac electric field of 100V/mm at frequencies ranging from 1Hz to 25MHz for duration of 30 minutes. Anisotropic SWNT bundles rotate in the direction

of electric field at all frequencies in ~1minute with no further change in microstructure even after 30 minutes. Electric field magnitude is increased to 300V/mm where we observe nanotube bundles again rotating in the direction of electric field and subsequently attract towards each other forming long chains in between the electrodes (Figure1).

In general, when a particle is under the influence of electric field, electrokinetic forces such as electrophoresis, electroosmosis, and dielectrophoresis are experienced by the particle. As a consequence, particle can undergo either rotation, translation or rotation and translation simultaneously. Rotation occurs as the anisotropic SWNT bundle is polarized when an electric field is applied and the polarizability along long axis is greater due to anisotropy, which induces a torque and the particle rotates in the direction of electric field. Chaining of SWNT bundles is due to dielectrophoresis, which results in translation of the particles. Dielectrophoretic force on a particle is . Both and are dependent on electric field(E), dielectric constant of medium and particle, volume(V), length(l) and radius(r) of the particle. Displacement of SWNTs in urethane polymer due to different forces is estimated. Displacement due to gravity is 10-11m, Brownian is 10-8m and dielectrophoresis at 100V/mm is 10-9m and at 300V/mm is 10-7m. Dielectrophoresis at 300 V/mm clearly overcomes gravity and Brownian, but at 100V/mm Brownian is dominant, which is the reason for the absence of chains.

OM images at 300V/mm, different frequencies and times are shown in Figure1. The density of the chains increase as the frequency is increased from 1Hz-25kHz. Chains start to interact laterally as the duration of applied electric field increases from 0-30 minutes. In-situ electrical and dielectric properties are measured after alignment in the liquid state. After 30 minutes the dielectric constant and conductivity increases as frequency of alignment increases from 1Hz-25kHz. Dielectric constant increased from 26 at 1Hz to 330 at 25kHz and conductivity increased from 10-8S/m at 1Hz to 10-5S/m at 25kHz.

In the next task, parameters identified by in-situ study are used to prepare solid aligned SWNT-polymer composites. 300V/mm at a frequency of 10Hz, 100Hz and 1kHz is applied to align SWNTs in urethane dimethacrylate system (photocurable) and in epoxy polymer (thermocurable). Polymer curing is started after the electric field is applied for 30 minutes, curing immobilizes the aligned network.

The final task is to characterize SWNT alignment. Raman spectroscopy is used to quantify SWNT alignment in polymers. An orientation distribution function(ODF) based on Raman data quantifies alignment at 10Hz and 1kHz. ODF shows that the probability of finding SWNTs between 0° and 30° is greater at 1kHz compared to 10Hz, 0° being the electric field axis. Dielectric constant is measured as a function of frequency in two directions, parallel and perpendicular alignment (Figure2). There are two different regions, one that is constant with frequency and other dependent on frequency. Random and all aligned samples have similar dielectric constant in perpendicular direction, and it is constant with frequency, indicative of an insulating behavior. Increasing alignment frequency from 10Hz to 1kHz increases parallel dielectric constant from 45 to 420. Also parallel dielectric constant of 10Hz and 100Hz is constant with frequency showing insulating behavior, but for 1 kHz parallel dielectric constant is dependent on frequency indicating conductive behavior. This indicates that percolation threshold can be controlled by applying an ac electric field and changing frequency. Similar results are observed when comparing storage modulus in the parallel and perpendicular direction 300v/mm, 100Hz, 1kHz condition; Storage modulus in the parallel direction is 60% greater than perpendicular direction.

In this study, we illustrated the use of ac electric field to control nanoparticle distribution in polymers, and quantified the effect of electric field parameters on orientation. We also showed that the resulting anisotropy in electrical and mechanical properties parallels that of morphology. Comparing random and field-tailored polymer nanocomposites allows us to quantify the relationship between processing parameters, morphology, and physical properties. Finally, in future work, we will show that tailoring electrical and mechanical properties of nanocomposites can induce sensing/actuation behavior, leading to multifunctionality in the composite system.

6929-31, Session 7

Fatigue behavior of glass fiber-epoxy laminates with embedded SHM sensors

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The main objective of this experimental research is to examine the effects of stress concentration due to embedded Structural Health Monitoring (SHM) sensors on the fatigue life of unidirectional glass fiber/epoxy laminates.

Damage induced by local stress concentration values around embedded devices is of main concern in smart materials manufacture and technology. The overall structural performance, such as strength and fatigue life, of a composite component in fact, needs to be carefully analyzed when a self-sensing diagnostic capability is added to the material. Although their small size achieved by the recent advancement in sensors technology, actuators and devices embedded within brittle polymeric matrix may cause precocious localized cracks growth that progressively propagate degrading the nearby material and leading to the overall failure.

To examine the tension-tension fatigue behavior and fatigue life of the smart composite under study, we fabricated a series of samples with and without embedded (dummy) sensors and micro-processors made of S2 glass fiber/epoxy. Afterwards, fatigue tests have been conducted at the constant frequency of 1 Hz and stress ratio $R=0.05$. S-N diagrams have been constructed for the material with and without embedded implants.

The low cycle fatigue tests have been also continuously monitored by the acoustic emission technique. In this manner we have also examined the process of damage initiation and evolution within the material with and without implants.

6929-32, Session 7

Mechanical damping and acoustic performance of multifunctional aluminium foam

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The mechanical damping and acoustic performance of multi functional stabilized aluminium foam has been studied. The foam was further processed, from it's as received closed cell structure using hole drilling techniques to produce an open cell structure for use in vibroacoustic automotive applications. Opening the cell structure allows air travel through the foam, thus improving acoustic absorption. The study analyzes the affect thickness, hole size and spacing have on mechanical damping and acoustic performance. An ASTM E 756 vibrating beam setup was assembled to measure the damping loss factor of aluminium foam beam samples for the study and the sound absorption measurements were conducted using an ASTM E 1050 impedance tube. Mechanical testing was conducted to quantify the reduction in stiffness and strength of aluminium foam with holes drilled. Finally, optimal parameters for use in stiff automotive panel applications are identified.

6929-33, Session 7

Three-dimensional FEA simulation of segmented reinforcement variable stiffness composites

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Reconfigurable and morphing structures have the potential to significantly improve overall platform performance through optimization over broad operating conditions. The realization of this concept requires structures that can accommodate the large deformations necessary with modest weight and strength penalties. Other studies have suggested morphing structures need new materials to realize the overall system benefits. To help meet this need, we have developed novel composite materials based on specially designed segmented reinforcement and shape memory polymer matrices that provide unique combinations of deformation and stiffness properties. To tailor and optimize the design and fabrication of these materials for particular structural applications, one must

understand the envelope of morphing material properties as a function of microstructural architecture and constituent properties. Here we extend our previous simulations of these materials by using 3D models to predict stiffness and deformation properties in variable stiffness segmented composite materials. To understand the effect of various geometry tradeoffs and constituent properties on the elastic stiffness in both the high and low stiffness states, we have performed a trade study using a commercial FEM analysis package. The modulus tensor is constructed and deformation properties are computed from representative volume elements (RVE) in which all (6) basic loading conditions are applied. Our test matrix consisted of four composite RVE geometries modeled using combinations of 5 SMP and 3 reinforcement elastic moduli. Effective composite stiffness and deformation results confirm earlier evidence of the essential performance tradeoffs of reduced stiffness for increasing reversible strain accommodation with especially heavy dependencies on matrix modulus and microstructural architecture. Furthermore, our results show these laminar materials are generally orthotropic and indicate that previous calculations of matrix gap and interlaminar strains based on kinematic approximations are accurate to within 10-20% for many material systems. We compare these models with experimental results for a narrow geometry and material set to show the accuracy of the models as compared to physical materials. Our simulations indicate that improved shape memory polymer materials could enable a composite material that can accommodate ~30% strain with a cold state stiffness of ~30GPa. This would improve the current state of the art 5-10x and significantly reduce the weight and stiffness costs of using a morphing component.

6929-34, Session 7

Quantitative assessment of microcrack healing in polymer composites

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We have produced glass and carbon fiber-reinforced composites using 2MEP4F healable polymer whose healing capability has been established and reported before (Plaisted and Nemat-Nasser 2007, "Quantitative Evaluation of Fracture, Healing and Re-Healing of a Reversibly Cross-Linked Polymer" Acta Mat, accepted). In the present work, we have demonstrated the ability of this thermally-reversible cross-linked polymer to heal microcracks in fiber-reinforced composites. We have introduced into the composites microcracks by cryogenic cycling in liquid nitrogen. The microcracks reduced the modulus of the composites, as measured using a Dynamic Mechanical Thermal Analyzer (DMTA). Heating the laminate with pressure applied normal to transverse microcracks appeared to repair the cracks, leading to the stiffness recovery. This was also confirmed through optical micrographs.

6929-35, Session 7

Wave dispersion in cellular composite with modulated microstructure

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Cellular composite has interesting properties, especially wave dispersion and acoustic localization due to modulation in microstructures and patterned cavities/voids. One can suppress/transform the propagating wave to a damped/evanescent wave. Here we consider a beam with stiffness modulation.

Although, such a problem has been studied previously in published literature, the details of microstructure design issues and physics based realization of the problem is less attended. With this view, we construct a cell-wall mechanics based approach to phenomenological constitutive modeling and a wavelength-scale homogenization scheme within the Hamiltonian framework. We obtain a relation for critical frequency (stop-band frequencies) as functions of microstructure properties. Numerical simulations show repetitive stop bands. Effects of various parameters such as thickness, stiffness modulation coefficient (a homogenized quantity) and frequency on the in-plane and shear impedances are analyzed. Experiments using honeycomb composite with polymer filled patterns are reported.

6929-36, Session 7

Meso- and nano-scale techniques for self-healing wire and cable insulation

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The breakdown of dielectric insulation in electrical wire and cable assemblies is a major source of accidents, failures and maintenance costs in modern engineered systems. This paper will discuss the results of an effort aimed at developing wire and cable insulation with self-healing capabilities. The potential promise for such active material systems is that many instances of damage due to abrasion, cracking, arc-tracking and possibly hydrolysis can be corrected autonomously with self-healing materials and material systems. High-performance systems, such as aircraft, may gain particular benefit from this family of technologies. At the meso scale, foaming, multireagent mixing, and microvascular techniques can have the potential to recover from some gross forms of damage. At the nano scale, specialized polymers can effect self-healing in response to microcracks. While a variety of techniques are viable, at room temperature and in benchtop conditions, the wide temperature and environmental ranges encountered in aerospace applications limit the range of viable techniques. A further constraint is insertion into existing manufacturing bases. Results from experimental measurements and numerical simulations will be presented along with recommendations as to which techniques are best suited for particular applications and manufacturing processes.

6929-37, Session 7

Piezoresistance property of cement-based composites filled with carbon black: theoretical model and experimental results

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Cement-based composites filled with carbon black (CB) were prepared in this paper, the volume concentration of CB was near threshold of percolation and the conduct mechanism of the composites was dominated by tunneling effect theory. Piezoresistance properties of the composite were investigated under longitudinal pressure and transverse pressure.

The size of specimen was 30_40_50mm. DC electrical resistance measurement was made in the longitudinal axis, using the four-probe method. Compressive testing was performed on a 30_40mm side of each specimen (longitudinal pressure) and on a 40_50mm side of each specimen (transverse pressure), respectively. During loading process, DC electrical resistance measurement was simultaneously made. A linear relationship between the fractional change in resistance and compressive strain was observed for both longitudinal pressure and transverse pressure, suggesting that the resistance change of composites was not only related to the strain parallel to the direction of resistance measurement, but was multiaxial stress dependent. To investigate the origin of piezoresistance under multiaxial stress and improve the applying of the composite as a strain sensor in real engineering, a model has been developed to predict the piezoresistivity under multiaxial stress.

According to tunneling effect theory, the resistance between CB particles was exponential function of the length of separation between adjacent CB particles (s), therefore, it was important to determine the relation between the change of s and the strain of composite. Based on the SEM pictures of the microstructures, it was found that the conducting chain was composed of separations of various directions, therefore, change of s was relative to the direction of separation and the strain of each axial. Then, based on the tunneling effect theory and the assumption of uniform distribution in direction of the separation, a model was proposed to interpret the piezoresistance property.

The influences of strain amplitude, strain direction, poisson ratio were discussed with this model. The model indicated that the piezoresistance of composites was multi-stress dependent, not only refer to the stress parallel to the direction of resistance measurement. With this model, the strain gauge factor under complex stress could be calculated, which should not be calibrated by test because of complexity. The theoretical data obtained from the model agreed well with the experimental ones.

Also, the predicted results of this model agreed with the experimental results of early studies on polymer-based composites, for example, the predicted results showed that when applied uniaxial compressive strain on composite, the resistance decreased with strain at first, then turned to increase with further increase in compressive strain, this prediction was supported by the experimental results of early studies by others.

6929-30, Poster Session

Nanofillers for property enhancement of polymer composites

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Nano fillers in general are considered to be highly potential fillers to improve the material properties of polymers generally used in composites. However, questions concerning incorporation of these materials in fiber-polymer composites with new processing techniques, selection of fillers, dispersion of fillers, chemical modifications and quantity optimization are still to be answered. First part of the study focuses on processing of nano silica filled epoxy resin blends. The second part discusses hydroxyl and amino functionalization of MWCNTs and their blending in epoxy resins. Influence of addition of nano materials on flow properties are investigated using rheology. Modified resins thus produced are used for processing on glass epoxy composites by Resin Film Infusion (RFI) technique. The nano filler modified composites exhibit enhanced mechanical properties and even more importantly, a significantly higher T_g.

6929-59, Poster Session

A thermo-magneto-mechanical free energy model for NiMnGa single-crystal thin films

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Research conducted during the last decade has shown NiMnGa and similar ferromagnetic shape memory alloys to be capable of generating large strokes - comparable to those of conventional shape memory alloys - under the application of a magnetic field. Unlike conventional SMAs, however, these materials are also capable of high actuation frequencies. This gives ferromagnetic shape memory alloys promise as the basis for actuators, particularly in MEMS where the force output of the materials significantly exceeds that of conventional electromechanical actuators of comparable size. The necessary inclusion of electromagnets capable of generating the required magnetic fields, however, typically makes actuators utilizing the magnetic shape memory effect difficult to miniaturize. Recently, however, Kohl, et al. [1], have proposed a thin-film actuator design that avoids this difficulty by utilizing a small permanent magnet and the conventional temperature-induced shape memory effect also present in ferromagnetic shape memory alloys.

Although a number of models exist that successfully reproduce the magnetic shape memory effect for FSMA's such as NiMnGa, few, if any, simulate the behavior of the material as it transitions to austenite and paramagnetism with increasing temperature. Additionally, few of the current models have been directed toward thin-film configurations, in which actuation is achieved by applying a magnetic field parallel to a tensile bias stress.

This paper discusses the authors' thermo-magneto-mechanical model for NiMnGa and its application to the tensile-stress regime. In the model, a Helmholtz free-energy landscape is constructed for meso-scale lattice elements with temperature, strain, and magnetization as order parameters. The landscape includes energy wells representing the two easy-axis and one hard-axis martensite variants and three austenite variants that are distinguishable in the chosen two-dimensional coordinate system. Phase transformations resulting from temperature changes and applied stresses and magnetic fields follow from a system of evolution laws based on the Gibbs free energy equations and the theory of thermally-activated processes. The relevant phase fractions are then used to determine the macroscopic strain and magnetization of a sample of NiMnGa by a standard averaging procedure. Temperature evolution of the sample follows from an energy balance equation, incorporating joule heating, heat transfer with the environment, and latent heats of transformation between

martensite and austenite. Results for a collinear stress-field configuration under varying temperature are presented.

The paper will demonstrate that the model is capable of reproducing many of the constitutive effects observed in NiMnGa including the conventional and magnetic shape memory effects and the transition of the material from ferro- to paramagnetism. It will show the predicted behavior of the material when temperature is gradually increased from room temperature to the austenite finish temperature and then to the Curie temperature. It will also show predictions for a collinear stress-field configuration, relevant to thin films.

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6929-77, Poster Session

Effects of electric field and poling on the response of multilayer piezoelectric film actuators with partial electrodes

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Piezoelectric bulk ceramic materials or thin films play a significant role as active electronic components in many areas of science and technology, such as smart and MEMS devices. In some actuator applications, high values of stress and electric field arise in the neighborhood of an electrode tip in piezoelectric multilayer actuators [1] and disk composites [2], and the field concentrations can result in electromechanical degradation. One of the limitations for practical use of piezoelectric bulk ceramic materials or thin films is also their nonlinear behavior, which occurs due to polarization switching and/or domain wall motion at high electromechanical field levels near the electrode tip. In order to optimize the performance of the advanced piezoelectric products and devices, it is essential to understand the electromechanical field concentrations due to electrodes in multilayer piezoelectric film actuators.

The main aim of this work is to evaluate the electromechanical fields in the neighborhood of surface and internal electrodes in multilayer piezoelectric film actuators. Actuators are fabricated using poled or unpoled piezoelectric layers. For the unpoled multilayer piezoelectric actuators, each grain has a random polarization. A nonlinear finite element analysis is performed to calculate the strain, stress, electric field and electric displacement by introducing models for polarization switching in local areas of the field concentrations. Displacement measurements are also presented to validate the predictions using a four layered piezoelectric actuator. A comparison of displacement is made between measurements and calculations, and a nonlinear behavior induced by localized polarization switching is discussed. The electric-field-induced displacement and polarization switching zone near the electrodes are further predicted for some electrode configurations in the multilayer piezoelectric film actuators.

References

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6929-78, Poster Session

The electrorheological responses and dielectrophoresis force of elastomers at various temperatures

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An electroactive polymer is a well known material for using in various applications such as actuators, MEMS, and artificial muscle. In our work, we investigated the electrorheological responses and the dielectrophoresis force of several elastomers as functions of electric field strength and

temperature. Within the temperature range between 300-370 K, the storage and loss moduli, storage modulus responses and storage modulus sensitivities of all elastomers were investigated under applied electric field strength varying from 0 to 2 kV/mm. The acrylic elastomers (AR70, AR71, and AR72) have positive storage modulus responses and sensitivities with increasing temperature and dielectric constant. In the case of styrene copolymers (SAR, SBS, and SIS), the storage modulus responses and sensitivities increase and attain the maximum at the glass transition temperature of the hard segment. We studied the dielectrophoresis forces of all elastomers by measuring the strain responses of specimens in a deflection mode under various electric field strengths. The strain responses and the dielectrophoresis forces increase linearly with increasing electric field strength.

6929-79, Poster Session

Characterization of piezoelectric materials at high-stress levels using electrical impedance analysis

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Mathematical and finite element modelling tools are becoming central to an early prediction of transducer performance, due to the fact they are substantially cheaper than the production and evaluation of a working prototype. However, an accurate model's prediction is highly dependent on precise materials data and transducer designers have suggested that a discrepancy exists between predictions and measured transducer performance. Piezoelectrics are the active material of choice in a wide range of applications including Sonar, sonochemistry, destructive ultrasonics and non-destructive evaluation. Therefore, accurate materials data about the piezoelectric is of paramount importance. Manufacturers publish piezoelectric material data, but these figures are invariably acquired at very low electric fields, under no bias stress or at low frequency. Piezoelectric materials have only a moderate strain, which means they must be operated at high electric fields and at their mechanical resonant frequency to achieve greater output power. This electric field causes high internal stresses. Due to the fact that ceramics are prone to fracturing if in tension, they must therefore be driven under a large pre-stress. Clearly, it is critical to have material data relevant to these operating conditions.

In this paper, the development of a new technique which facilitates the characterisation of piezoelectric materials over a wide range of operating stresses (0 -140MPa) at their resonant frequency and with the facility of applying high electric fields is described. The measured material properties exhibit substantial variation with stress and demonstrate the importance of characterising piezoelectric materials under realistic operating conditions. Using this derived data, a more informed evaluation of transducer materials and more accurate predictions of transducer performance can be made.

6929-80, Poster Session

Poly(ethylene oxide)- poly(ethylene glycol) blended cellulose electroactive paper

J. Kim, S. K. Mahadeva, J. Nayak, Inha Univ. (South Korea)

Cellulose based Electro-Active Paper (EAPap) has been reported as a smart material that can be used as sensor and actuator materials. It has merits in terms of lightweight, dry condition, biodegradability, sustainability, large displacement output and low actuation voltage. The actuation principle of EAPap is a combination of piezoelectric effect and ion migration effect. However, the actuator performance of cellulose based EAPap is sensitive to humidity level. Thus, we attempt to develop an EAPap of which its actuator performance is less sensitive to humidity level. This paper will describe the preparation of Poly (ethylene oxide) - Poly (ethylene glycol) [PEO - PEG] cellulose blend films. The interaction between cellulose and PEO - PEG will be studied by means of scanning electron microscope and infrared spectroscopy. The potential applications of PEO-PEG cellulose blend film, as an actuator will be demonstrated by testing the actuator performance in terms of bending displacement, blocked force, power consumption and power output with respect to actuation voltage, frequency and humidity level.

6929-81, Poster Session

Research on natural characteristics of magnetostrictive actuators

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Abstract: For rare-earth alloys such as Terfenol-D(Tb_{0.3}Dy_{0.7}Fe_{1.9}), the generated strains and forces are sufficiently large to prove advantageous in actuator design. Due to these capacities, magnetostrictive actuators have been widely applied in active vibration isolation system of thick structure and heavy industrial machinery, not only as active components but also as support elements. Accordingly, structural natural characteristics of magnetostrictive actuators play an important role in the whole smart structure system.

Generally, structural dynamics of magnetostrictive actuators are modeled by force balancing, which yield a wave equation or kinematics differential equation. When the actuators are applied in high input frequency and heavy load conditions, the stress and the magnetic field on the Terfenol-D rod will change greatly. As one of the coefficients of the equation, the Young's modulus of a Terfenol-D rod is not a constant, because it changes with the stress and the magnetic field nonlinearly, which is called the ΔE effect. Obviously, the variability of Young's modulus (ΔE effect) in Terfenol-D has a significant impact on the performance and natural characteristics of magnetostrictive actuators. However, Young's modulus of Terfenol-D is always treated as a constant in many existed models.

In this paper, stress-strain relationship in Terfenol-D under different stress and magnetic field is characterized through quasi-static compressive stress testing, and Young's modulus is acquired under controlled magnetic field and stress conditions. The results demonstrate that Young's modulus of Terfenol-D changes from the variation of applied magnetic fields(H) and stress (σ). Three dimensional graphs of E (H, σ) are pictured. ΔE effect is introduced in structural dynamics of magnetostrictive actuators, and a nonconstant coefficient differential dynamics equation is founded, which can be solved by use of step-iterative algorithm for Hermite interpolation. Then more accurate natural frequency of actuators can be obtained by theory methods. Numerical simulations are operated in virtue of the finite element commercial software(Ansys) and modal experimental investigation are also conducted. The experimental results and that of simulation and theory methods are given and in good qualitative agreement with each other. The acquirement of natural characteristics of magnetostrictive actuators is helpful to know the whole smart structure dynamics characteristics, and can provide useful conclusion for control bandwidth design,

6929-82, Poster Session

Characterization of the actuator behavior of blended-system ferrogels

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A ferrogel is a highly pliant smart material activated by a magnetic field. Generally, these materials are synthesized by adding a magnetic powder filler to a matrix material of either Polyvinyl Alcohol (PVA) or gelatin which is then cross-linked. The optimization of the ferrogels for specific applications has been hindered by limitations of the matrix materials. For example, PVA has poor solubility of emulsion limiting the amount of water retention while the narrow temperature range over which gelatin can be used limits its applicability. This paper introduces ferrogels with a blended PVA-Gelatin matrix which has been shown in standard hydrogel applications to overcome some of the limitations of single matrix systems. The actuator behavior of these materials will be studied. Specifically, the magnetically activated strain under load will be measured for a variety of dead loads and the both free strain and blocked load will be identified. The dependence of this material's actuator behavior on (a) PVA-Gelatin proportions, (b) magnetic filler volume percent and (c) cross-linking method will be determined in order to develop the knowledge base necessary to optimize these materials for a variety of applications. Changing the proportions of PVA and Gelatin in the blended system is expected to result in control over the tradeoffs between the limitations of the two base systems allowing the material to be customized for specific behaviors. As the volume percent of magnetic filler is increased the sensitivity of the material to a magnetic field is expected to increase. However, an optimal value will be identified above with the benefits are counteracted by problems bonding the filler material into the PVA-Gelatin matrix. Finally, the effect of cross-linking

on the actuator behavior of ferrogels will be studied by examining both physical and chemical cross-linking methods and combinations thereof. Physical cross-linking is achieved by submitting the ferrogels to a series of Freeze-Thaw-Cycles (FTC) which crystallize portions of the gel and cause cross-linking between the molecular chains. This process is generally time consuming as it may involve many cycles. Chemical cross-linking involves the addition of Glutaraldehyde (GA) groups which is a faster process but the toxicity of GA limits the biocompatibility of the ferrogel for biomedical applications. This paper will investigate the effects of a variety of cross-linking methods looking at number of cycles, speed, and temperatures for the FTC as well as amount GA and will present results for blended methods involving a combination of physical and chemical cross-linking. The overall goal of this work is the improvement of the actuator behavior of ferrogels through the use of a blended PVA-Gelatin matrix material and a blended FTC-GA cross-linking technique. The experimental characterization of such ferrogels is presented here.

6929-83, Poster Session

Coupled electromechanical behavior of an interface electrode in a piezoelectric layer

B. Wang, Y. Mai, The Univ. of Sydney (Australia)

This paper considers an interface electrode in a layered piezoelectric medium of finite thickness. Closed-form expressions for the electromechanical fields at the electrode tip are obtained in terms of the applied electric field intensity factor. Effect of the layer thickness on the electrode tip fields is studied. The values of the electric field intensity factor are obtained exactly for infinite layer thickness and numerically for finite layer thickness. Effects of layer thickness on the stress, electric displacement, and electric field are graphically shown. It is found that the electromechanical intensity factors at the electrode tip can be reduced considerably by decreasing the thickness of the piezoelectric layer. The paper also provides a solution for two identical and collinear interface electrodes in the piezoelectric medium. It is observed that relative distance between the electrodes has a pronounced effect on the electromechanical field in the piezoelectric layer.

6929-84, Poster Session

Effect of electric field on effective electromechanical properties of two-phase piezoelectric composites

N. Mallik, Univ. of Cincinnati

A two phase piezoelectric composites with 1-1 connectivity is considered. It is assumed that the proposed composite is a homogeneous, the fibers are continuous, parallel and are oriented longitudinally. The fibers are rectangular parallelepiped type. It is also assumed that the materials of the fiber and matrix are linearly elastic. In general, the micromechanical analysis is confined to a representative volume that includes both fiber and the surrounding matrix. The micromechanics model of 1-1 composites is derived employing the strength of materials approach. It can be assumed that no slippage occurs at the fiber-matrix interface during longitudinal mode of deformation. This implies the existence of perfect bonding between the fiber and matrix. Thus the normal strains are same in both the phases and are equal to the composite strain. The existence of perfect bonding also implies that the lateral stress is same in both the phases and is equal to the respective composite stress. Rule of mixture is employed to obtain the composite stresses in normal and transverse directions. As fibers are oriented longitudinally in the matrix and electric field is applied transverse to the fibers maintenance of equality of field in the transverse direction in fiber and matrix mediums is difficult. The maintenance of equality of fields is possible only when each fiber is considered as actuators i.e. electrodes are placed on top and bottom surfaces of the fibers. In such case the interface of fiber and matrix medium acts as conductor thus providing equal normal component of the electric field in two phases and the corresponding field is independent of the thickness of the constituent mediums. When the fibers are not considered as actuators then electric field in the composite is computed from rule of mixture and the dielectric displacement of each phases are equal and same as composite dielectric displacement. Effective axial stiffness co-efficient of PZT5H and Epoxy composite is derived for both the cases of equal

electric field and average electric field. For the case of equal electric field the values of axial stiffness for every volume fraction ratio of fiber is less than that of average electric field. Similar explanations are applicable for transverse stiffness and axial and transverse compliances. It is observable that the effective mechanical properties do not vary much with the nature of electric field in the constituent mediums. The variation of axial and transverse piezoelectric stress co-efficients with fiber volume fraction for PZT5H and Epoxy composite is also derived. It is observed that equal electric field provides better effective coefficient than average electric field for the kind of composite where matrix is piezoelectrically inactive. In the contrary it is also observed that piezoelectric stress coefficient do not vary much with nature of electric field for the composite where matrix is also piezoelectrically active. Similar explanations can be made for piezoelectric strain coefficients. Another interesting conclusion can also be drawn for composite where matrix is piezoelectrically active that the stiffness property does not vary much with nature of electric field.

6929-85, Poster Session

Mechanics of interface deformable magneto-electro-elastic layered structures

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In recent years, solid state devices utilizing magneto-electro-elastic coupling effects have drawn a considerable interest with both the scientific and technological significance, because of a high demand for actuators and sensors in broad engineering fields. In general, such devices consist of several sub-layers due to particular demands of designs and applications, among which one or more sub-layers may be of the elastic, electric, or magnetic material. As a consequence, many interfaces are formed within such kind of multi-layered structures. Due to high stress concentrations exist in the interfaces, especially at the locations near the edges of the layered structures or tips of delaminated regions, interface fracture often occurs, which may lead to premature failure of the structures. Therefore, a need exists to explore the behavior of magneto-electro-mechanical layered systems and in particular to better understand the coupling effect and related interface mechanical behavior.

In this study, an interface deformable bi-layered beam model is proposed to study the interface stress distributions in a magneto-electro-elastic layered structure. Like most current approaches in the literature, the layer-wise approximations of the electric and magnetic potentials are employed. While in contrast to the linear approximation where the induced electric and magnetic fields are ignored, the present model takes a quadratic variation of the potentials across the thickness, thus warranting an efficient and accurate modeling of the electric and magnetic fields. Completely different from the widely used equivalent single layer model in which the whole laminate is assumed to deform as a single layer and thus has a smooth variation of the displacement field over the thickness, the present model considers each sub-layer as a single linearly elastic Timoshenko beam perfectly bonded together and therefore with individual deformations. To ensure the continuity of deformations of two adjacent sub-layers along the interface, two interfacial compliance coefficients are introduced, by which both the longitudinal and vertical displacement components along the interface of two sub-layers due to interface shear and normal stresses are taken into account.

Governing differential equation of the magneto-electro-elastic layered system along with the associated mechanical and electric or magnetic boundary conditions is first established, and closed-form solutions of resultant forces and interface stresses are then obtained. To assess the performance of the present model, a number of benchmark tests are performed for a magneto-electro-elastic bi-layer beam subjected to (i) a force density normal to the upper face, and (ii) an electric and/or magnetic potential applied to the top and bottom faces. A remarkable agreement achieved between the present solution and the finite element computations illustrates the validity of the present study. The present model not only predicts well the global responses (displacement, electric and magnetic charge), but also provides excellent estimates of the local responses (through-the-thickness variations of the magneto-electro-mechanical state) of the magneto-electro-elastic layered structures. The novel mechanics model of magneto-electro-elastic layered structures presented can be used to characterize hybrid smart devices and develop/optimize new multi-functional materials.

6929-87, Poster Session

Fabrication and electromagnetic characteristics of microwave absorbers containing carbon nanofibers and magnetic metals

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The absorption and the interference shielding of electromagnetic wave have been very important issues for commercial and military purposes. The stealth technique is one of the most typical applications of electromagnetic wave absorption technology. There have been many studies on radar absorbing materials (RAM) such as composites containing conductive nano fillers or magnetic materials. However, in general, the dielectric absorbers with conductive nano materials have the heavy matching thickness and narrow absorbing bandwidth. Magnetic absorbers with magnetic lossy materials are known to have the heavy weight and poor characteristics in the GHz range due to their Snoek's limit.; This research aims to overcome the drawback of previous dielectric or magnetic absorbers. This paper has focused on the development of radar absorbing materials (RAMs) or radar absorbing structures (RASS) containing both dielectric and magnetic lossy materials. Carbon nanofiber (CNFs), conductive nano particles were used as dielectric lossy materials and Fe and Co particles etc. were used as magnetic lossy materials. Several glass fabric/epoxy composites containing CNFs and glass fabric/epoxy composites containing magnetic metals were fabricated respectively. Generally three kinds of laminated specimens such as dielectric type, magnetic type and mixed type were fabricated. Their permittivity and permeability in the 2 ~ 18 GHz were measured using the transmission line technique (Network analyzer Agilent N5230A). Microstructures (Scanning Electron Microscopy) for the cross section of fabricated specimens were observed. The reflection loss characteristics for multi-layered structures were calculated using the theory of transmission and reflection in a multi-layered medium. Microwave absorbers with thin and broadband absorbing characteristics through the parametric study for each type were selected and fabricated. Finally, the reflection losses of several fabricated specimens were measured using the transmission line technique. Experimental results were compared with simulation results in terms of 10dB absorbing bandwidth, matching center frequency and matching thickness.

6929-88, Poster Session

Sensing properties and their applications of carbon fiber and hybrid-fiber reinforced-polymer bars as strain sensors

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The carbon-fiber-reinforced-polymer bars (CFRP) can be considered as a self-monitoring material without additional sensing elements. The feasibility of hybrid-fiber-reinforced-polymer bars (HFRP) that demonstrate the important safety features of self-monitoring capability and pseudo-ductility is demonstrated. In this paper, the stress, strain and electrical resistance of three different carbon fiber volume content CFRP bars (the volume content of carbon fiber are 54%,60%,65%) and HFRP bar (the volume content of carbon fiber and glass fiber are 45%,15%, respectively) specimens are recorded under tensile load. Six concrete beams reinforced with HFRP bars are tested to failure under third-point static loading. The curves of electrical resistance change of HFRP bars in concrete beams versus load are presented. The results show that electrical resistance change of three different carbon fiber volume content CFRP bars are about 100%~150% at CFRP bars fracture; the sensibility factor is 116.59, 132.275, 82.237, respectively. The electrical resistance change of HFRP bar is about 25~45%; the sensibility factor is 20.414. The electrical resistance change of HFRP bar reinforced concrete beam is about 4.12~6.74% at concrete beam failure. The experimental results show that CFRP bars and HFRP bars are excellent construction materials for smart civil engineering

structures, can be conveniently used in reinforced concrete structures as sensors as well as reinforcing bars.

6929-89, Poster Session

Characterization of material parameters in the constitutive model for chemomechanical actuation using ion co-transport

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Force and displacement developed by active materials result from energy conversion of the applied form into force and motion. Piezoelectric materials, electroactive polymers, electrostrictive materials and the like exhibit strain for an applied electrical field, shape memory alloys and shape memory polymers demonstrate strain for thermal stimulus and hydrogels demonstrate strain for a chemical stimulus applied across the shell. In our recent work, we have demonstrated a chemomechanical actuator that uses cell membrane proteins reconstituted in a bilayer lipid membrane (BLM) as the active component. The protein used in this actuator is a proton-sucrose cotransporter that transports proton, sucrose and water for an applied pH and sucrose gradient. The BLM with the protein transporters formed in the pores of a porous substrate, referred to as the membrane assembly, is subjected to a pH and sucrose gradient in the actuator to demonstrate deformation [1]. The strain in the system results from the membrane assembly in the actuator functioning as a micro-fluidic pump that moves fluid to balance the applied chemical stimulus. We had developed a constitutive model for characterizing the material properties of the chemomechanical actuator that uses a biological membrane in the early developmental stages of the actuator[2]. The expression derived from the fundamental laws and shown in our previous work for the chemomechanical actuator relates the physical conditions across the membrane using material coefficients for the transported species and the membrane assembly. This abstract outlines our current work in experimentally characterizing the material properties of the biological membrane and predict its behavior as a molecular pump and as the active element in a chemomechanical actuator. A chemical gradient applied across a semi-permeable membrane without transporters is used to validate the model for osmotic regulation. Material properties of the semi-permeable membrane, obtained from the experimental data applied to the constitutive model, are compared with the coefficients obtained from Onsager's reciprocal laws using the same data. In the next step, the material properties of the membrane assembly in the chemomechanical actuator are obtained from fluid transport experiments to characterize the membrane assembly as a pump. In the final step, the constitutive model is modified to include the mechanics of the deforming surfaces of the actuator, compute the material properties of the membrane assembly and compare it with that of the membrane assembly functioning as a pump. The model will assist in designing an actuator that uses microfluidic transport for developing force and strain in a structure.

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6929-92, Poster Session

Transient response of three-phase magneto-electro-elastic beam using finite elements

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1. INTRODUCTION

Magneto-electro-elastic (MEE) material exhibits a coupling between mechanical-electric and magnetic fields. Due to this property these materials have gained considerable importance currently as sensors and actuators. This property is obtained when a composite is made of a piezomagnetic and a piezoelectric phase. One such example is Cobalt Ferrite- Barium Titanate. Coupling between the electric field, magnetic field, and strain of composite materials can also be achieved when electro-elastic (piezoelectric) and magneto-elastic (piezomagnetic) particles are joined by

an elastic matrix. This three-phase MEE composite should have greater ductility and formability than a two phase composite [1]. Jiang et.al. [2] has obtained analytical solutions to MEE beams for different boundary conditions. Anand et.al. [3] has studied the free vibration behavior of multiphase and layered MEE beam made up of Cobalt Ferrite-Barium Titanate. According to authors best knowledge no such studies have been done for three phase material so far.

In this paper the transient response of a beam made of three phase MEE material has been presented using the finite element method employing Newmark Beta method. Numerical examples are presented for different volume fractions (v_f) of the piezomagnetic phase in three phase composite under clamped boundary conditions. It is felt that the study of response of beams made of three phase MEE materials would be very useful for the design of sensors and actuators, active vibration control of structures. Ansys 8.1 has been used to validate the displacement and potentials (electric, magnetic) for PECP and MSCP material with the code.

2. FINITE ELEMENT FORMULATION

Using the constitutive equations for the MEE medium [3] relating the stress, electric displacement and magnetic induction to strain, electric field and magnetic field, exhibiting linear coupling between magnetic, electric and elastic field, the formulation for coupled field can be written in terms of the coupled matrices. The Newmark Beta method is employed to solve the second order differential equation of vibration for the transient response for three phase magneto-electro-elastic beam.

3. Results:

A computer code has been developed to study the coupled response of the rectangular beam made of three phase MEE materials subjected to a uniformly distributed load of 100N/m. Ansys cannot solve problems involving MEE materials and hence the code has been validated with Ansys for the response of PECP (piezoelectric) and MSCP (magnetostrictive) material beam. The results are in good agreement. The response is studied for different volume fractions of piezomagnetic phase in the three phase MEE composite keeping the volume fraction of the piezoelectric phase as constant i.e. 0.4 in the composite. The influence of v_f on the material behaviour is studied. The material properties are taken from Lee et.al. [1].

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6929-94, Poster Session

Giant magnetoimpedance in Fe(Co)Ni/ amorphous microwire multilayered composite and its application

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Nowadays, the design and development of novel magnetic materials with optimized properties is of relevance to study new phenomena and to use them for multifunctional applications of sensor technologies and magnetoelectronic devices. In this letter, we present a detailed investigation of giant magnetoimpedance (GMI) effect in multilayered magnetic microwires. A new series of Fe(Co)Ni film/amorphous microwire composite materials were fabricated by using combined magnetron-sputtering and electroplating techniques. The measurements were performed using an impedance analyzer (HP 4191A) in the frequency range of 100 - 1000 MHz and a varying applied dc magnetic field within ± 300 Oe. Interestingly, the GMI ratio and its field sensitivity reached the largest values of 1200% and 400 %/Oe at the measuring frequency of 450 MHz. This result is very

ideal for developing a new class of ultra-sensitive and high-frequency GMI-based magnetic sensors. The observed GMI behavior of multilayered microwires can be explained in terms of magnetostatic coupling between the two-magnetic-phases. Finally, the multilayered composite magnetic material developed with advanced properties ideally represents a new class of magnetic materials with great technological potential in sensor devices.

6929-96, Poster Session

Phase-field modeling of domain switching near crack tips in single-crystal ferroelectrics

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Domain switching near a stationary crack tip in a single crystal of ferroelectric material is investigated. The phase-field approach applying the material polarization as the order parameter is used as the theoretical modeling framework, and the finite element method is used for the numerical solution technique. Results are given for the critical levels of electromechanical loading to nucleate new domains at the crack tip and the evolving shape of the new domains. The electromechanical form of the J-integral is appropriately modified to account for the polarization gradient energy terms, and analyzed to illustrate the amount of shielding, or lack thereof, due to domain switching at the crack tip.

6929-99, Poster Session

Structural dielectrics for multifunctional capacitors

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As US Army systems and vehicles are developed to implement the latest technological advancements, there is an increasing need for reducing the mass and volume dedicated to energy storage components. The conventional approach for saving mass and volume is to increase component energy density. Alternatively, overall system weight can be reduced by replacing purely structural platform components, such as armor or frame members, with structures that also store energy. Specifically, we are developing capacitors that can also carry structural loads by intercalating glass fiber reinforced polymer dielectric layers with metalized polymer film electrodes.

In previous work, we developed a metric, the multifunctional efficiency (MFE), for comparing various structural capacitor preparations and guiding multifunctional design. Modeling and characterization of fiber composite-based structural capacitors has shown that the MFE is very sensitive to fiber shape, orientation, volume fraction, and dielectric constant. In this work, various dielectric materials are studied against this MFE metric and the effect of fiber properties and volume fraction on MFE is explored experimentally.

6929-100, Poster Session

Carbon nanotube epoxy modified CFRPs toward improved mechanical and sensing properties for multifunctional aerostructures

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No abstract available

6929-101, Poster Session

Electrospinning of Continuous Piezoelectric Yarns For Composite Application

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The focus of this research is to electrospin continuous yarns of piezoelectric nanofibers. Incorporating piezoelectric polymer fibers in traditional composites can add sensing and actuation capabilities, which creates a wide array of potential applications. To create fibers with piezoelectric properties, the process of electrospinning poly(vinylidene fluoride) (PVDF)

with DMAc was chosen. Through this technique, the non-polar α phase of the polymer is converted to the polar β phase PVDF, which is responsible for its piezoelectric behavior. To understand the various aspects of electrospinning, an investigation of parameters is conducted to observe their effects on the successful formation of homogeneous PVDF fibers without beading. Three processing techniques are examined, including spinning onto a static collection plate, spinning onto a rotating drum, and spinning onto a deionized water surface and drawing the fibers to a rotating collector. Finally, the continuous yarn of PVDF fibers is tested using mechanical, electrical and piezoelectric characterization.

6929-38, Session 8

Development of test procedures for thermomechanical characterization of a shape-memory alloy for high-force actuator applications and their use in characterizing a 55NiTi alloy

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Over the past few decades, binary NiTi shape memory alloys have received considerable attention as a result of their unique mechanical characteristics, which show promise for low-temperature, solid-state actuator applications. However, prior to using these materials for such applications, the physical response of these systems to mechanical and thermal stimuli must be better understood and modeled to aid designers in developing systems that accurately predict the actuator's in-service performance. Even though shape memory alloys have been around for almost five decades, very little effort has been made to standardize testing procedures. Although some standards for measuring the transition temperatures of SMA's do exist, no real standards exist for determining the various mechanical and thermomechanical properties that govern the usefulness of these unique materials. This study involved round-robin testing of a 55NiTi alloy from the same heat and batch. The various groups involved in the testing reported substantial variations in the characteristic responses observed. Reported transformation temperatures showed measured M_f values that differed by as much as 15 °C which translates into discrepancies on the order of ~25-30% of the actual M_f value. Measurements made for other transformation temperatures for this alloy showed similar results, although the variations were reduced. Monotonic tensile experiments also showed substantial variation, with the onset of detwinning stress varying by as much as 100 MPa. Again, these levels of variation are a significant fraction of the characteristic response being measured, which in this case is approximately 250 MPa. These results indicate the need for the development of testing standards so that useful and meaningful data can be generated and successfully translated into the development of useful models and hardware. To this end, differences in the observed responses will be presented, contrasted and rationalized. Recommendations for the development of appropriate testing standards will then be discussed.

6929-39, Session 8

Experimentally validated numerical analysis of aerostructures incorporating shape-memory alloys

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As active structures become more prominent in the aerospace field, the use of more accurate numerical modeling has gained importance as an aid to the design process. As an example of an active aerostructure, active chevrons incorporating Shape Memory Alloys (SMAs) have been shown to greatly decrease engine noises at take-off and landing while increasing efficiency at cruise, which was proven in Boeing flight tests. Future applications are also being designed, including a variable geometry nozzle for use on jet engines and a torque tube actuator used to vary the twist angle for rotor blades. This work concentrates on the FEA modeling of the Ni60Ti40 (wt %) SMA used in these three applications and subsequent experimental validation.

FEA modeling was applied to the active chevron, nozzle, and torque tube, wherein the constitutive model for the SMA material accounts for the full thermomechanical response. The fully 3-D models also accounts for such particular aspects as variable maximum transformation strain and smooth material hardening during transition. Model calibration is performed via uniaxial material characterization performed using standard materials testing tools and methods. An overview of the models and material properties is presented followed by a discussion of the analysis results for the complex aerospace actuation applications and comparisons to experimental validation of the overall system response are made as applicable.

To validate the analysis predictions in the specific case of the variable geometry chevron, experimental results were generated in a controlled laboratory environment through the application of thermomechanical loading paths to various chevron subcomponents. The multi-layer composite substrate was subjected to several concentrated loads to confirm the ability to accurately predict the response of this elastic yet complex structure. The experimental and analytical data are compared. The SMA beams were also subjected to multiple loads levels which induced both elastic and thermomechanical responses. Comparison of experimentation and analysis allowed confirmation of the model accuracy in capturing the SMA behaviors. The accuracy of the elastic prediction was examined followed by those from thermal phase transformations. Based on the positive nature of these validation results, validation of the full chevron predictions was performed. Employing the same validation methodology as used for the chevron, a similar validation effort is performed to assess the system response of the variable geometry nozzle and SMA torque tube. To compare the model and experimental results, contour plots which reflect deformations at various SMA temperature states are shown for both the experimental and numerical analysis results.

6929-40, Session 8

Pseudoelastic low-cycle fatigue response of ultrafine grained TiNb shape-memory alloys

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Titanium-Niobium based shape memory alloys (SMAs) are strong candidates for biomedical applications that require pseudoelastic properties due to their superior corrosion resistance and biocompatibility of all alloying elements. In certain applications such as coronary stents, stable pseudoelastic cyclic behavior -- characterized by limited irrecoverable strain and stable stress levels -- also becomes imperative. In an effort to produce Titanium-Niobium based SMAs with stable cyclic behavior and to establish the effects of severe plastic deformation (SPD) on cyclic properties, Equal Channel Angular Extrusion (ECAE) and rolling were performed on metastable β titanium Ti-Nb alloys. The material billets were processed at room temperature using multi-pass ECAE or cold-rolling. Various post-processing low-temperature, short-time annealing treatments were utilized to recover undesired deformation features and to induce fine omega (ω) precipitates. Tensile pseudoelastic experiments up to 1000 cycles at various strain levels were carried out at room temperature. Four-pass ECAE and cold rolled materials exhibited superior cyclic stability over single-pass ECAE samples, and their cyclic properties were further enhanced in samples treated to produce ω precipitates. The stress required for the onset of martensitic transformation and pseudoelastic stress hysteresis decreased monotonically with increasing number of cycles for all samples, reaching minute values at conclusion of the experiments. Total irrecoverable strain accumulation reaches maximum at approximately 100-300 cycles, and was then followed by a reduction in total irrecoverable strain. The appearance of this recovery suggests that the majority of irrecoverable strain accumulated during cycling was not caused by long-range plastic deformation, but rather other mechanisms such as stabilization of martensite. Changes in the pseudoelastic behavior were also observed in samples stored at room temperature for several days between the first cycle and subsequent cycles. After the period of room temperature aging, dramatic increases in both transformation stress and stress hysteresis were found. Similar phenomenon was observed in samples tested days after the initial experiments of 1000 cycles. Increases in transformation stress after room temperature storage was also observed in Ni-rich NiTi SMAs, but recovery of irrecoverable strain during cycling was not observed.

The mechanisms responsible for these observed phenomena are believed

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to be rooted deeply in four distinct possibilities: dislocation generation and interaction during martensitic transformation, diffusional effects, crystallographic texture, and formation of ultra-fine ω precipitates. The individual effects of these mechanisms, the interactions among them, and their effects on and correlations with the pseudoelastic cyclic behavior will be discussed in the present paper.

6929-41, Session 9

High-temperature superelastic response of CoNi(Al,Ga) shape-memory alloys under tension and compression (future of SMA)

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Ferromagnetic SMAs have attracted increasing interest because of the ability to obtain one order of magnitude higher recoverable magnetic field induced strain than other active materials. A recently discovered ferromagnetic shape memory CoNiAl and CoNiGa alloys have promising shape memory characteristics for medium to high temperature applications. We have conducted an extensive work to capture several aspects of the shape memory behavior of both alloys in single and polycrystalline forms. It has been demonstrated that these alloys have perfect pseudoelasticity with low stress hysteresis even at temperatures higher than 400 °C, high strength for dislocation slip, large recoverable strain levels (10%), large pseudoelastic temperature window (>450 °C), low stress for martensite reorientation, and stable response to cyclic deformation at high temperatures. It was observed that the stress hysteresis decreases with increasing temperature above austenite finish temperature and temperature hysteresis decreases with increasing constant stress level. Strong orientation dependence and tension/compression asymmetry in shape memory characteristics has also been investigated. An unexpected phenomena, transformation induced twinning in the parent phase, was observed. This mechanism led to recovery of more strain than the applied one under tension due to back transformation into the twinned structure instead of into the initial single crystal. Selected experimental findings on single and polycrystals that summarize these findings will be presented and the challenges will be addressed.

6929-42, Session 9

Thermomechanical cyclic loading and fatigue life characterization of nickel rich NiTi shape-memory alloy actuators (future of SMA)

O. Bertacchini, D. C. Lagoudas, Texas A&M Univ.; F. T. Calkins, J. Mabe, The Boeing Co.

After a temporary slow down in the development of new ideas applying Shape Memory Alloys (SMAs) in industrial and commercial applications, the study of new alloy compositions as well as the ingenious design of SMA integrated structural elements is driving the need to develop new experimental and numerical tools. As a leading example, Boeing has been developing and working on a new composition for the NiTi SMA binary system, Ni60Ti40 (wt.%), also referred to as Ni60. Such composition leads to the formation of different Ni rich precipitates such as Ti3Ni4, Ti2Ni3 and TiNi2. The presence of those precipitates results in the capacity for the alloy to exhibit SME and pseudoelasticity without the need of any cold work. The Ni60 SMA is used as a bending actuator and is clamped to a chevron structure placed at the rear end of the jet engines of commercial airplanes. The purpose of such design is to induce actuation in the SMA components, producing an inward deflection of the variable geometry chevrons (VGC). Such deflection causes the hot gases and cold air coming from the rear end of the jet engine to mix in a less turbulent manner and therefore reducing the noise generated by the turbulences during take-off and landing. In addition, such innovative application requires compliance with safety standards. Fatigue testing and validation of the required service life are certainly the most crucial parts of the characterization process and design. For this purpose, a custom built test frame is utilized to perform thermally induced fatigue testing of Ni60 actuators under isobaric loading conditions for various constant stress levels going from

100MPa to 250MPa. The results are fatigue life results spreading from nearly 5000 cycles for the largest stress levels and up to nearly 60000 cycles for the lowest ones. The application of thermomechanical fatigue cycles to SMA actuators inducing cyclic martensitic phase transformation results in the generation of a large amount of irreversible strain, also called plastic strain. In order to identify the influence of Ni rich precipitates on the transformation temperatures, on the stability of the generated transformation strain and on the amount of accumulated plastic strain recorded at failure, two different heat treatments were selected. The design of the fatigue specimens is representative of the VGC application in terms of amount of transformation strains and actuation stresses. Besides, the geometry of the fatigue specimen being very small, an additional parameter needs to be considered, i.e., the specimen thickness. For fatigue testing reproducibility, it is recommended to get away from any size effect; therefore three different thicknesses were selected. Test results for all sets of parameters are presented in the herein work. A detailed comparison and post failure analysis of the fatigue results led to the selection of an optimum set of parameters for the featured application. In a more general manner, the set of experiments presented in this paper is a great example of how it appears more and more necessary to develop tools and standards in the procedures of smart material testing.

6929-43, Session 9

Improvement in dimensional stability and ductility of TiNiPd shape-memory alloys after severe plastic deformation (future of SMA)

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NiTi alloys are ideal for actuator applications in automotive industry, aeronautics and in medicine due to their extraordinary properties such as superelasticity, shape memory, low weight, and high work output. Nevertheless, their transformation temperatures are well below 100°C, restricting their use to low temperature applications. Hence, there is an urgent need to develop high temperature shape memory alloys (HTSMA). TiNiPd alloys have attracted considerable attention as HTSMA since their martensitic transformation temperatures can be varied from room temperature up to 525°C. However, they suffer from embrittlement due to the second phase particles that contain predominantly titanium. In addition, even though the shape memory response of TiNiPd alloys is fairly stable at room temperature, it deteriorates with increasing temperature due to extensive plastic strain accumulation as a result of the decrease in critical shear stress for slip.

In this study, we aim to increase the critical stress for slip (CSS) in TiNiPd alloys by refining the grain size to nanometer range via a severe plastic deformation technique called equal channel angular extrusion (ECAE). Two TiNiPd alloys were ECAE processed at temperatures as low as 400°C. The microstructural evolution of the alloys was monitored using Scanning and Transmission Electron Microscopy. Isothermal monotonic and isobaric thermal cyclic experiments were conducted to evaluate the effect of ECAE-induced microstructural changes on the functional properties. We have observed considerable improvement in thermal cyclic and dimensional stability after ECAE which can be attributed to the increase in CSS. Transmission electron microscopy observations revealed that this improvement is caused by ultrafine-scale grains on the order of few hundred nanometers. ECAE also enhances the ductility of the TiNiPd shape memory alloys by breaking up the Ti-rich second phase particles during processing. It has been determined that the fracture toughness of the TiNiPd alloys was increased after ECAE process.

6929-44, Session 9

An integrated numerical aero-elastic study aimed at helicopter blade morphing

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The evaluation of noise generated by rotating blades and irradiated in the far-field and at ground, is one of the most important analysis related to helicopter main rotor performance and acoustic certification. Since the first half of the 90's the interests of the aeroacoustic community

and structural engineers have been focused on the assessment and improvement of numerical tools, able to predict the pressure disturbance in the flow-field (in different flight conditions) as well as on the assessment and manufacture of integrated systems to reduce the noise itself. In spite of the availability of different strategies based on current technologies involved in the reduction of noise and vibration, their practical realization is currently limited to few approaches.

BVI occurs when strong tip vortices, dominating the rotor wake, impinge or pass closely to the rotor blades resulting in impulsive changes of the blade loads that produce, in turn, high noise and vibration levels. It is well documented that the interaction of the shed tip vortex with the following blade concerns mainly the descent flight at relatively low speed (or the hover condition, for particular blade geometries); this leads to a strong resistance for the widespread operation of helicopters in densely populated areas. Moreover, the induced vibrations increase pilot workload, reduce component fatigue life and increase maintenance costs.

Recent research effort has significantly improved the understanding of the BVI problem and, accordingly, many noise reduction concepts have been developed. Among them, there has been much interest in using active blade architectures such Higher Harmonic Control (HHC) or Individual Blade Control (IBC) strategies [4, 6].

The aim of this paper is to present an innovative concept devoted to achieve an anhedral blade configuration; it is based on the realization of a stiffness-variable active structure able to modify its shape next to the tip region during approach and landing. Such a kind of morphing is based on an integrated smart system made of a magneto-rheological fluid-based (MRF) device, a shape memory alloy ribbon-based (SMA) device and a set of concentrated masses, properly distributed at the upper side of the blade box.

The authors already faced the problem in the past [13], referring to a simplified structural model and coming to an elementary smart actuation system without concentrated masses effects. Taking advantage from that work, the present investigation is devoted to obtain BVI noise alleviation by reducing the interactional effects between the shed tip vortex and the following blades; to this aim, the magneto-rheological device is called to locally provide a spanwise reduction of the bending stiffness against the centrifugal stiffening, whereas the SMA elements and the forces induced by the concentrated masses allow achieving the wanted anhedral configuration.

The final aim of this work is to investigate the potentiality of the presented methodology and to provide some guidelines for realizing an anhedral shape in a rotating structure. The analysis of BVI noise reduction due to the tip morphing is beyond the aim of this work and is postponed to further studies.

6929-45, Session 9

Large strain variable stiffness composites for shear deformations with applications to morphing aircraft skins

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Morphing or reconfigurable structures potentially allow for previously unattainable vehicle performance by permitting several optimized structures to be achieved using a single platform. The key to enabling this technology in applications such as aircraft wings, nozzles, and control surfaces, are new engineered materials which can achieve the necessary deformations but limit losses in structural efficiency (stiffness/weight). These materials must combine exhibit precise control over deformation properties through large deformations and provide high stiffness combined with large deformations. In this work, we build upon previous efforts in segmented reinforcement variable stiffness composites employing shape memory polymers to create hybrid composite materials that combine the benefits of cellular materials with those of discontinuous reinforcement composites. In particular, we design, fabricate, and test composite materials intended for shear deformation for application to variable area wing skins. Two key challenges to shearing wing skins are addressed in this work: the resistance to out of plane buckling induced by shear loading, and resistance to membrane deflections resulting from distributed aerodynamic pressure loading. Our designs are based on the kinematic engineering of reinforcement platelets such that desired microstructural kinematics is achieved through known, prescribed

boundary conditions. We achieve this kinematic control by etching sheets of metallic reinforcement into regular patterns of platelets and connecting ligaments. This kinematic engineering allows optimization of materials properties for a known deformation pathway. We use mechanical analysis and full field photogrammetry to relate local scale kinematics and strains to global deformations for both axial tension loading and shearing loading with a pinned-diamond type fixture. Results show reinforcement platelets achieve both rotation and translation when accommodating shear loading. Furthermore, the Poisson ratio of the kinematically engineered composite is ~3x higher than generically designed isotropic variable stiffness composites. This design allows us to create composite materials that have high stiffness in the cold state below SMP T_g (4-10GPa) and yet achieve large shear deformation (5-20%) in the hot state (above SMP T_g).

6929-46, Session 10

Thermomechanical characterization of the nonlinear rate-dependent response of shape-memory polymers

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Shape Memory Polymers (SMPs) are a class of polymers, which can undergo deformation in a flexible state at elevated temperatures, and when cooled below the glass transition temperature, while retaining their deformed shape, will enter and remain in a rigid state. Upon heating above the glass transition temperature, the shape memory polymer will return to its original, unaltered shape. SMPs have been reported to recover strains of over 400%. It is important to understand the stress and strain recovery behavior of SMPs to better develop constitutive models which predict material behavior. Initial modeling efforts did not account for large deformations beyond 25% strain. However, a model under current development is capable of describing large deformations of the material. This model considers the coexisting active (rubber) and frozen (glass) phases of the polymer, as well as the transitions between the material phases. The constitutive equations at the continuum level are established with internal state variables to describe the micro-structural changes associated with the phase transitions. For small deformations, the model reduces to a linear model that agrees with those reported in the literature. Thermomechanical characterization is necessary for the development, calibration, and validation of a constitutive model. The experimental data gathered will assist in model development by providing a better understanding of the stress and strain recovery behavior of the material. This study presents the testing techniques used to characterize the thermomechanical material properties of a shape memory polymer as well as the resulting data. An innovative visualphotographic apparatus, known as a Vision Image Correlation system was used to measure the strain. A series of tensile tests were performed on specimens such that strain levels of 10, 25, 50, and 100% were applied to the material while it was above its glass transition temperature. After deforming the material to a specified applied strain, the material was then cooled to below the glass transition temperature while retaining the deformed shape. Finally, the specimen was heated again to above the transition temperature, and the resulting shape recovery profile was measured. The dependence of the recoverable strain on the heating and cooling rate is investigated in this work. Results show that strain recovery occurs at a nonlinear rate with respect to time. Results also indicate that the ratio of recoverable strain/applied strain increases as the applied strain increases. The data reported in this paper will provide a better understanding of the strain and stress recovery behavior of the material, and the data will be used for development and validation of constitutive models for SMPs.

6929-47, Session 10

Electro-thermo-mechanical analysis of shape-memory actuator/sensor wires

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The electro- and thermo-mechanical behavior of a commercially available micro-scale shape memory alloy wire actuator/sensor (Flexinol) is presented in this paper. The work is motivated by the desire to develop an actuator displacement controller with resistance feedback, thus exploiting the multifunctional nature of SMA materials in order to minimize system complexity by abandoning extra sensors. Though the subject is not

new [1,2,3], comprehensive data under controlled conditions for time-resolved and hysteresis-based experiments is not readily available from the literature.

In order to systematically study the SMA behavior, we used a simple benchmark platform, consisting of a horizontal cantilever beam and a Flexinol wire mounted vertically to the tip of the cantilever beam (see Figure 1). A Labview-based data acquisition system measures actuator displacement and controls the power level within the SMA actuator wire. The experimental setup is carefully insulated from ambient conditions (see Figure 2), as the thermal response of a 50-micron diameter Flexinol wire is extremely sensitive to temperature fluctuation due to convective heat transfer.

Actuator performance is reported for a wide range of actuation frequencies and input power levels. SMA resistance data is also documented using a novel combination power supply/measurement instrument. The effect of varying actuator pre-stress is reported, as well as the effect of forced-airflow convective cooling and heating.

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6929-48, Session 10

Damping of high-temperature shape-memory alloys

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Aircraft engine components are subject to vibratory loading that can lead to high cycle fatigue failures. As part of the Fundamental Aeronautics research program, researchers at NASA Glenn Research Center are developing new technologies to alleviate excessive vibratory stresses at high engine temperatures. Several damping methods have been investigated in the past for use in aircraft engines, including viscoelastic damping, impact damping, and plasma sprayed damping coatings. Other researchers have shown elevated damping arising from the superelastic properties of NiTi shape memory alloys (SMAs)[1]. However, these SMAs can only be used at or near room temperature, making them unsuitable for use in engines. NASA has recently developed several new ternary NiTi-based high temperature shape memory alloys (HTSMAs), and two compositions were tested for storage modulus and damping properties over a range of strain levels, temperatures, and frequencies.

Shape memory alloys can have very high damping arising from hysteresis within the martensite-austenite phase transition region. When a cyclical load is applied to an SMA near the phase transition region, the material undergoes a stress-induced austenite-to-martensite phase change, yielding large recoverable strains and significant hysteresis (energy dissipation). This property is known as superelasticity. Due to the nature of this type of damping, it should be temperature-dependent.

A Boeing patent[2] shows a concept where an HTSMA could be used to suppress aircraft engine blade vibrations. HTSMA patches are placed within the blade at locations where the temperature is near the phase transition temperature. Vibratory stresses will cause these patches to deform, initiating the phase transformation that leads to elevated damping.

Before such a concept can be developed, the basic material properties of HTSMAs must be measured. Researchers at NASA Glenn Research Center have developed several HTSMA formulations that can function at up to 300oC. Two different Ni-Ti-Hf compositions were tested for elastic modulus and loss factor (damping) at various strain levels, temperatures and frequencies. Initial modulus testing showed the phase transition occurring over a large temperature range. While this makes the materials less suitable for shape memory actuation, it might yield high damping

over a wider temperature range. This would make the materials more viable for use in applications where the temperature is not well-controlled. Additionally, the high phase transition temperature make these materials well-suited for use in certain parts of an aircraft engine (e.g. compressor).

The HTSMAs investigated here are two samples each of extruded 50Ni-35Ti-15Hf and cast 49.5Ni-35.5Ti-15Hf. The samples were tested on a TA Instruments dynamic mechanical analyzer (DMA), model 2980. An alternating force was applied to the center of each sample, with the strain amplitude controlled to a prescribed value. The DMA measured the storage (elastic) modulus and loss modulus (damping) of each sample from room temperature to 300oC in both heating and cooling, at frequencies from 0.1-100 Hz, and at various strain levels up to 1000 microstrain.

Results show that at the lower frequencies, the loss factor is very high within the martensite phase transition region. At the lowest frequency tested, 0.1 Hz, the peak loss factor is higher than 0.1. However, as the frequency increases, the damping level also decreases. Since the maximum frequency of the DMA is 200 Hz, results from a separate high-frequency test will give the loss factor within the kilohertz range, which is closer to the typical resonance frequencies in engines.

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6929-49, Session 10

Simultaneous transformation and plastic/viscoplastic deformation in shape-memory alloys

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The constitutive modeling of Shape Memory Alloys (SMAs) has traditionally focused on capturing the elastic and transformation behaviors of the material. Several varied models exist which can account for the generation and recovery of inelastic deformation resulting from the martensitic transformation and these are suitable for modeling the response of conventional SMAs as used in applications exhibiting repeated system responses. However, as SMAs are more commonly being formed into complex shapes and used at higher temperatures (so-called high temperature SMAs), the need to also accurately account for irrecoverable inelastic strains has become increasingly important. Such irreversible deformation occurs in SMAs at both conventional temperature ranges ($T < 100\text{C}$), where it is often rate-independent, and at higher temperatures, where it is rate dependent.

Past work on plastic strain generation in SMAs has focused on two distinct phenomena. The first is known as transformation-induced plasticity (TRIP) while the second is associated with slip mechanisms common in metals which initiate at sufficiently high stresses (i.e., yield stresses). TRIP accounts for irrecoverable strain generated due to the cyclic thermomechanical transformation of shape memory alloys during which dislocations, grain boundary mismatches, and other effects can accumulate [1,2]. A non-negligible permanent macroscopic deformation (relative to the original reference configuration) is observed. Modeling of this plastic behavior does not include the conventional notion of a yield surface, but rather proposes evolution equations for the plastic variables which are strictly dependent on the number of transformation cycles completed.

The second current class of SMA constitutive model intended to account for irrecoverable strains combines known phenomenological SMA models with conventional metal plasticity formulated using yielding surfaces in stress space and are formulated in both 1-D [2], and 3-D. However, the current models, in the forms presented in the literature, are intended to address permanent plastic yield which occurs outside of active transformation regions. Simultaneous transformation and yield is not considered. Example results from such a model formulated in three dimensions are shown below in Fig. 1. Figure 1a illustrates the modeled thermomechanical loading paths in stress-temperature space, where the transformation regions are shown (slanted lines). Note that the loading path enters the yield region where no transformation is expected to occur (i.e., above the transformation regions in Path 1, below them in Path 2).

The corresponding stress-strain results are shown in Fig. 1b. A von Mises-type (J2) plastic yield surface and isotropic hardening were assumed for this model. A schematic illustration of such yield and transformation surfaces are shown in Fig. 2 for a case of biaxial plane stress. It is again noted that, in the past models, the transformation surfaces were assumed to be strictly distinct from the plastic yield surface.

Figure 1 - Model results for uncoupled transformation/plastic response of an SMA material

Figure 2 - Schematic of J2 transformation and yield surfaces considering biaxial plane stress

This new work involves experimental investigation and theoretical modeling of both rate-independent and rate-dependent inelasticity in SMAs and accounts for simultaneous transformation and plastic strain generation. Previous work has not addressed the generation and accumulation of plastic strains in SMA materials exhibiting rate-dependency (i.e., high temperature shape memory alloys). The experimental characterization effort is intended to motivate the form of the theoretical models and the effect of interest is the influence of irrecoverable inelastic strain formation on phase transformation. Initial loading paths consider plastic strains which are generated apart from transformation. Loading to yield is applied to material in the pure austenite, pure martensite, and mixed phases. The material behavior is also closely examined when plastic slip and martensitic transformation are occurring simultaneously. Thermomechanical loading paths are therefore applied which lead to simultaneous martensitic transformation and plastic strain generation. One important path is the nominally isothermal, variable stress path at temperatures much higher than the austenitic finish temperature which lead to simultaneous yield and stress-induced martensite. Another path imposes a nominally fixed deformation while variable temperature is applied, which lead to induced stresses exceeding the limit for slip. Following this, loads are applied at higher temperatures which initiate material creep and relaxation, and the coupling between transformation mechanisms and viscoplastic mechanisms is also investigated.

Motivated by these experiments, two types of SMA models which additionally capture the formation and evolution of plastic and viscoplastic strains are proposed. These models are capable of predicting material response when the plastic or viscoplastic deformation is occurring in a pure phase, in mixed phases, or in a material simultaneously undergoing transformation. One dimensional and three dimensional models are derived. Each model is derived using continuum thermodynamics where appropriate dissipation potentials and flow criteria have been chosen. Multiple "yield" surfaces are used to capture the transformation and plastic yield behaviors simultaneously. With regards to the martensitic transformation mechanisms, both models assume a rate-independent form, although the overall force/displacement relations in the viscous model exhibit a dependence on rate. Model predictions for boundary value problems are compared to experimental results, and the accuracy of the models is discussed.

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6929-50, Session 10

Self-healing simulation of a shape-memory alloy composite

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1. Introduction:

Shape Memory Alloys are being used for various type of applications. Recently there is an interest in self-healing applications. A self healing

composite has been realized experimentally by Olson's group [1]. Brinson et al [2] have studied self-healing behavior of SMA composite using finite element simulation. Present study extends further the scope of self healing composite to shell structure, using a more rigorous analysis to simulate the 3-D behavior of the structure. The Variational Asymptotic Method (VAM), introduced by Berdichevsky [3] applies asymptotic analysis for the energy functional instead of the system of differential equations. VAM is more compact and less cumbersome than other standard alternatives. Atilgan, Hodges, Sutyryn and Wenbin Yu [4] simplified and extended the theory for composite plates and shell applications.

2. SMA and composite formulation:

The Liang-Brinson one-dimensional constitutive model for SMA materials is used.

The geometry of the reference surface (mid surface) of a shell is represented by a set of arbitrary curvilinear coordinates. The lines of curvature itself are chosen to be the curvilinear coordinates. The deformed state is given by a global deformation and warping of the normal line element. The unknown warping functions are solved by minimizing the energy functional through finite element discretization. Original 3-D problem is reduced to a 2-D problem, by taking advantage of smallness of h/l , h/R and order of strains.

3. Results:

The material is elastic-plastic with temperature-dependent softening. The matrix softening at high temperature enables the crack to fully close when the wires pull the crack back together. The structure analyzed is a doubly curved shell. The shell is collapsed along the thickness direction by the VAM to get a 2-D constitutive description of the original 3-D shell. The 2-D finite element model is constructed for solving 2-D displacement and strains. These results are applied to VAM to recover 3-D stress field. The pre-notched composite model containing pre-strained wires is loaded at one end. The SMA wires accommodate the elongation by forming detwinned martensite. The area ahead of the crack tip is highly stressed and undergoes plastic deformation. After the crack propagates across the full width of the composite, the loading boundary condition of the end is released to allow the wires to recover elastically.

The whole composite is now subjected to uniform heating, and when the temperature is increased in the austenite transformation zone for the SMA wires, the reverse transformation to the austenite causes the wires to shorten and pull the fractured matrix halves back into the position.

4. Conclusion:

In the present study a self-healing SMA hybrid composite is simulated by using variational asymptotic approach. The simulation tool developed can be used to design composite structures using matrix with appropriate properties that will allow self-healing of the cracked composite.

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6929-51, Session 11

Shakedown response of shape-memory alloy wire: experiments and modeling

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A number of SMA models have been proposed that adequately describe the behavior of SMA wire. Very few of them account for shakedown behavior. Shakedown is defined as the evolution of constitutive behavior and material properties under thermomechanical cycling. From preliminary experiments on SMA wire (Iadicola, JIMSS 2002), shakedown in the superelastic regime can vary in both the evolution of constitutive

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response and the number of cycles needed to reach a cycle response limit. For example, at a relatively low temperature and load, superelastic cycling will depress the Austenite to Martensite transformation stress and a small permanent set will develop over hundreds of cycles. At relatively high temperatures and loads, however, the transformation plateau softens significantly, a large permanent set develops, and hysteresis upon unloading is nearly eliminated in only tens of cycles.

The existence of nonuniform temperature and strain fields, a result of the material's strong thermomechanical coupling, can also have a strong influence on shakedown. Partial transformation loops can cause different areas of the same wire to experience different strain histories. Cycling tends to reduce the severity of thermomechanical coupling, stabilize the mechanical response, and eliminate the appearance of nonuniform strains. Once again, high loads tend to accelerate and amplify this effect.

A careful series of experiments will be presented to quantify the relationships discussed. Wire specimens include both "virgin" SMA wire (Nitinol) as well as conditioned SMA wire (Flexinol) from Dynalloy Corporation. Multiple modes of shakedown are explored. Slow, isothermal superelastic cycling (displacement control) is performed at various temperatures, and non-isothermal superelastic cycling is performed at various displacement rates. Shape-memory cycling is performed at various dead-loads. Bias-spring loading under various spring stiffnesses and prestrains is performed to simulate cyclic actuator performance.

In order to develop a consistent set of data over a large range of conditions, a single testbed has been assembled for all experiments. Temperature control is accomplished with custom heated grips and a thermoelectric device on the back side of the wire. Both temperature areas (wire and grips) are actively controlled. Axial temperature and strain fields are monitored from the front side via infrared thermography and digital image correlation, respectively. The average strain and resistance of a local gauge length are monitored via laser extensometry and a four-point probe, respectively. Average resistivity can be derived from the measured resistance and axial strain by assuming a purely isochoric deformation. This setup is mounted in an MTS servo-hydraulic load frame, which allows both displacement and load control.

A new 1-D SMA model is proposed, based on the thermodynamic framework laid out in Bi-Chiau (CMT, 2006). New internal variables and kinetic relations are added to capture the shakedown response by tracking the evolution of plasticity. This creates residual stress, permanent set, and a modified shape of the effective stress-strain response, similar to the changes seen in the experiments.

6929-52, Session 11

Performance of shape-memory alloy cables

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In their most common form, cables (or ropes) are composed of wires helically wound into strands, which, in turn, are wound around a core. Variants of this geometry, fabricated with passive materials, such as steel, have been used for centuries in areas that require large tensile stiffness, but low bending stiffness. Cables made from shape memory alloy (SMA) wires are a new structural element with promising properties for a range of new applications. In fact, SMA cables have already found use in the biomedical industry, and they may also have a place in fields that typically do not utilize cables, such as SMA actuators or energy absorbers. Contrasted with a monolithic wire, SMA cables can be tightly bent into compact spools, have inherent redundancy that minimizes the impact of defects, and have reduced thermal lag due to the increased surface area for cooling. Furthermore, an actuator designer has far greater flexibility to vary the layout, wire geometry, and even material properties through the cross section of a cable to achieve the desired performance goals.

With these new benefits and design options comes a need for a thorough understanding of SMA cable behavior since there are no known studies of SMA cables in the literature. Initial thermo-mechanical experiments were performed to 1) quantify the expected advantages of SMA cables, and 2) to probe the complex physical interactions between wires for a deeper comprehension of cable mechanics. In the first category, several commercially available designs were compared to monolithic wires of similar cross sectional area. Basic quantities such as axial stiffness, minimum bend radius, thermal response time, and defect sensitivity were investigated. In the second category, tensile experiments were performed

on a single wire wound around a rigid mandrel, thus eliminating not only the mechanical interactions, but also the heat transfer between the wires. Lubricated, un-lubricated, insulated, and conductive mandrels were all used to characterize the relative importance of each effect. The simplest type of cable was also studied, a single strand made up of multiple wires wrapped around a core. All samples were instrumented with thermocouples and a non-contacting laser extensometer to obtain discrete measurements, and, when possible, specimens were monitored by optical and infrared imaging to capture the full strain and temperature fields. In many cases, experiments were repeated using a linear elastic material instead of a SMA as the specimen. These direct comparisons helped determine whether the observed non-linearity and other phenomena in the SMA data were due to the kinematics or the material itself. Future work will focus on modeling the SMA cable behavior, and the linear elastic specimen data will also assist in verifying the simplifying assumptions prior to moving on to the full thermodynamically based model.

6929-53, Session 11

A model for the shape-memory effects in shape-memory polymers

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The non-linear thermomechanical relationship in shape memory polymers (SMPs) has drawn considerable attention in many fields ranging from aeronautics to medicine largely due to their ability to withstand deformations several orders of magnitude larger than in shape memory alloys (SMAs). At high temperatures, SMPs share attributes with compliant elastomers and exhibit long-range reversibility. In contrast, at low temperatures they become very rigid and are susceptible to plastic, although recoverable, deformations.

With this high-temperature compliance and low-temperature rigidity dual characteristic, model development that bridges the threshold between the two is limited. We develop a macroscopic model using free energy principles to predict the rate-dependent thermomechanical response of shape memory polymers. Consideration is given to the microscopic nature of plastic flow in glassy polymers. In addition, we develop material-based equations for the frozen volume fraction using principals of polymer crystallization. We illustrate aspects of the model through comparison with SMP data.

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Development of multifunctional wire that combines shape-memory alloy to piezo electric material

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The shape-memory alloy, for example NiTi (Nickel Titanium), is used for an actuator and frame by the shape- memory effect and the super-elasticity effect. And piezoelectric material, for example PZT (Lead Zirconate Titanate), is used for an actuator and sensor by the piezoelectric effect and the pyroelectric effect. However, each of the materials has been used for the sensor and the actuator independently because the principle of the function of each of materials is different.

In this research, a new multi functional device combines these four functions is developed by coating the PZT thin film of 20 μ m to the surface of the NiTi wire by the chemical reaction by using the hydrothermal crystallization method.

The PZT film of 20 μ m was coated to the NiTi base that contained 50% Titanium by the hydrothermal crystallization method by controlling the solution. This new combined wire can be used as a multi function device with four effects of piezoelectric, pyroelectric, shape memory and superelastic.

We succeeded in the detection of the displacement at a super-elastic deformation of this multi functional device from the piezoelectric effect of the PZT film on the surface.

By fusing these four functions, we will produce a new sensor actuator device such as the self-sensing actuator where the transformation by the shape- memory effect is detected by the piezoelectric effect or the

pyroelectric effect, and we will produce a rough and precision actuator that performs the rough movement by the shape memory effect and performs the precise movement by the piezoelectric effect. And multi functional wire has high flexibility by thin film and low density of piezoelectric materials. It is also possible to wrap around the pipe and the structure by using high flexibility and to add the function of the sensor and the actuator.

6929-55, Session 11

Structural evaluation of a nickel-base super-alloy metal foam

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Cellular materials are known to be useful in the application of designing light but stiff structures. This applies to various components used in various industries such as rotorcraft blades, car bodies or portable electronic devices. Structural application of the metal foam is typically confined to light weight sandwich panels, made up of thin solid face sheets and a metallic foam core. The resulting high-stiffness structure is lighter than that constructed only out of the solid metal material. The face sheets carry the applied in-plane and bending loads and the role of the foam core is separate the face sheets to carry some of the shear stresses, while remaining integral with the face sheet. Many challenges relating to the fabrication and testing of these metal foam panels continue to exist due to some mechanical properties falling short of their theoretical potential. Hence in this study, a detailed three dimensional foam structure is generated using series of 2D Computer Tomography (CT) scans, on Haynes 25 metal foam. Series of the 2D images are utilized to construct a high precision solid model including all the fine details within the metal foam as detected by the CT scanning technique. In addition, a finite element analysis is then performed on as fabricated metal foam microstructures, to calculate the foam density and mechanical properties. The open cell metal foam material is a cobalt-nickel-chromium-tungsten alloy that combines excellent high-temperature strength with good resistance to oxidizing environments up to 1800°F (980°C) for prolonged exposures. The foam is formed by a powder metallurgy process with an approximate 100 pores per inch. Results obtained from the finite elements are utilized with the NDE data to assess the structural behavior as compared to experimental compressive material properties as well as with idealized foam model theories.

Micrograph of 100 PPI Haynes-25 Metal Foam

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6929-56, Session 11

Carbon nanotube (CNT) fins for enhanced cooling of shape-memory alloy wire

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Shape Memory Alloys (SMA's) are often used as actuators for applications benefiting from their high actuating strains, large energy density, and low weight. SMA's are typically not known for their speed, but for single actuation they are fast, with response times on the order of milliseconds, achieved through ohmic heating. High speed cyclic actuation, however, is more difficult to accomplish because there is no simple mechanism to extract heat from the bulk material. Heat exchangers such as thermoelectric coolers, liquid coolants, and forced convective coolers, have demonstrated some success, allowing frequencies up to 40 Hz for thin wires. Changes in geometry such as using thin SMA ribbons and films have also been used for their increased surface area allowing greater heat transfer. However, these solutions detract from the overall benefit of SMA wires (simplicity, small size, and low weight); heat exchangers add extra weight, bulk, and in some cases power consumption to the system, while thin films are difficult to attach, are fragile, and typically produce less force than wires. Applications that have strict weight and space requirements (such as hand-held devices or micro-systems) consequently do not benefit from relying exclusively on many of these solutions.

Heat dissipation in high performance micro-electronics poses analogous problem as the SMA's because it is difficult to fit heat exchangers in such small spaces. The recent estimates of high thermal conductivity in carbon nanotubes (CNT's) have prompted work towards their use for heat dissipation. Recently, micro-fins laser etched from aligned CNT's have been fabricated and demonstrated to increase heat transfer in chips by 11% under free convection and 19% under forced. Similar work has also shown a 10-15% increase in performance over silicon fins. In these efforts, performance was limited because the carbon nanotubes were not in direct contact with the heated surface because they were grown on a separate substrate.

This paper introduces the concept of using aligned CNT's to produce micro-fin architectures on SMA wires to decrease overall cooling time and increase cycle speed by expanding overall surface area. Using dc plasma enhanced chemical vapor deposition (PECVD), aligned CNT's were successfully grown directly on 1/2 of the surface of a 0.38 mm diameter SMA wire, achieving desirable thermal contact. Cooling performance was measured by recording cooling times with a thermal imaging camera. The effective cooling constant was extracted from the temperature profiles, indicating a 33% increase in effective surface area and thus cooling performance from the added CNT's. An increase in the density of the deposited CNT's -- as much as 10 times have been reported on Si substrates -- along with longer fin lengths and total wire coverage would all contribute towards further increasing wire cooling performance.

6929-57, Session 11

Electro-induced shape-memory polymer nanocomposite containing conductive particles and short fibers

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There is a strong interest in the use of conductive shape memory polymer (SMP) for shape recovery or actuation by passing an electrical current. In addition to the fabrication of shape memory thermoset polymer nanocomposites filled with conductive nanoparticles and short fiber fillers, this present paper is focused on the effect of conductive particulate and fibrous fillers on the electrical property of composite. It was shown that the particulate additives are dispersed homogeneously within matrix and served as interconnections between the fibers, while the fibrous additives act as long distance charge transporter by forming local conductive paths observed from Scanning Electron Microscope (SEM). The existing of short carbon fiber may be considered as a rigid long aggregate of carbon, leading to easy formation of continuous conductive networks, and the amount of the networks generally determines the effectiveness of electrical conductivity. The glass transition temperature of nanocomposites are 29.08°C for composite containing 5 wt.-% carbon black (CB) and 0.5 wt.-% short carbon fiber (SCF), 26.65°C for composite containing 5 wt.-%

CB and 1 wt.-% SCF, and 25.78°C for composite containing 5 wt.-% CB and 2 wt.-% SCF, which drop sharply as compared with that of pure SMP, obtained from the Differential Scanning Calorimetry (DSC) curves. The N-H, C=O bonds which are introduced by using additional solution are used to explain the low transition temperature of the nanocomposites obtained from FT-IR spectra. For the composite containing 5 wt.-% CB and 2 wt.-% SCF, the storage modulus increases by 16.2% compared to that of the composite containing 5 wt.-% CB and 0.5 wt.-% SCF and by 4.7% compared to that of the composite containing 5 wt.-% CB and 1 wt.-% SCF; The tangent delta curve of composite containing 5 wt.-% CB and 2 wt.-% SCF approaches the peak value 0.252 at 69.44°C, while the peak of loss modulus curve approaches 53.03°C, the average temperature of the two peaks is used to determine T_g here, thus the glass transition temperature is determined as 62.2°C from Dynamic Mechanical Analyzer (DMA) test. The electrical conductivity of the composites achieves 8.73_10⁻², 9.63_10⁻² and 1.13_10⁻¹ S/cm by DC method and 0.12, 1.05 and 3 S/cm by four-point Van De Pauw measurement. Their shape recovery can be activated by passing an electrical current of 25 V voltages through them, and an insulator-to-conductor transition is evidenced. Finally temperature-dependent resistivity test is done to investigate the thermo-sensitive effects in conducting polymer composite, and the composites containing SCF show a classical negative temperature coefficient (NTC) effect ranged from 70°C to 90°C, show a positive temperature coefficient (PTC) effect at the other temperature. So the above characterization of SMP composite is similar with that of pure carbon fiber.

6929-58, Session 12

Magnetic field-induced phase transformation in NiMnGa and NiMnCoIn shape-memory alloys

I. Karaman, H. E. Karaca, B. Basaran, Texas A&M Univ.

Magnetic shape memory alloys (MSMAs) have the ability to obtain one order of magnitude higher magnetic field induced strain (MFIS) than magnetostrictive materials and few orders of magnitude faster dynamic response than conventional shape memory alloys. They are truly multifunctional materials since they can also be used for sensing and passive power generation via changes in magnetization upon the application of fluctuating mechanical forces or displacements. Field-induced martensite variant reorientation is the main governing mechanism for the magnetic field-induced shape change, especially in NiMnGa alloys, which has resulted in low actuation stress levels. We have recently shown that field-induced phase transition is possible in NiMnGa alloys and it can be reversible or irreversible depending on the magnitudes of stress hysteresis, magnetocrystalline anisotropy and saturation magnetization. Utilizing field-induced phase transformation in NiMnGa alloys instead of variant reorientation, more than one order of magnitude increase in actuation stress is achieved. Recently, a new family of MSMAs, e.g. NiMnIn, NiMnCoIn, NiMnSn, are discovered where magnetic field-induced phase transformation can be observed with large actuation stress and work outputs. Unfortunately, the requirement for large magnetic field (~4T) restricts the potential application of these alloys. However, there are some physical parameters e.g stress hysteresis, orientation dependence of transformation strain, stress and temperature hysteresis that can be engineered to provide us an opportunity to decrease the required magnetic field magnitude for phase transformation. An extensive experimental program is undertaken on NiMnGa and NiMnCoIn single crystals in quest for identifying physical and microstructural parameters critical in field-induced phase transformation phenomena. A thermodynamical framework based on microstructural, mechanical and magnetic requirements for field-induced phase transformation is constructed and will be discussed to provide guidelines to increase the actuation stress levels and possible future directions for research on magnetic shape memory alloys will be presented.

6929-60, Session 12

A continuum thermodynamics formulation for micro-magneto-mechanics with applications to ferromagnetic shape-memory alloys

C. M. Landis, The Univ. of Texas at Austin

A continuum thermodynamics formulation for micromagnetics coupled with mechanics is devised to model the evolution of magnetic domain and martensite twin structures in ferromagnetic shape memory alloys. The theory falls into the class of phase-field or diffuse-interface modeling approaches. In addition to the standard mechanical and magnetic balance laws, a two sets of micro-forces their associated balance laws are postulated, one set for the magnetization order parameter and one set for the martensite order parameter. Thereafter, the second law of thermodynamics is analyzed to identify the appropriate material constitutive relationships. The general formulation does not constrain the magnitude of the magnetization to be constant, allowing for the possibilities of spontaneous magnetization changes associated with strain and temperature. The equations governing the evolution of the magnetization are shown to reduce to the commonly accepted Landau-Lifshitz-Gilbert equations when the magnetization magnitude is constant. Also, under certain limiting conditions the equations governing the evolution of the martensite free strain are shown to be equivalent to a hyperelastic strain gradient theory. Numerical solutions to the governing equations are presented to investigate the fundamental interactions between the magnetic domain wall and the martensite twin boundary in ferromagnetic shape memory alloys. Calculations are performed to determine under what conditions the magnetic domain wall and the martensite twin boundary can be dissociated, resulting in a limit to the actuating strength of the material.

6929-95, Session 12

Micromechanical modeling of magnetic shape memory alloy Ni₂MnGa single crystals

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Magnetic shape memory (MSM) alloys are smart materials which can undergo large reversible deformations in an applied magnetic field. As such, they can function both as sensors and as actuators. Compared to the ordinary (temperature driven) shape memory alloys the magnetic control offers faster response, as the heating and especially cooling is slower than applying the magnetic field. Also, the maximum deformation obtained from MSM alloys is larger than in the ordinary magnetostrictive materials. At the moment, the largest magnetic field induced deformations have been observed in Ni-Mn-Ga alloys close to the stoichiometric composition Ni₂MnGa, where strains up to 6 %.

The work affects the micromechanical modelling of the Magnetic Shape Memory Alloy Ni₂MnGa Single Crystal, and accounts the intragranular interaction between variants. Mechanical and magnetic loadings are simulated and discussed.

6929-61, Session 13

Micromagnetic theory of ferromagnetic shape-memory alloys

J. Li, Univ. of Washington

It is widely recognized that the rearrangement of martensite variants in a ferromagnetic shape memory alloy (FSMA) can lead to much higher strain than conventional magnetostriction. In this work, we develop micromagnetic theory to study the magnetic field induced strain in FSMA from energy minimization point of view. For single crystalline FSMA, we show that magnetization rotation can reduce ferromagnetic shape memory effect substantially when motion of the interface is severely hindered under a relatively large stress, which seriously limits the energy density of FSMA actuators. A solution to overcome this deficiency is also proposed. For polycrystalline FSMA, we estimate the magnetic field induced strain from Taylor bound, and identify the optimal textures for maximum actuation strain in FSMA polycrystals of various crystallographic symmetries. These analyses agree well with experiments.

6929-62, Session 13

Energy harvesting using NiMnGa magnetic shape-memory alloys

B. Basaran, H. E. Karaca, I. Karaman, A. I. Karsilayan, Texas A&M Univ.

Magnetic shape memory alloys (MSMAs) are functional materials with the capability to convert mechanical, thermal, and magnetic stimuli into magnetic, mechanical, and thermal responses for potential applications in actuation, sensing and power generation. They offer actuation strains around 10% and response frequencies in kHz regime. MSMAs can harvest waste energy from mechanical vibrations to energize self-powered wireless sensors and actuators. In this talk; feasibility of employing NiMnGa MSMAs as a power harvester, effects of external parameters (applied stress frequency, stroke amplitude, bias field) and materials parameters (magnetic properties, demagnetization) on induced voltage output will be presented. It will also be introduced how to obtain a few milliwatts power output via martensite variant reorientation mechanism under slowly fluctuating loads (10 Hz). Additionally, some guidelines and possible new mechanisms to further increase the power output will be discussed.

6929-63, Session 13

Dynamic strain-field hysteresis model for ferromagnetic shape-memory Ni-Mn-Ga

N. N. Sarawate, M. J. Dapino, The Ohio State Univ.

We present a model for magnetic field induced strain in ferromagnetic shape memory alloys employed in a dynamic actuator consisting of a Ni-Mn-Ga element, return spring, and external mechanical load. Due to magnetic field diffusion and structural actuator dynamics, the strain-field relationship changes significantly relative to the quasistatic response as the frequency of applied field is increased. The model is constructed in three steps: (i) The magnitude and phase of the magnetic field inside the sample is modeled as a 1-D magnetic diffusion problem with applied dynamic field known on the surface of the sample, from where an effective field acting on the material is calculated. (ii) A continuum thermodynamics constitutive model quantifies the hysteretic response of the martensite volume fraction due to the effective magnetic field. (iii) To quantify the dynamic strain output, the actuator is represented as a lumped-parameter 1-DOF resonator with force input dictated by th

e volume fraction. This results in a second order, linear ODE whose periodic force input is expressed as a summation of Fourier series terms. The total dynamic strain output is given by superposition of strain solutions due to each harmonic force input. The model accurately describes experimental measurements at frequencies of up to 250-Hz. Further, this approach can be used to calculate the input field waveform required for obtaining a given strain output.

6929-64, Session 13

Acoustic-assisted, magnetic-field-induced strain and stress output of a Ni-Mn-Ga single crystal

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The effect of acoustic energy input from a piezoelectric actuator on the magnetic-field-induced strain (MFIS) of Ni-Mn-Ga ferromagnetic shape memory alloys (FSMAs) near the composition Ni₂MnGa is observed to enhance the MFIS performance in FSMAs [1]. The threshold field required to induce twin boundary motion is reduced by this new technique by up to one kOe and the strain can be increased by an order of magnitude depending on the magnetic field. The twinning-yield stress is also reduced by the acoustic-assisted effect by up to 0.5 MPa. The significant reduction in the twinning stress or the threshold field by the acoustic-assistance is beneficial to reduce the size of a FSMA actuator with a given output. To appreciate the benefit of the acoustic-assistance better, the stress output of the FSMA actuation under the acoustic-assisted effect was studied.

In this work, the stress-biased, field-induced strain of a Ni₂MnGa single crystal (100-cut measuring 15x5x2 mm) is measured. A cyclic transverse field, driven at 0.01 Hz from 0 to 5 kOe, is applied along the sample's width direction. A constant compressive load is applied to one end of the sample (perpendicular to the field direction). A 33-mode piezo stack is attached at the other end to generate a longitudinal vibration along its length. The sample displacement under varying bias stress is measured with and without piezo assist.

Both operating stress and strain outputs of the FSMA actuation are clearly enhanced by the piezo-assisted effect. Without the piezo-assist, the maximum reversible strain of 3% is obtained in a limited stress range between 0.7 and 1 MPa. With the piezo-assist, the maximum reversible strain increases to 4.5% and appears in a broader stress output range between 0.4 and 1.2 MPa. Smaller magnetic energy is required for twin motion as the twinning stress is reduced by the acoustic assist; the unused magnetic energy can be utilized to work against a larger external stress.

The piezo assist effect on FSMA actuation can be understood in terms of the alternating stress waves provided to facilitate twin boundary motion. Acoustic wave theory, based on elastic and isotropic assumption, is used to estimate the amplitude of stress waves. The applied stress values from acoustic wave theory are comparable to the measured yield stress reductions. The empirical stress wave amplitudes are generally lower than the calculated ones, because the actual stress waves generated in FSMA are limited by inelastic and anisotropic nature of the FSMA samples.

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6929-66, Session 14

Effects of aluminum additions in polycrystalline iron-gallium (Galfenol) alloys

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Galfenol alloys show promise as a new magnetically activated smart material based on their unique combination of relatively high magnetostrictive performance and good mechanical robustness. Investigations of aluminum additions to single crystal iron-gallium alloys have been done previously, and the magnetostrictive response seems to follow the rule of mixtures with decreasing saturation magnetostriction with increasing aluminum content. Aluminum is assumed to substitute for Ga directly in the alloy. Directionally solidified polycrystalline Galfenol alloys with aluminum additions were produced to determine the effects on the magnetic properties. Iron-gallium-aluminum alloys were investigated for two primary reasons: (1) Fe-Al alloys are well established and are typically manufactured using conventional thermo-mechanical processing techniques such as rolling; it is anticipated that aluminum additions will aid in the development of Galfenol alloy rolled sheets (2) Gallium prices continue to rise and a cost effective alternative needs to be investigated.

Several Fe-Ga-Al alloy compositions were prepared using the Free Stand Zone Melting (FSZM) directional solidification technique. Alloy composition ranges investigated include: Fe(80.5)Ga(x)Al(19.5-x) (4.9 ≤ x ≤ 13), Fe(81.6)Ga(y)Al(18.4-y) (4.6 ≤ x ≤ 13.8), and Fe(85)Ga(z)Al(15-z) (3.75 ≤ x ≤ 11.25). Alloys were studied using EDS (chemistry verification), EBSD (crystallite orientation), and magnetic characterization techniques to determine the effect of aluminum addition on the polycrystalline binary Fe-Ga system. Magnetic properties such as saturation magnetostriction (λ_{sat}), piezomagnetic constant (d_{33}), and relative magnetic permeability (μ_r) of directionally solidified Fe-Ga-Al polycrystalline alloys will be compared to binary Fe-Ga alloys including investigations into the crystal orientation effects on these properties. Preliminary results suggest that close to 5 at% or more aluminum can be added to the alloy while maintaining considerable saturation magnetostriction. Further results will determine the effect aluminum addition has on the crystal growth process.

6929-67, Session 14

Elastic properties and auxetic behavior of Galfenol for a range of compositions

H. Schurter, A. B. Flatau, Univ. of Maryland/College Park

Iron-gallium alloys (known as Galfenol), are one of only a few metal alloys known to exhibit large auxetic or negative Poisson's ratio behavior, with measured values of as low as -0.6 and lower. In contrast to most other auxetic materials, this alloy also typically has a high modulus of elasticity (~50-60GPa) and other desirable properties including that it is magnetostrictive. This makes it a unique material that may be well suited for novel applications that no existing metals can achieve. The mechanical properties, including the auxeticity, of Galfenol are strongly dependent on the composition. This research seeks to measure the elastic properties of Galfenol through a range of practical compositions (from about 15% gallium to 33%) in order to create a thorough database as well as present trends in the elastic properties. Other researchers have measured the elastic properties of a few specific compositions, but each used different testing methods, and there are large gaps in the data. This project aims to create a complete, uniform database of the elastic properties of Galfenol, specifically the modulus of elasticity, Poisson's ratio, elastic constants, and elastic anisotropy. This will be achieved through tensile testing of single-crystal Galfenol dog-bone-shaped specimens of varying compositions. For each composition, there will be one specimen aligned along the [100] crystallographic axis and one aligned along the [110] axis. This project will enable future researchers to confidently know the elastic properties of the alloy, as well as enable them to select the alloy with optimum elastic properties for their applications.

6929-68, Session 14

Miniature spherical motor using iron-gallium alloy (Galfenol)

T. Ueno, The Univ. of Tokyo (Japan); C. Saito, N. Imaizumi, Namiki Precision Jewel Co., Ltd. (Japan); T. Higuchi, The Univ. of Tokyo (Japan)

We propose a miniature spherical motor using Iron-Gallium Alloy (Galfenol). This motor consists of four square of magnetostrictive material (Iron-Gallium alloy, Fe_{81.6}Ga_{18.4}) with wound coil, a permanent magnet, iron yoke and spherical rotor placed on the edge of the rods. Magnetomotive force of the magnet is used to provide bias magnetostriction for four rods and attractive force between the rotor and rods. When current for push-pull motion is induced on a pair of opponent coils, the rotor is exerted torque by pushing (expansion) and pulling (contraction) of the rods. One directional rotation is conducted by saw current, where the rotor rotates at slow expansion and slips at fast contraction. The motor can be fabricated small and is strong against mechanical force using Galfenol with ductile and machinable property. In addition, this can be driven with few voltages and lower driving frequency compared with motors of PZT type.

6929-69, Session 14

Fully coupled magnetoelastic model for Galfenol alloys incorporating eddy-current losses and thermal relaxation

P. G. Evans, M. J. Dapino, The Ohio State Univ.

A dynamic, fully-coupled, nonlinear and hysteretic model is presented that characterizes the strain and magnetization response of Galfenol to applied magnetic fields and mechanical stresses. The model provides a framework for characterization, design, and control of Galfenol devices with 3-D functionality subjected to combined dynamic magnetic field and stress loading. A thermodynamic approach determines the local constitutive behavior by considering a Helmholtz energy composed of magnetocrystalline anisotropy, magnetoelastic, elastic energies and a Gibbs energy constructed through Legendre transformation of the Helmholtz energy. Thermal relaxation effects are included by employing Boltzmann statistics while dynamic spatial variation in the magnetic field is incorporated by coupling the constitutive behavior with Maxwell's equations. Subsequent discretization yields an efficient, low-order model suitable for design, parametric analysis, and real-time control of dynamic devices.

6929-98, Session 14

Equivalence of magnetoelastic and elastic energies with stress-induced anisotropy and its use in the Armstrong model for magnetostriction

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Magnetostrictive materials exhibit dimensional and magnetization changes in response to magnetic fields and stresses. The dimensional change due to the application of a magnetic field (inverse effect) is used for actuation. The magnetization change due to stress (direct effect) is used for sensing. The development of new magnetostrictive materials like Galfenol (Fe_xGa_{1-x}) demonstrating moderate magnetostriction and ductile properties enables these materials to be used in applications involving bending, torsion, etc. in 3D structures. Such applications require modeling tools that capture the nonlinear constitutive response of magnetostrictive materials.

Nonlinear modeling of magnetostriction often involves the calculation of the system free energy [1] where the internal states are magnetization and strain and the applied work is due to mechanical stresses and magnetic fields. Alternative energy approaches such as the theory of the magnetomechanical effect [2] and the Armstrong model [3, 4] use an energy devoid of strain by considering the stress-induced anisotropy energy in place of magnetoelastic and strain energy densities. The Armstrong model is of particular interest for 3D applications due its simplicity and ability to quantify the magnetization and magnetostriction in arbitrary directions.

The stress-induced anisotropy energy [5, 6] needs to be investigated for thermodynamic consistency and accuracy. This paper shows that no assumptions are made which would limit the application of the energy containing only magnetization as compared to the energy containing both magnetization and strain. The internal energy of the system is expressed as the sum of the magnetocrystalline anisotropy, elastic, and magnetoelastic energy densities. The Gibbs free energy is then formulated as the Legendre transformation of the internal energy, assuming isothermal and isentropic processes. Finally, a total energy devoid of strains is obtained by assuming that the strains follow the equilibrium strain functions of magnetization and stress. Inspection of this reduced energy shows that it includes the magnetocrystalline anisotropy, stress-induced anisotropy, and magnetic work energy densities. In the absence of assumptions on the magnetomechanical coupling, it is concluded that the validity of models using stress-induced anisotropy energy in place of the magnetoelastic and elastic energies is not affected by this substitution. Finally, 3D modeling of the inverse and direct effects using the Armstrong model - recently employed to model the magnetomechanical behavior of Galfenol [7] - is discussed.

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6929-70, Session 15

The performance improvement of Galfenol laminated rod with stress annealing

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Magnetostrictive materials are distinguished by the phenomenon of dimensional changes occurring in response to changes in magnetization of a ferromagnetic material. However, the usual preparation of magnetostrictive materials does not build in any preferred direction of the strain. In a material with a positive magnetostriction, a compressive stress drives the magnetic moments to point in a direction perpendicular to the stress axis. Here, a magnetic field applied along the stress axis rotates the moments parallel to the stress axis and this generates the maximum magnetostriction. This built-in uniaxial magnetic anisotropy can be achieved through stress annealing to hold the magnetic moments perpendicular to the rod axis without the application of an external stress. This built-in uniaxial anisotropy has the effect of extending the high power capability of these alloys to operate under both tensile as well as compressive loads [1].

The recent discovery of Galfenol as a "large" magnetostrictive material (as high as 400ppm) offers a particularly promising candidate material that combines largely desirable mechanical attributes with superior magnetic properties [2]. Even though the high permeability of the material makes it easy to design a magnetic driver, eddy current losses at high frequencies result in high power losses. To reduce the eddy currents losses, the driver rods are laminated for high frequency applications.

The objective of this study is to develop an appropriate process to build in a high uniaxial anisotropy in laminated Galfenol rods. The stress annealing device used has a hydraulic actuator to apply compressive stress to the sample. In this configuration, two linear guides were included to ensure a normal compression load to reduce the buckling of thin laminations. In addition, a mechanical holding fixture was used to maintain proper alignment of the thin laminations during stress annealing. Data are presented that demonstrate the magnetic uniaxial anisotropy developed by stress annealing for laminated Galfenol rods.

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6929-71, Session 15

Magnetomechanical coupling factor and energy density of single-crystal iron-gallium alloys

S. Datta, A. B. Flatau, Univ. of Maryland/College Park

Magnetostrictive Iron-Gallium alloys (Galfenol) exhibit high free strain of 350 ppm at low magnetic fields of 200 Oe and have also shown high stress sensitivity of 30 T/GPa thus making them promising materials for actuator and sensor applications. With a Young's modulus of 65 GPa and tensile strength of 515 MPa Galfenol can be used as a structural magnetostrictive material which can work under uniaxial compression and tension as well as under bending or torsional loads. Such advantages offered by Galfenol have motivated the study of its magnetomechanical coupling factor and energy density. The magnetomechanical coupling factor is a measure of the transduction efficiency of the material and the energy density gives a measure of the energy that can be obtained from the material. These two parameters are widely used as figures of merit for comparing different active materials. In this work, an in-house built transducer was used to characterize a 25-mm-long and 6.25-mm-diameter single crystal rod of Fe₈₄Ga₁₆. The actuator characterization involved subjecting the sample to different compressive pre-stresses and acquiring the magnetic induction and magnetostriction data as a function of the applied quasi-static magnetic field at each constant stress state. The sensor characterization involved subjecting the sample to various magnitudes of DC bias magnetic fields and acquiring the magnetic induction and strain data as a function of the applied quasi-static stress cycle at each value of constant bias field

in the sample. A feedback controller was used to keep the DC magnetic bias fields constant. An energy based approach was used to model the magnetic induction and strain in the sample as a non-linear function of the applied stress and magnetic field. The material parameters such as relative permeability, Young's modulus and magnetomechanical coupling coefficient were evaluated using the experimental data as well as the energy based model and were used to calculate the magnetomechanical coupling factor as a function of the stress and magnetic field in the material. The material parameters were also used to calculate the energy density of the Galfenol sample. Coupling factor as high as 0.98 and energy density of 3.5 kJ/m³ were observed.

6929-72, Session 15

Modeling and computational analysis of materials exhibiting intrinsic magnetomechanical coupling at finite strains

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Active and multifunctional materials used in modern actuator, sensor and smart structure applications exhibit different combinations of thermal, electrical, magnetic and mechanical coupling. Magnetomechanical coupling, for example, is exhibited by piezomagnetic, magnetostrictive, magnetorheological materials as well as ferromagnetic shape memory alloys (MSMAs). Magnetorheological elastomers (MRE), in which the stiffness and damping properties can be controlled by magnetic fields, are often subjected to strains of a few hundred percent.

A general modeling approach for such materials is presented which a priori ensures objectivity, properly accounts for rotations and uses a frame-invariant description of material symmetries; issues that have relevance even for materials only exhibiting small or moderate strains. The modeling of these materials is often complicated by the lack of computational tools to solve fully-coupled boundary value problems. To overcome this difficulty a finite element formulation has been developed which solves the coupled magnetostatic and mechanical equilibrium equations for a typical material, e.g. a generalized Neo-Hookean material with simple magnetomechanical coupling, in a finite strain setting. Different sources of magnetomechanical coupling are accounted for, namely the constitutive behavior, magnetic force, couple terms in the momentum balance, the deformation of the computational domain for the magnetostatic problem, and interface jump conditions. The formulation of the algorithmic setting is described in detail and numerical results for technologically relevant example problems are presented.

6929-73, Session 15

Translatory and wobbling magnetostrictive actuator

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We present a magnetostrictive actuator composed with a quadratic shaped Fe-Ga bar (1mm², 10 to 15mm in length) having opposite and orthogonal positioned U-shaped slit at the each end, and a Fe-Ga block with the same cross-section connected in series at the one end. Yokes in the U-shaped slits are laminated with a kind of negative magnetostrictive material, and are put in driving coils. To control the driving current, we are able to create both translatory and wobbly motions at the tip of the actuator bar. We also demonstrate dynamic characteristics of the actuator.

6929-74, Session 15

Fully coupled model for the direct and inverse effects in cubic magnetostrictive materials

P. G. Evans, M. J. Dapino, The Ohio State Univ.

A fully-coupled, nonlinear and hysteretic model is presented that characterizes the strain and magnetization response of Galfenol to applied magnetic fields and mechanical stresses. The model provides

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a framework for characterization, design, and control of Galfenol devices with 3-D functionality subjected to combined magnetic field and stress loading. A thermodynamic approach is taken to determine the microscopic constitutive behavior by considering a Helmholtz free energy composed of magnetocrystalline anisotropy, magnetoelastic, and elastic energies. Macroscopic behavior incorporating material defects, polycrystallinity, and variable effective fields is modeled by employing stochastic homogenization techniques based on the assumption that parameters such as local coercive and interaction fields are manifestations of underlying distributions. Subsequent discretization yields an efficient, low-order model suitable for device design, parametric analysis, and real-time control.

6929-75, Session 15

Coupling effects of finite magneto-electric laminate composites

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The coupling effects of finite magneto-electric laminate composites (MELC) consisting of piezoelectric and magnetostrictive layers are studied by comparing analytical modeling, finite element simulation, and experimental results. A total of three different piezoelectric volume fractions of 0.17, 0.29 and 0.44 were prepared to investigate the strain variation in the sample and the effective M-E voltage coefficient α bar as a function of bias magnetic field H_{bias} . Analytical modeling incorporating shear lag and demagnetization effects shows substantial strain decay near the free ends while demagnetizing effect additionally decreases the far-field strain values. By using a longer sample with a thinner and stiffer bonding layer, the shear lag effects can be reduced. When a magnetostrictive layer with smaller relative permeability values and higher aspect ratio (i.e. longer length) is used, the demagnetization becomes less significant. Similar results are obtained through the finite element (FEM) simulation with emphasis on the position dependent deformation and electric performance of the piezoelectric material. The analytical predictions agree with the experimental results well within 5 % for all samples. This demonstrates that shear lag and demagnetizing effects must be considered for the finite MELC.

6929-76, Session 15

Predicting relationship between magnetostriction and applied field of magnetostrictive composites

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Previous theoretical studies on magnetostrictive composites only focused on predicting its saturation magnetostriction, while little study predicting the applied field needed to reach saturation and the relationship between magnetostriction and applied field. In this study, single inclusion model is established based on the assumption of the induction field experienced by the single particulate embedded in the matrix is the sum of two parts: one due to the pure matrix and the other due to the magnetization of the particles. Using above model, the relationship between the effective magnetic field and the applied magnetic field is established. Combined with the relationship between magnetostriction of magnetostrictive particulate and effective field, the relation between the magnetostriction of single particle to the applied field is also built up. Then treating the magnetostriction of particulate as an eigenstrain, the average magnetostriction of the composites under any applied field as well as saturation magnetostriction is also calculated based on Eshelby equivalent inclusion and Mori-Tanaka method. The results indicates that magnetostriction of magnetostrictive composites depends on particle shape and volume fraction, 'Young' moduli of matrix and particles and applied field. Finally, experiments are also done for epoxy-bonded Terfenol-D composites to verify the effectiveness of the approach

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6930-01, Session 1

General Motors/University of Michigan smart materials and structures collaborative research laboratory the first year

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As the field of Smart Materials and Structures matures, it is becoming more viable for commercial mass-production industries. To expedite the transition from an “enabling” field to “competitive” device technologies, General Motors (GM) teamed with the College of Engineering at the University of Michigan (UM) to establish a \$2.9 Million Collaborative Research Laboratory (CRL) in Smart Materials and Structures in 2006. This CRL is a global effort with partners across the nation and world from GM’s Global Research Network such as HRL Laboratories in California and GM’s India Science Lab in Bangalore, India. This paper gives a brief overview of the mission, infrastructure and collaborative philosophy core to the CRL. It also summarizes progress made during the first year of the CRL in its three thrust areas. For example, there were several new device technologies developed in the Smart Device Technology Innovation thrust area, from which two different projects will be highlighted. First is the T-latch which is a fully resettable, ultrafast rotary latch actuated by a compactly packaged spooled Shape Memory Alloy wire actuator. Second is the SMART lift, Shape Memory Alloy Resettable Lift for Pedestrian Protection, for which two different approaches were developed from a blank slate through successful demonstration in a hood bay testbed as full-scale prototypes. The Mechatronic System Design Methodology thrust is focused on methodologies, facilities and protocols to aid in the development of leapfrog technologies and successful transition to suppliers. In the first year, state-of-the-art facilities, IDEAS (Innovative Device rEvolutionary Advancement Space) and SMARTT (Smart Material Advanced Research and Technology Transfer) Lab, were established from the ground up, along with methodologies to support the full design cycle from conceptualization to fabricated prototype as well as validation and characterization in an automotive testbed. Progress was also made in developing key protocols for SMA wire shakedown to provide optimally stable long-term actuation performance under a variety of loads, strains, and load forms, as well as packaging strategies such as spooling with the fundamental models to support actuation performance prediction. The Smart Material Maturity thrust area laid the basic science for which all the other CRL work is built upon, completing in the first year a full phenomenological thermo-mechanical model characterization of two types of commercially available SMA wires, and a reduced order SMA actuator model suitable for design and control purposes. The most important accomplishment during the first year is the collaborative relationship built and successful cross-talk between all the thrust areas and amongst the CRL team composed of researchers, students, engineers across the world resulting in synergism between the projects quickening and a reduction in the time between concept and true, applicable results.

6930-02, Session 1

Active material reversible attachments: shape-memory polymer based

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In this paper we detail the joint concept generation and embodiment development by HRL and GMR&D of shape memory polymer (SMP) based reversible-on-demand attachments. Motivating this effort was the realization that reversible-on-demand attachments, if proved to be both feasible and practical, have potentially a wide range of automotive applications, being an enabler for reconfigurable interiors, reconfigurable and relocatable storage compartments and cargo containers, and distributed reversible-on-demand attachment mechanisms for assembly/disassembly of modular vehicle elements, an example being the attachment

of the “passenger pod” to the “skateboard” of the GM Autonomy vehicle.

In this, our initial study of active material enabled reversible-on-demand attachments, our primary focus was on hook-and-loop type fasteners. The approach followed, in broader context, was to incorporate an active material, defined as a material which changes a fundamental mechanical property upon exposure to an appropriate field, in at least one component of the hook-and-loop assembly, in this way allowing a field activated change in the stiffness (raising/lowering) and/or geometry (straightening of the hook) of the component and thus on-demand release of the attachment. In contrast, current hook and loop attachment mechanisms can be easily released only through a peeling action which requires that at least one of the two bodies so attached be flexible. This paper describes the fabrication method and properties of one of the two principle classes of embodiments made during the development of the concept. This class of embodiments, which utilized thermally activated shape memory polymer materials, was shown to exhibit pull-off forces similar to conventional “non-active” hook-and-loop fasteners, and significantly, as desired, was reversible with a reduction in the pull-off force of a factor of ~100. Response times for release of a couple of second were readily achievable though the time required for a full cycle of operation was on the order of several tens of seconds unless forced cooling methods were to be employed. This study was thus successful in demonstrating the feasibility of a thermally activated SMP based reversible-on-demand distributed attachment.

6930-03, Session 1

Behavioral model and experimental validation for spool-packaged shape-memory alloy actuators

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Shape memory alloy (SMA) based actuation has been used successfully in industry, space, and defense for its unparalleled energy and power densities at a level of simplicity that cannot be matched by traditional actuators such as electric motors or fluidic power devices. SMA, when used as an actuator, can take a variety of geometrical forms, but is most often used in the wire form due to lower cost, ability to efficiently and simply heat and control electrically, achievable high speed of response relative to tube and cylinder forms, and higher work densities relative to forms in which SMA can experience shear such as tubes and helical springs. Unfortunately, long lengths of wire are often necessary to achieve reasonable actuation distances, and using wires strictly in tension can cause actuators to have inconvenient package shapes and sizes. By spooling SMA wires around pulleys or mandrels, long lengths of wire can be packaged more compactly. Actuators that spool wire have been shown to produce useful forces and displacements while adhering to packaging constraints in examples including automotive latches, prosthetic and orthotic devices, motion stabilization, and panel deployment. While a spooling technique that wraps wire around pulleys or mandrels has potential to make more customizable, compactly packaged actuators, there is a lack of predictive models for actuator design that account for the variation of stress and strain along the wire’s length and the losses due to friction. Developing a spooling model for actuator design is a critical step toward overcoming the packaging limitations on SMA actuators.

This paper introduces a predictive model for rotary spooled SMA actuators and describes an experimental validation study and the related findings. An analytical model was derived based on quasi-static loads and Coulomb friction, and it predicts actuator displacement as it varies between the austenite and martensite phases using an empirically determined constitutive law to account for SMA’s material behavior. Achievable actuation distance is defined with respect to general geometric parameters (including mandrel diameter, wire length, wire diameter, and wrap angle), material friction parameters, and the external loading profile. The model assumes that when the wire changes phase it is always under pure tension and that the entire wire is either stretching or contracting. This assumption is valid for wrap angles below a “binding” limitation, and the limitation is predicted analytically with the model. To validate the model,

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a spooled test apparatus was built that measures angular deflection and tension of the SMA wire actuator and allows for different spool materials, actuator geometries, and external loads to be tested. The predictions for rotation as a function of applied load and for rotation as a function of wrap angle were tested by measuring the actuator displacement between martensite and austenite through a range of applied loads (1 - 30 N, ~ 10 - 300 MPa) and with several lengths of wire and corresponding wrap angles between ~30 - 720 degrees. While the effect of bending of the SMA wire is not captured in the model, the sensitivity of the model to the wire's curvature was evaluated by testing the actuator deflection as a function of mandrel diameter at different loads and wrap angles. Based on the modeling and experimental studies, this paper provides a predictive tool, which is a key element required for designing compact, customizable packaging for SMA actuators.

6930-04, Session 1

SMARt (Shape-Memory Alloy ReseTable) spring lift for pedestrian protection

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Pedestrian protection has become an increasingly important aspect of automotive safety with new pedestrian impact regulations taking effect around the world. Because it is increasingly difficult to meet these new regulations with passive approaches, active lifts are being evaluated that increase the "crush zone" between the hood and rigid underhood components upon detection of a pedestrian impact. This is a challenging actuation problem due to critical timing, large displacements and subsequent large forces required to lift a hood.

This paper introduces the SMARt (Shape Memory Alloy ReseTable) Spring Lift, an automatically resettable and fully reusable device which introduces added functionality compared to state of the art single use devices. The SMARt Spring Lift is a marriage between conventional and smart material technology using standard compression springs to store the energy required for a hood lift, while using integrated SMA actuators to achieve both an ultra high speed release of the spring and automatic reset of the system for multiple uses. The device can be broken into four different subsystems: lift, release, lower, and reset. During normal driving conditions the device would be in an armed state with the spring in the lift sub-system compressed. Upon detection of an impact, the ultra fast SMA latch in the release sub-system can actuate in under 5 ms releasing the spring to lift the hood. If a deployment should occur without subsequent hood impact, the lower system is activated which uses a pair of rotary SMA latches to release the device from the vehicle frame and lower the hood under its own weight with the lift spring uncompressed. With the hood out of the line-of-sight, the reset subsystem can recompress the spring with the SMA ratchet engine. The ratchet uses "time leveraging", turning multiple short actuations of shape memory alloy wires into a high force large stroke actuator capable of both compressing the spring for automatic resetability and slowly releasing the stored energy for safe servicing. In addition to the description and benchtop experimental characterization of each of these individual subsystems, this paper presents the demonstration of the entire system (two identical, complete prototypes mounted at the rear corners of the hood) incorporated within a full-scale vehicle testbed. Full cycle testing conducted confirms the ultrafast latch release, controlled lift profile, gravity lower to reposition the hood, and spring recompression via the ratchet engine successfully rearming the device for repeat cycles. It is recognized that this device is, however, still at the early stages of development, i.e. it is strictly a laboratory prototype intended for feasibility demonstration only, with extensive additional testing of performance and robustness required in a dynamic impact environment before it should be considered suitable and appropriate to take further in the development process. Subject to these qualifiers, this experimental study was successful in demonstrating the SMARt lift approach as a feasible alternative approach for pedestrian protection.

6930-05, Session 1

Experimental investigation of active adaptability of the SMARt (SMA ReseTable) dual-chamber pneumatic lift device for pedestrian protection

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As technology advances and spreads, an ever increasing percentage of the world is undergoing urbanization with dense populations. These trends force large numbers of pedestrians and automotive vehicles to share common thoroughfares with a higher level of interactivity than seen in the past. One of the primary approaches being investigated within the automotive and supplier industries for pedestrian protection is the use of an active hood lift which increases the crush zone under the hood upon detection of pedestrian impact. These devices are carefully designed and tuned to respond in sufficient time. Such exacting requirements tend to force device specialization. A single hood lift device that could be fitted to a large variety of vehicle platforms, dramatically cutting the time and cost of design, production, and assembly of this pedestrian protective measure would thus be desirable.

The dual chamber SMARt (SMA ReseTable) lift system presented in this paper is an adaptive automatic resettable system that can tailor lift performance to actively compensate for extrinsic effects such as changes in temperature, mass, and vehicle model. This system is a pneumatic spring balanced by compressed air in opposing sides of the pneumatic cylinder. The piston lifts the hood by quickly evacuating the upper chamber via a SMA controlled Quick Exhaust Valve (QEV). Control of the pressure in each chamber allows the system to be automatically reset and allows for the dissipation of energy for safe servicing of the device. Performance of the system can be adjusted in-situ through changes in cylinder pressure and valve opening profile. To demonstrate the device adaptability, two dual chamber prototypes were fabricated and installed within a vehicle hood bay testbed for full-scale demonstration and experimental characterization. Full cycle tests demonstrated the functions of lift, lower and reset. To demonstrate the effect of additional hood mass, 0 to 3 kg, equivalent to 3 in of snow, was added to the back of the hood resulting in an increase of 5 ms or more which can produce lift times out of the acceptable timing window. In-Situ tailorability experiments show that extrinsic factors can be compensated for by as much as 300% before an event by varying the pressure between 50 and 170 psi and by 78% during an event using valve timing. It is recognized that this laboratory prototype is intended for feasibility demonstration only, with extensive additional testing of performance and robustness required in a dynamic impact environment before it should be considered suitable and appropriate to take further in the development process. Subject to these qualifiers, the results from this experimental study indicate that the dual chamber SMARt lift device may be a feasible alternative approach for pedestrian protect with automatic reset/reusability along with capability to adapt in-situ to maintain performance within a narrow timing window by compensating for extrinsic effects such as temperature, mass or vehicle model.

6930-06, Session 2

Establishment of the NSF industry/university cooperative research center on smart vehicle concepts

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This presentation will discuss the steps taken in the establishment of the National Science Foundation Industry/University Cooperative Research Center (I/JCRC) in Smart Vehicle Concepts (SVC), which should become a national focal point for the development of innovative smart material technologies. The Center was successfully launched in July 2007 with NSF support and 11 industrial members. The mission of SVC is as follows: (1) Conduct basic and applied research in advanced smart materials for application to vehicle sub-systems and components, (2) Build an unmatched base of research, engineering education, and technology transfer with emphasis on improved automotive performance, unprecedented safety improvements and enhanced vehicle efficiency,

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and (3) Develop well-trained engineers and researchers (at the MS and PhD levels) with an experimental viewpoint to complement theoretical understanding.

Many vehicle integrators and top tier suppliers have identified smart materials as a future technological and strategic thrust. Nonetheless, three major roadblocks continue to stifle the incorporation of these devices in future automotive designs. First, the typical development cycles of automotive products are inconsistent with the development time frame needed to move smart material technologies from laboratory concepts to next generation automotive products. Second, in contrast to conventional technologies, the commercial smart materials market lacks a technical and supplier infrastructure solely dedicated to transportation applications. Finally, since many of these materials are not being manufactured in large quantities, the cost of production can in some cases be relatively high. In spite of these issues, several smart material based subsystems are currently being offered in production automobiles. Two examples are Delphi's MagneRide system, which consists of a MR fluid based tunable vehicle body damper, and Belkin's piezoelectric based yaw rate sensor. In order to facilitate the incorporation of smart material technologies into the broader automotive framework, SVC lies at the knowledge intersection of academia, vehicle integrators and component and subsystem manufacturers. The Center's faculty and student researchers generate new scientific knowledge, identify and develop novel smart material-based components, subsystems and systems, and advance the associated dynamic models and constitutive relationships. Inherent in these responsibilities are the development of mechanisms for the dissemination of knowledge to practicing engineers who will utilize and incorporate these technologies.

A Planning Conference/Workshop jointly took place on October 19 & 20, 2006 in Columbus, Ohio with an attendance of about 25 company representatives and about 15 faculty and students. As a result of this Conference and subsequent meetings, visits and tele-conferences, with the feedback from the prospective company members, we identified the fundamental research needs and defined the underlying pre-competitive issues in the area of smart vehicle components and sub-systems. The Center and its research program have received overwhelming responses from companies and research organizations. In order to achieve its objectives, the Center cooperates with its industrial partners to conduct R&D and education in 4 thrust areas: (1) Interfacial mechanisms, (2) Adaptive NVH, (3) Safety, and (4) Energy. The Center focuses on active material based composites, piezoelectric and magnetostrictive materials, ferromagnetic shape memory alloys, and MR fluid based devices to achieve force, motion, noise & vibration control performance goals including superior spectral bandwidth, reduced mass, and reduced complexity. We are investigating some aspects of environmental requirements, safety, and comfort and performance, and are developing technologies aimed at reduction in cost, improved reliability, and enhanced functionality. In addition to conducting relevant research, the Center will provide advanced industrial education (short courses, web based tutorials, and conceptual demonstrations) to improve the knowledge and skill base of practicing engineers.

6930-07, Session 2

Model-based design of fluid rectification valves for smart material electro-hydrostatic actuator (EHA)

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Smart Vehicles Workshop

A smart material-based EHA consists of a smart material driver and rectification valves which convert high frequency fluid displacement into pseudo-continuous, low-frequency fluid displacement. These systems reduce complexity and mass compared with distributed hydraulic systems and are particularly well suited for automotive and aerospace applications. The EHA must run in the several thousand kHz range to meet performance specifications while current rectification valves are limited to several hundred Hz. This paper focuses on increasing the rectification speed over the state-of-the-art through model-based design of reed-type rectification valves and needle-type active valves. Several techniques are investigated including inertia, vibration, and pressure based models to quantify the overall EHA. Finite element modeling of fluid-structure interactions and in-

situ valve testing are used to validate the valve models. This model-based design for high bandwidth rectification valves will be used along with a second iteration system model to design a next generation smart material EHA with improved performance and larger bandwidth.

6930-08, Session 2

Drop tests of a magnetorheological energy absorber

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Magnetorheological (MR) fluids (MRFs) are smart fluids that have field dependent rheological properties that can rapidly (5 - 10 ms time constant) be changed from a free flowing fluid into a semi-solid when exposing to a magnetic field. The rapid, reversible, and continuous field dependent variation in rheological properties can be exploited in a MRF-based damper or energy absorber to provide adaptive vibration and shock mitigation capabilities. The magnetorheological (MR) effect can be used to adapt the resistive force to varying payloads, vibration spectra, and shock pulses, as well as other environmental factors. Electro-magnetic coils are typically used to activate the MR effect, and these electromagnetic coils can be controlled electronically, so that feedback control implementation is practical. MR devices have been investigated for a variety of applications including: seismic mitigation, crashworthy vertical stroking helicopter seats, gun recoil alleviation, helicopter stability augmentation.

The focus of this study is the design, fabrication, testing and analysis of a magnetorheological energy absorber (MREA) for nominal impact speeds of up to 6.75 m/s. A key issue in this project, is the accurate analysis of MR flows in the MREA across this speed range. Generally, analyses fall into two categories: quasi-static models and dynamic models. Quasi-static models are usually based on Bingham plastic or Hershel-Bulkley constitutive laws and serve well in sizing analyses for MR device design and for excitations that induce low shear rate flows in the MR valve. Quasi-static models do not adequately represent MREA behavior under impact or shock loads. Therefore, there is a need to develop dynamic models that can capture built-up damper effects such as friction effects due to seals, compressibility, as well as force response due to shock or impact. The focus of this project is to develop experimentally validated design and dynamic response analyses as these are especially needed to improve understanding of MREAs under shock or impact loads.

A key consideration in damper performance is the ratio of the force at maximum field to the force in the absence of field, that is, dynamic range, D . As the piston velocity increases, viscous forces grow stronger than the yield forces, and this dynamic range tends to decrease as piston velocity increases. In the context of shock or impact, the dynamic range is typically defined as the ratio of the average MREA force at maximum field to that in the absence of field. Ahmadian's group examined the controllability of a double-ended MREA subject to impact velocities of up to 6.6 m/s. At 2.2 m/s (86 in/s) a dynamic range of $D=2.75$ was achieved. However, at a speed of 6.6 m/s (260 in/s), the dynamic range had reduced to nominally $D=1$, indicating no controllable damper force was achieved. They hypothesized that the transition from uncontrollable to controllable is related to the transition of fluid flow from turbulent to laminar, which is supported by the analysis in Ref. 3. Browne and coworkers (GM) conducted impact tests of an MR damper at stroking velocities ranging from 1.0 to 10 m/s and showed that the MR damper force could be tuned by adjusting magnetic field. However, it was noted that similar trend was found in these two studies-the dynamic range of the MR damper significantly degraded for high velocities.

The key goals of this study are to improve understanding of MREA behavior and to enable design of MR devices so as to avoid loss of dynamic range at high speeds (herein defined as nominal speed up to 6.75 m/s). To achieve these goals for valve mode MREAs, a nonlinear hydromechanical analysis, considering both laminar and turbulent flow, was derived and an effective design strategy was established. The key conclusion from this analysis was that the flow through the MR valve must be laminar to have sufficient dynamic range (e.g., $D=2$) and the Reynold's number must be kept sufficiently low to ensure this ($Re=850$). To validate the effectiveness of the design strategy at high speeds, a high force bifold valve MREA was designed keeping the Reynolds number was kept below 850. The MREA was then fabricated and tested at UMCP under low sinusoidal velocities using a damper dynamometer. The MREA was also tested at the GM R&D

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Center's Drop Tower Facility for a range of speeds up to 6 m/s in increments of 1 m/s, where a 100 lb weight was dropped onto the damper shaft at these speeds. In these drop tests, the dynamic range was as desired, $D > 2$, over the entire range of speed tested. Also, the hydromechanical analysis was re-examined and refined using the measured MREA force behavior using the drop tower test data. Simulation results from the refined hydromechanical model agree well with the experimental data. Thus, this study had the following conclusions: 1) maintaining a low Reynolds number is essential to achieving a useful dynamic range, where in our case, a $Re = 850$ led to a predicted dynamic range of $D = 2$, 2) a hydromechanical analysis incorporating laminar and turbulent effects is a useful and accurate tool for predicting this MREA for drop test data.

6930-09, Session 2

Nonlinear force feedback control of piezoelectric-hydraulic pump actuator for automatic transmission shift control

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In the last several years, researchers and engineers have investigated the utilization of piezoelectric-hydraulic pumps to replace the current pure hydraulic actuation system in a wide range of applications. For example, recently, the piezoelectric-hydraulic pump system has been explored for the usage in automotive transmissions. This new concept could eventually reduce the complexity, weight, and fuel consumption of the current transmission actuation system. In this research, we will focus on how to utilize this new approach on the shift control of automatic transmissions (AT), which generally requires pressure profiling control for friction elements during a shift operation. To do this, we will consider the 1->2 up shift control using band brake as the friction element. In order to perform the actuation force tracking for AT shift control, two nonlinear force feedback controllers are designed based on the Lyapunov direct method for the given nonlinear system. This paper will describe the modeling of the band brake actuation system, the design of the nonlinear controller, and the simulation and experimental efforts for the demonstration of the new concept.

6930-10, Session 2

Motorcycle-waste heat-energy harvesting smart vehicles workshop

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Due to the surge in environmental concerns and the increase in conservation efforts, energy harvesting research has experienced a rebirth in the last decade. Dramatic breakthroughs in available materials have also created opportunities for new applications of waste heat energy harvesting devices. The Thermoelectric, or Seebeck, effect states that when the junction of two dissimilar metals is heated it will produce a potential difference. Thermocouples are temperature sensors that utilize this effect by having two different metals soldered together and scaling the output voltage. Thermoelectric modules connect multiple thermocouples composed of P and N type thermoelements together electrically in series and have primarily been utilized as cooling devices because of the low efficiencies of the modules. However, with the availability of doped bismuth telluride for use in thermoelectric modules, the efficiencies have risen to a level capable of creating practical waste heat energy harvesting systems that use the Seebeck effect to generate electric power from a temperature gradient. Therefore, thermoelectric generators (TEGs) are being tested for use in various applications in efforts to reduce moving parts, increase mobility, decrease weight, and increase fuel efficiency. An important application that has been receiving much attention recently is the use of TEGs as waste heat energy harvesters for internal combustion engines. With an automobile, the exhaust pipes are underneath the car where airflow is minimal. However, on a motorcycle, the exhaust pipes are typically on the side of the frame completely open to airflow. The focus of this paper is to determine the feasibility of mounting a TEG on the exhaust of a motorcycle in hopes of replacing the alternator with commercially available thermoelectric modules. A 1995 Kawasaki Ninja 250R will be used in this study. It has a two cylinder, 248cc internal combustion engine.

Initial tests with an infrared thermometer after various drives around town and on the highway showed that the headers reached at least 280C. In addition to this temperature being too high for most commercially available high temperature thermoelectric modules, where the typical maximum operating temperature is around 220C, the headers are highly curved and are situated behind the front wheel. Therefore, the ideal location for a TEG would occur farther along the exhaust, right before the muffler. In this location, not only is the outside temperature of the pipe within the operating limits of the modules, but it is more exposed to air flow presenting the possibility of a lower cold side temperature and hopefully a large enough voltage output to feasibly match the alternator output with a TEG.

6930-11, Session 2

Thermoelectrics as elements of hybrid-electric vehicle thermal energy systems

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Despite vast technological improvements, the traditional internal combustion powered vehicle still achieves only 25-30% efficiency, with the remainder lost primarily as heat. While the load leveling offered by hybrid-electric vehicle technology helps to improve this overall efficiency, part of the efficiency gains are achieved by making new systems such as regenerative braking viable. In a similar fashion, thermoelectric (TE) energy recovery has long been considered for traditional vehicles with mixed results, but little has been done to consider thermoelectrics in the framework of the unique energy systems of hybrid vehicles. Besides an increased use for electrical energy, the internal combustion engine on a hybrid vehicle may not run continuously, making it difficult to power belt-driven accessories and maintain comfortable cabin temperatures. Also, in order to maximize the vehicle durability and efficiency and to minimize emissions, it is necessary to regulate engine, battery, and catalytic converter temperatures during this engine cycling.

Previous research on thermoelectrics for vehicle applications has predominantly focused on the viability and design of heat recovery devices between two working fluids-typically two of the following: ambient air, engine coolant, and exhaust gas. In contrast, this research examines thermoelectrics as part of the entire hybrid vehicle thermal energy system. Taking a systems level approach allows for multiple needs to be addressed simultaneously. Thus, the benefits of a system containing thermoelectrics can extend beyond efficiency to also improve passenger comfort and emissions. An example system is shown in Figure 1, where thermoelectrics (TE's) can pump heat when the vehicle is started to preheat the catalytic converter, and operate as a generator after the vehicle has been warmed up. Likewise, a combustion heater could be added to facilitate system pre-heating and engine cycling. This configuration uses a second stage of thermoelectrics for energy recovery between a cool radiator loop and the engine coolant.

In order to evaluate, select, and optimize thermal energy configurations, a computer model was developed to model thermal energy systems in hybrid vehicles. This model used mapped engine data to provide exhaust and coolant heat as functions of engine speed and load. The heat exchangers were modeled using basic heat transfer equations, and the thermoelectrics were modeled with the generated power equal to, the heat input equal to, and the conversion efficiency given by the ratio. This simulation was used to model the two traditional configurations: coolant (hot side) to ambient air (cold side), and exhaust gas (hot side) to coolant (cold side). However, little work has been done on the viability of systems with added fluid loops or split coolant flows. Two novel systems configurations were examined. The first included an additional liquid loop operating between the exhaust gas, via a liquid-gas exchanger, and the hot side of a TE generator system. The cold side of the TE generator system was the engine coolant. The second configuration utilized a split coolant flow system, where part of the engine coolant coming from the engine was diverted through an exhaust exchanger to be further heated while the remainder passed through the radiator to be cooled. These two coolant paths passed through a liquid-liquid TE generator before being remixed and returning to the engine. One major advantage of these systems is the improved heat transfer and simplified exchanger design introduced by using liquid-liquid TE generators. Adding loops and coolant valves also introduces more control variables, thus allowing for improved efficiencies and temperature regulation. Simulation results predicted an energy

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recovery of over 300 Watts generated depending on the configuration, number of thermoelectric modules, and engine speed and load.

A scaled-down benchtop experimental setup was designed and constructed to test the performance of various thermoelectric systems for comparison against the performance predicted by the computer simulation. The experimental setup allowed for configuring the various working fluid flows, using inline air and liquid heaters to simulate engine heat inputted to the exhaust gas and engine coolant, and radiators to cool the coolant. Testing of ten thermoelectric modules placed between simple exhaust gas and engine coolant exchangers yielded 11 Watts, for a thermoelectric conversion efficiency of approximately 2% which is consistent with the modules' specified performance.

Recent work on thermoelectric materials and modules shows tremendous promise for significant improvements in conversion efficiency. In view of these advancements, the performance of projected, improved materials was evaluated, and the viability of recovery systems based on these materials was examined.

In summary, little has been published regarding the opportunities that are offered by the unique characteristics of hybrid vehicles for thermoelectrics in novel thermal energy systems. Systems that may not have been viable or even possible with traditional vehicles may offer improvements to system efficiency as well as emissions, vehicle durability, passenger comfort, and cost. This research described a simulation developed for evaluating and optimizing thermoelectric energy recovery systems and results for four different system configurations. Two novel system configurations were presented which offer the potential for additional benefits such as emissions reduction that will soon be quantified. In addition, a test setup was presented which was constructed for the testing and validation of various thermoelectric recovery systems. These results showed good agreement with expected theoretical results and support the conclusions reached from the computer simulation results.

6930-12, Session 3

Optimum design of MR damper based on FE analysis of electromagnetic field

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Got Higher adjustable force in least time is the main requirement of one MR damper. And optimal structural parameter which can generate highest effective magnetic field and make largest MR magnetic is the important guarantee to realize above requirement. The aim of this work is to find the optimum parameter of the MR damper based on the finite element analysis of electromagnetic field. Consequently, a finite element nonlinear model which considers the coupling of circuit and electromagnetic field was built with ANSYS. In order to accomplish aim of optimization, above model is also integrated into modeFRONTIER software which is apt at optimization. During optimization, the effective amount of the magnetized MR (EAMM), whose definition is the sum of product of effective magnetic strength in MR elements and corresponding elemental volumes, is appointed as the objective function. Using above model, the influence of various structural parameters such as shapes and arrangement of multiple coils on dampers' performance were studied in detail, and design principles of the MR dampers from view of magnetism were given.

6930-13, Session 3

A practical design method for TEP-GT MRFD

J. Li, Dalian Univ. of Technology (China); X. Guan, J. Ou, Harbin Institute of Technology (China)

Magnetorheological fluid damper (MRFD) is a smart controllable damping device, which often plays semi-active actuator in vibration control system. It must have two key properties: the appropriate adjustable damping force and accurate and prompt response. If an accurate and practical design method is provided, the performance of damper will be much easier to achieve. For the above purpose, this paper launches the following research work.

Firstly, mechanical calculation model is established for two-exserted-pole gap type (TEP-GT) MRFD. TEP-GT MRFD is mainly composed of three parts: pole, piston and cylinder. The pole can move out from two ends

of cylinder and there is gap between piston and cylinder. The gap is very small compared with diameter of cylinder, so the behavior of MR fluid in TEP-GT MRFD can be considered as Poiseuille flow of Herschel-Bulkley fluid in infinite parallel plates. Therefore, the relation between damping force and internal dimensions is given.

Secondly, the magnetic circuit model is established for TEP-GT MRFD and the materials and structures of main components are discussed. The results show that pole, piston and cylinder should be made with low permeability material, high permeability material and medium permeability material respectively and the shape of the piston should be cone.

Thirdly, a practical design method for TEP-GT MRFD is obtained and several key expressions are given:

(i)The gap size of damping channel h_m is determined by balancing the adjustable multiples and maximal damping force;

(ii)The relationship between the length of damping channel L_d and diameter of cylinder D_2 is determined by damping force expression;

(iii)The length of coil L_c is determined by magnetic Ohm's law.

Finally, a TEP-GT MRFD for the cable-stayed vibration control system is designed and manufactured. In order to validate the effectiveness of the design method, we compared the design and measured parameters. From the result, we can see that the design is efficient.

6930-15, Session 3

Active component and control design for torsional-mode vibration reduction for a parallel kinematic machine tool structure

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This paper reports the development of an active piezo-based component concerning the design of the mechanical structure and the control. The active component is used for the reduction of torsional vibrations in a so-called tripod parallel kinematic machine structure. Due to this new component the main drawback of the x,y,z-tripod structure was eliminated. The testing results of the 3rd design generation will be presented.

According to nonexisting calculation algorithms the impact of piezoceramic actuators in mechanical engineering is mostly not achieved. By the use of an electro-mechanical analogy, it is possible to map the properties of the piezo actuator. The calculation shows the compliance of the connection between actuators and the adjacent mechanical parts as the most sensitive point of the active component design. With design factors that describe this compliance, the characteristic values of the piezo actuator, blocking force and stroke, were transformed to the active component.

For reducing the structural vibrations two control laws are presented. The first is used to change the properties of the electro-mechanical structure, like damping or stiffness. This is possible by a feedback of motion signals, e.g. velocity. The second one uses the methods of the state space approach to formulate the plant, which includes the passive mechanical structure and the active component. The model is validated by an experimental identification. By using the LQ-algorithm, enhanced by frequency shaping, a model based controller is developed. Both controllers were implemented and tested at the tripod parallel kinematic machine.

6930-16, Session 3

Manufacturing technique for robust and modular smart composites

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Smart composites can be defined as composite structures that through the medium of embedded transducers possess sensory and actuating properties. In engineering practice the embedded transducers are often piezoceramic plates that employ the direct and inverse piezoelectric effect to sense and actuate strain, respectively. Commercially available piezoceramic transducers often come in the form of lead zirconium titanate (PZT) wafers that are coated on both sides with sputtered nickel or silver electrodes. These wafers come in thicknesses ranging from 0.125 mm to 1.5 mm and can be diced to various shapes and sizes.

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Embedding the PZT wafers into a structural composite is beneficial because the wafers are extremely fragile and need protective enclosure to be of practical use as sensors or actuators. The commonly available technique of embedding PZT wafers in polyimide coatings suffers from several disadvantages such as poor strain transfer, temperature sensitivity, and water retention, making a structural composite such as glass or carbon fiber enclosure highly desirable.

The main challenge of successfully embedding the wafers in a composite ply is making a robust electrical connection to both sides of the wafers. This is particularly challenging when multiple layers of PZT wafers are desired. Previous efforts involved the attachment of single wire leads to the electrode surfaces of the wafers. However this technique often proved to be insufficiently robust due to the breaking of the wire leads or the micro-cracking of the PZT wafer under the high-pressure composite curing cycle.

Current paper describes a new approach to the manufacturing of smart composites involving the use of conductive wire mesh layers throughout the composite ply area. The use of such meshes offers several advantages both in terms of the manufacturing process and in terms of the performance and usefulness of the finished product. The manufacturing process is completely compatible with standard composite manufacturing techniques, allowing curing temperatures of up to 350F with standard autoclave or vacuum curing pressures. Standard epoxy matrices can be used throughout the composite ply and no specialized tooling is required. Multiple layers of PZT wafers can be robustly and reliably embedded and each layer can have its own electrical address. The resulting smart composite is entirely modular, since each embedded transducer can be reconfigured on the fly to serve as bimorph or unimorph strain sensor or actuator.

The paper describes in detail how the proposed modular smart composite can be utilized as an active and passive structural health monitoring device as well as part of a high-precision active vibration damping system. Experimental as well as analytical results for these applications are presented. Specific examples include the detection of boundary condition change through transfer function comparison and the active damping of a positioning device. The smart composite is demonstrated in a stand-alone application as well as bonded to a metal structure thus covering most common industrial use case scenarios for smart composites.

6930-17, Session 4

Thermo-mechanical analysis of thin membranes and application in active flatness control design

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Membrane structures are attracting attention as excellent candidates to be implemented in lightweight large space structures, which can be utilized to improve the performance and reduce the cost of space exploration and earth observation missions. Surface accuracy is very important for performance of membrane structures. For membrane antennae and membrane optics, the requirements on membrane surface accuracy are very stringent because surface flatness is crucial to relative phase relationship and hence signal transmission accuracy. On-orbit thermal disturbance is the main cause of membrane wrinkling, which deteriorates surface accuracy of membrane structures and therefore adversely affect the performance of structures. Untensioned membranes have little bending and compressive stiffness. Improper tensioning could cause compressive load and therefore would induce local buckling, i.e. wrinkling. Properly tensioned membranes have finite bending and compressive stiffness to prevent generation of wrinkles. Constant tension scheme, i.e. passive flatness control, do not adapt to time-varying environments, especially thermal disturbances. Active flatness control is superior in adapting time-varying environment. At the Canadian Space Agency, an in-house research project has been initiated to enable the development of a C-band membrane Synthetic Aperture Radar (SAR) antenna. Active flatness control using shape memory alloy actuators (SMA) is used to reduce wrinkling and ensure satisfactory surface accuracy.

In order to properly mitigate wrinkling effect through optimized structure design and active flatness control, several fundamental questions have to be answered. Two of them are to determine the effect of thermal disturbance on wrinkling and to determine the mechanism through which

tensioning force would reduce wrinkling. In this paper, a large displacement Von-Kármán plate theory is used to explain these two effects. A nonlinear ABAQUS model is developed for a corner-loaded square membrane is developed. Artificial imperfection level study, an edge size study and a load ratio study are performed to verify the model. Since plate and shell theory is used, this model can predict wrinkle amplitude and wrinkle number. In this paper, a thermo-mechanical analysis (TMA) procedure is applied to this FE model to evaluate thermal disturbance effects. It is demonstrated thermal disturbance would cause wrinkling of membrane with a bubble shape, which agree with experimental observation very well. The effects of tension forces applied around the boundary in compensating for wrinkling are also demonstrated.

By varying corner loads in the numerical model, it is demonstrated that corner loads could efficiently reduce wrinkles caused by a center-located heat source. There is an optimal tension combination existing for such a disturbance. Using the corner-loaded membrane with different off-center thermal locations, it is showed that corner loads are not always able to reduce wrinkle amplitudes. This raised the question of controllability for active flatness control. Sufficient numbers of tension forces and proper mechanical design are required to achieve an efficient active flatness control system. Designing tensioning systems and active flatness control algorithms for practical membrane structures are discussed.

6930-18, Session 4

A multifunctional satellite structural architecture for operationally responsive space

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The Department of Defense is working to develop an Operationally Responsive Space (ORS) capability, and has recently stood up the ORS Joint Program Office, at Kirtland AFB, NM, in support of that goal. As stated in the "Plan for ORS" [1], "ORS is focused on the timely satisfaction of the urgent needs of the JFC (Joint Force Commander) and other users." The "Plan for ORS" also describes a three-tiered approach to delivering these capabilities to our combatant commanders:

Tier 1: Utilizes existing, or on-orbit capabilities to provide the required space-based capability within days from establishing the need.

Tier 2: Utilizes field-ready, or nearly field-ready capabilities to satisfy warfighter needs within days-to-weeks of establishing the need.

Tier 3: Development of an entirely new, or unforeseen capability, within a year.

In order to meet the unique demands of this approach, the DOD research community has invested heavily in technologies that allow satellites to be designed and assembled via more modular approaches. Today satellites tend to be highly optimized point designs, but these traditional methods will not allow us to meet Tier 3 objectives. Additionally, traditional methods are cost prohibitive (and lead to obsolescence) in order to meet Tier 2 timelines for the wide range of mission that fall under the purview of ORS.

At the Air Force Research Laboratory/Space Vehicles Directorate (AFRL/VS), many technology development efforts are aimed at enabling modular satellite architectures, to include: Space Plug-and-play Avionics [2], reconfigurable thermal management systems [3], autonomous satellite operations [4], satellite design tools, modular flight software, and configuration-independent structural health monitoring systems [5]. This paper describes efforts at the Air Force Research Laboratory's Space Vehicles Directorate to develop, test, and certify a modular satellite structural architecture that meets the following requirements, in support of ORS.

1 Survive the Launch sequence. Provide sufficient strength and stiffness to enable launch on any pertinent launch vehicle.

2 Flexibility to accommodate a wide range of configurations. ORS covers a wide range of potential missions; Intelligence, Surveillance, and Reconnaissance, Communications, Blue Force Tracking, Space Situational Awareness, as well as many currently unanticipated missions. The DOD must be able to maximize mission options, while minimizing inventory, and ensure the ability to incorporate new technologies, as they

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become available.

3 Allow rapid assembly, disassembly. Additionally, integrators must be able to open the satellite rapidly in case components need to be replaced due to failure, or upgrades.

4 The structure must be Multifunctional. Thermal and electrical infrastructure must be integrated within the satellite's structure, so that simultaneous, and/or simplified, mechanical/electrical/thermal connections can be made, via standard interfaces. Additionally, Structural Health Monitoring must be integrated into the structure to enable rapid check-out and structural surety assessments [5].

5 Induce minimal alignment errors. In order to accommodate missions that require high pointing accuracy, the structure must present minimal alignment errors, ensuring precision between the orientation of star-trackers, thrusters, control moment gyros, or other Guidance, Navigation, and Control (GN&C) components, and the primary payload.

6930-19, Session 4

Cross-track infrared sounder isolation system

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Vibration transmitted from a spacecraft bus is a common problem for highly-sensitive precision payloads on space vehicles. Ideally, addressing potential vibration issues early in the design process provides the flexibility to efficiently architect high performance isolation systems. In some cases, vibration isolation is an afterthought in spacecraft design or preliminary analysis indicates it is unnecessary. When more detailed analysis shows that vibration isolation is needed, adding isolators in the later design phases creates packaging challenges that can compromise isolation system performance. For ITT's Cross-track Infrared Sounder (CrIS), bus-to-payload disturbances were not found to be significant until late in the design cycle, necessitating a creative solution to reduce disturbances transmitted to the payload.

This paper summarizes the efforts to optimize the performance of a compliant hexapod isolating the CrIS remote sensing payload from disturbance sources on the spacecraft bus. Trade studies were conducted to determine the effects of volume constraints on vibration isolation performance for the payload consisting of viscous damped "tuned" three-parameter isolators. Increased performance was demonstrated by varying hexapod geometry within a specified volume via an optimization routine in Matlab constructed to vary isolator mounting locations to minimize the mode spread and coupling between degrees of freedom. After the hexapod geometry was fixed, the three isolator parameters were tuned to obtain the desired modal frequencies and damping. The final optimization step occurred after the isolators were manufactured and performance tested. Each individual isolator's measured performance was used in a full-permutation simulation to uniquely place each isolator in its optimal mounting location. System performance tests of the optimized hexapod showed excellent isolation performance that met the needs of the CrIS program.

6930-20, Session 5

Design of piezoceramic-driven synthetic-jet actuator for aerodynamic performance improvement

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The interest in synthetic-jet actuators is elicited by their usefulness in fluid-control applications, including boundary-layer control, combustion control etc. These actuators are zero net-mass-flux device, and generally consist of a diaphragm mounted to enclose a volume of fluid in a cavity. The diaphragm bends sinusoidally, and fluid is periodically absorbed into and ejected from the cavity through an orifice. The outflow entrains the fluid around it and establishes a mean jet flow at some distance from the source. Piezoceramic materials have been employed to drive the actuator diaphragm, especially when actuation frequencies are on the order of

hundreds of Hertz or more. The piezoceramic is glued directly to a silicon diaphragm. In combustion systems, improved turbulent mixing of air and fuel proper can significantly improve efficiency and reduce pollution. In boundary-layer separation control applications, synthetic-jets are used to improve aerodynamic performance by delaying separation and stall over the airfoil. The current work describes the modeling, design and optimization of a piezoceramic-driven synthetic-jet actuator intended to improve aerodynamic characteristics of an airfoil. This task was achieved by running fluid-structure numerical analyses. A separate study consisting of numerical analyses performed with the aid of computational fluid dynamics (CFD) have been run to define the necessary performance parameters for the synthetic-jet actuator.

6930-21, Session 5

Development of a 1/4-scale NiTiInol actuator for reconfigurable structures

R. T. Ruggeri, R. C. Bussom, D. J. Arbogast, The Boeing Co.

Wind Tunnel tests of a NiTiInol based actuator has been conducted for the reconfigurable rotor blade program demonstrating the potential to improve rotorcraft performance by optimizing the configuration of major structures in flight. The actuator is integrated into the rotor blade as a structural element controlling blade twist. A three-blade scale rotor was tested in a Boeing wind tunnel. The tests validated actuator design and performance by demonstrating simultaneous blade twist and control of twist position over the entire test matrix.

Testing of the CDI V8 rotor blades with the RRB actuators consisted of hover testing with tip Mach numbers between 0.50 and 0.705. The maximum hover thrust coefficient was limited to approximately 0.13 at the high tip Mach numbers due to high blade root bending loads. (Higher thrust coefficients were achieved at lower rotor RPM's). Maximum peak accelerations up to approximately 200g were experienced under standard test conditions. In-flight actuation of the blades and intentional blade mis-match cases were also conducted to examine the effect of the blade actuation on steady and transient loads.

The RRB actuator operates by antagonistic actuation of one of two NiTiInol torsional torque tubes by controlling the temperature of both tubes. The NiTiInol tubes were trained to rotate in opposite directions under austenite, and both exhibited substantial two-way shape memory effect. This approach lead to an extremely lightweight and rugged actuator capable of providing powered rotation in both twist directions.

In addition to unusual thermomechanical training the actuator relies on an advanced thermal management system employing thermoelectric modules to control heat flow and temperature. Waste heat is rejected through the blade spar by an advanced high-g thermosiphon capable of operating in the high-vibration, high-g environment of the rotor blade.

The rotary position of the actuator is managed with a new control system designed to effectively deal with NiTiInol hysteresis and reduce input power to the lowest possible value.

A description of system requirements and compromises associated with the actuator and its integration into the rotor blade will be provided and discussed. Test results showed that the RRB actuators were able to successfully twist the blade, control the twist between one twist state and the other, and simultaneously control three rotor blades to change state within 3 seconds of each other despite unanticipated electrical noise in the system.

6930-22, Session 5

Development of highly reliable advanced grid structure (HRAGS) demonstrator using FBG sensors

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There is a growing demand in recent years for lightweight structures in aircraft systems from the viewpoints of energy and cost savings. Composite materials, such as Carbon Fiber Reinforced Plastics (CFRP), are promising candidates that meet these requirements. However, since extremely high

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reliability is required in aircraft systems, composite materials have not been fully applied, especially to commercial aircraft. A structural health monitoring system is one of the most effective technologies to resolve this issue. The authors have therefore continued development of the Highly Reliable Advanced Grid Structure (HRAGS) with the aim of application of the same to aircraft. HRAGS is provided with health monitoring functions that make use of Fiber Bragg Grating (FBG) sensors in advanced grid structures, which have been the focus of attention in recent years as lightweight structures, and is a new lightweight structural concept that enables lighter weight to be obtained while maintaining high reliability. An advanced grid structure is a composite material structure formed by repetitive trusses (grids) made of simple ribs. In principle, a simple stress state exists in this structure. For this reason, a sensor network using FBG sensors with a more rational structure compared to general structures can be provided, with sensors mounted close to the middle of the ribs.

Until now, the authors have continued with the development of manufacturing techniques, design techniques and sensing systems for HRAGS, and have confirmed that the damage occurring in a structure can be detected by the HRAGS Proto System included with these elemental technologies and by FBG sensors embedded in grid structures. Henceforth, to apply HRAGS technology to aircraft structures, a full-scale demonstrator visualizing the actual aircraft structure needs to be built and evaluated so that the effectiveness of the technology can be validated. So the authors selected the wing tip as the candidate structural member and proceeded to design and build a demonstrator for the same. A box-structure was adopted as the structure for the wing-tip demonstrator, and HRAGS panels were used as the skin panels on the upper and lower surface of the structure. In this case, the main loads of the HRAGS are tensile and compressive loads. Next, coupling IF conditions of panels for forming the box structure were studied. Subsequently, a demonstrator using FBG sensors of size 1 x 2 m at 600 points was designed, and it was analytically confirmed to detect damage. Furthermore, an actual structure was made for trial purpose based on the design and evaluated. The results of the design and evaluation of the demonstrator are reported here.

6930-23, Session 5

Stability in hovering ornithopter flight

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Ornithopters have shown promise as mesoscale intelligence, surveillance, and reconnaissance platforms, with capabilities for sustained forward flight, vertical takeoff and landing, and energy harvesting. These abilities may permit extended range, longer endurance, or increased stealth for UAV missions.

A quasi-steady aerodynamics model of ornithopter flight is required for subsequent analysis. The model consists of explicit empirical formulas for aerodynamic forces and moments as functions of the wings' speed and acceleration, and rotational speed and acceleration. The faster computation time (compared to computational fluid dynamics) is bought through discarding vortex dynamics and other flow features in oscillating wing flight. Two quasi-steady models from the literature are discussed (DeLaurier and Wang), with one selected for greater verisimilitude to the ornithopter of given size.

The quasi-steady aerodynamics model is coupled to a dynamic model of ornithopter flight. Previously, the combined model has been used to calculate forward flight trajectories, each a limit cycle in the vehicle's states. The limit cycle results from the periodic wing beat, producing a periodic force while on the cycle's trajectory. This was accomplished using a multiple shooting algorithm and numerical integration in MATLAB. (Jacobians were calculated using an algorithm called automatic differentiation, a method to compute the derivatives of algorithms with vector inputs and outputs.)

This work is expanded with an analysis of hover, a crucial element to vertical takeoff and landing in adverse conditions. A method to calculate plausible wing flapping motions and control surface deflections for hover is developed, employing the above flight dynamics model. Once a hovering limit cycle trajectory is found, it can be linearized in discrete time and analyzed for stability (by calculating the trajectory's Floquet multipliers a type of discrete-time eigenvalue) are calculated. The dynamic mode shapes and control strategies for stabilization and robustness are discussed.

6930-24, Session 5

An analytical study of a novel flow vectoring airfoil via macro-fiber-composites

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A type of piezoceramic composite actuator commonly known as Macro Fiber Composite is used for actuation in a novel airfoil design. Two concepts are analytically studied that can be actuated to output deflection in both direction from a straight mean chord; a thin circular arc airfoil in a bimorph configuration, and a "thick" airfoil that is actuated using MFC actuated unimorphs/bimorphs. Preliminary testing has proven that the concept physically demonstrates the predicted deflection output. Study focuses on aerodynamic and kinematical modeling of the airfoils, and static/dynamic response characterization under aerodynamic loads. Review of literature in the field of smart materials, adaptive structures, and aerospace did not reveal a morphing wing concept that is presented in this study. From a broader perspective, the study aims to understand the behavior of solid-state aerodynamic vectoring under low speed, quasi steady air flow. The wings will be studied in the low Reynolds Number regime for fixed wing aircraft, as well as at higher Reynolds Numbers that is seen in guide vanes for ducted fan aircraft. The high actuation bandwidth of the MFC actuators provides advantage over the conventional control surface actuators that employ mechanical linkages.

6930-25, Session 6

Development and test of an HTSMA supersonic inlet ramp actuator (future of SMA)

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Enabling a new generation of high speed civil aircraft will require breakthrough developments in propulsion systems, including novel techniques to optimize inlet performance in multiple operating conditions. Rapidly maturing smart materials technology can help to enable adaptive control of inlet geometry for in-flight optimization of engine flows while minimizing weight and mechanical complexity. This paper will describe the results of recent NASA-sponsored activity that built on established device technology using Shape Memory Alloy (SMA) actuators and initiated development of adaptive inlet concepts suitable for application to Supersonic Business Jets (SSBJs). A critical element of this work entailed leveraging new developments in High Temperature SMA (HTSMA) device design and testing to enable the first steps in the development of a family of actuation devices for use in flight applications. The project featured mutually supporting design, analysis, and test activities including: analysis of the effectiveness of geometry adaptation in improving installed engine flows at multiple flight speeds; extension of the data base on NiTiPt HTSMA materials for propulsion applications; construction and test of a benchtop adaptive inlet component demonstrator using HTSMA actuators; and wind tunnel testing of a model scale HTSMA-driven ramp control device in high speed flow with loads representative of supersonic flight.

The chief technical output of this effort was initial demonstration of HTSMA technology for actuating a variable geometry, high speed inlet to help meet functional airflow needs of high Mach number propulsion systems. Building on guidance on practical inlet designs from industry, a tabletop demonstrator was constructed to illustrate possible mechanisms for leveraging the available strain/force capability of HTSMA wires for physically useful motion results. In addition, the integrated aero/thermo/elastic models of actuator environment were developed to assist the analysis and design of "smart" propulsion systems incorporating HTSMA devices. Most importantly, wind tunnel test results at loading levels at and above that of supersonic flight at altitude showed the suitability of HTSMA technology for this application.

The paper will describe concept design and development, model fabrication, and test results for both the benchtop demonstrator and the wind tunnel ramp model. Assessment of the effectiveness of the NiTiPt material developed and supplied for support of this project by investigators at NASA/Glenn Research Center will also be outlined. Finally, ongoing work on additional aeropropulsion applications of HTSMAs will be briefly outlined.

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6930-26, Session 6

Stabilizing shape-memory alloy actuator performance through cyclic shakedown: an empirical study

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Shape memory alloy (SMA) wires are used increasingly in place of traditional actuators because of their compactness, high work density, low cost, ruggedness, high force generation, and relatively large strains. One well known issue with SMA wires is a potential degradation in performance as actuation cycles accumulate, with significant reductions observed in their motion generation capability after hundreds or only tens of cycles. To insure stable long-term performance, SMA manufacturers typically provide conservative limits on the suggested maximum force generated by a wire during actuation, ensuring minimal losses in actuator stroke at the cost of reduced overall performance. An alternative approach involves cycling or shaking down the wire under controlled conditions prior to installation, which enables the designer to employ the stable post-shakedown specification of the wire to produce actuators with larger forcing capabilities, fully realizing the high force potential of the SMA material. Since the motion loss during shakedown is highly dependent on the loading and strain history experienced by the wire during cycling (level, form, etc.), an understanding of the relationship between these parameters and the resulting stable motion is required to enable the designer to fully harness the capabilities of SMA actuation.

The work presented in this paper establishes an initial empirical shakedown protocol, providing insight into the motion loss and post-shakedown specifications of SMA wire given a variety of loading/strain profiles. A series of experiments with 15 mil Flexinol 700 C wire were conducted, each over 600 cycles, varying the load form (constant and spring), magnitude (29-78 N) or allowed strain (4-7%) in each trial. Based on the shape of the strain curve plotted from cycling data, a double exponential fit is an excellent predictor of the motion degradation and can be used reliably for all test results. The fit allowed for multiple actuation performance parameters to be calculated, including the amount of lost motion during cycling and the number of cycles required for stabilized performance. Examination of the dependencies of these parameters on the load variations led to three observations. First, varying the maximum allowed strain does not have a significant effect on the percentage of motion lost after cycling. Second, increasing the applied constant load above the supplier's specified threshold load causes an increase in the percentage of motion lost; however, when loads increase above twice the threshold load, the required number of cycles drops by more than 50%. Third, cycling the wire under a spring load with austenite loads and martensite strains matching those of the constant-load tests resulted in 66% less motion loss, with shakedown requiring 28% fewer cycles. The test procedure included the generation of force-deflection curves for each wire before and after cycling in order to understand changes in material properties. These properties provide insight into the origins of the performance variation and suggest potential precautions for wire operation. Shakedown testing revealed multiple material property changes: an increase in the transformation temperature, a decrease in the austenite elastic modulus, a decrease in the martensite stress plateau level, and the introduction of a partial two-way shape memory effect. This preliminary study demonstrates the significant functional dependency of post-shakedown characteristics on the load magnitude, form, and strain level, and that a full understanding of these dependencies can provide the basis for detailed SMA wire shakedown protocols that will enable high performance, stable actuation designs.

6930-27, Session 6

High-temperature shape-memory alloy actuators through mechanical treatments for an oil and gas down-hole valve

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Shape memory alloy actuators, with their simple operation through heating, and high solid state strain and force output are ideally suited to a range

of robust engineering applications within the oil & gas industry, such as down-well flow control valves. Because reservoir temperatures can reach up to 200°C for very deep wells, a range of alloys with high transition temperatures are required. The inducement of mechanical stresses within nickel-titanium alloys can influence the transitional temperature range of the alloy. This characteristic was exploited to raise the martensitic-to-austenitic transition temperature (A_p) of 'NiTiInol Alloy H' (Ni:Ti ratio of 49.5%:50.5%) from 90°C to 130°C, through the application of large compressive pre-stresses (equivalent to 10% compressive strains). Long-term thermal stability tests were carried out to ensure the constancy of the temporarily-raised transition temperature.

Similar treatments and tests were undertaken on fabricated Ni-Ti-Hf alloy (47%:47%:6% Ni:Ti:Hf content). In this case the application of the large compressive pre-strain of 10% to a 7mm diameter rod of this alloy raised the martensitic-to-austenitic transition temperature (A_p) from 160°C to 180°C.

For a specific 'single-shot' valve application, with an operational temperature requirement of 110°C, a robust shape memory alloy (SMA) actuator, capable of delivering a stroke of 2 mm with high force output (4 kN), was developed and tested from the pre-stressed Nitinol alloy H. The actuator acted as an electrically-activated trigger within a hybrid SMA-hydraulic valve. Once activated the actuator releases a high pressure seal allowing stored hydraulic pressure to operate the main mechanism of the valve. The operation of the SMA actuator and complete valve assembly, inclusive of battery pack and control electronics to activate the SMA, was successfully tested within a test-well environment at depths up to 900 metres and under hydrostatic pressures of 7,500 psi (51 MPa).

6930-28, Session 6

Spray forming of NiTi and NiTiPd shape-memory alloys

R. W. Smith, Materials Resources International; R. T. Ruggeri, J. H. Mabe, The Boeing Co.; R. D. Noebe, NASA Glenn Research Ctr.

In the work to be presented, vacuum plasma spray forming has been used as a process to deposit and consolidate pre-alloyed NiTi and NiTiPd powders into near net shape actuators. Testing showed that excellent shape memory behavior could be developed in the deposited materials and the investigation proved that VPS forming could be a means to directly form a wide range of shape memory alloys. The testing and the results of DSC characterization and actual actuation test results will be presented demonstrating the behavior of a Nitinol 55 alloy and a higher transition temperature NiTiPd alloys as torque tube actuators that could be used in aerospace controls.

6930-29, Session 6

Variable area jet nozzle using shape-memory alloy actuators in an antagonistic design (future of SMA)

J. H. Mabe, F. T. Calkins, M. B. Alkislar, The Boeing Co.

A variable area jet engine nozzle can provide considerable benefit to current commercial jet engines and is an enabling technology for future engines. A significant reduction in takeoff and approach noise and improved fuel consumption can be achieved by varying the area of a commercial jet engine's fan nozzle for each flight condition. A larger diameter at takeoff and approach can reduce jet velocity reducing noise.

Adjusting the nozzle's diameter in cruise, to account for varying Mach number, altitude, etc, can optimize fan loading and reduce specific fuel consumption. The added weight and complexity of many proposed Variable Area Nozzle (VAN) concepts using conventional actuators tends to negate any operational gains.

Boeing recently tested a scaled variable area jet nozzle capable of a 20% area change. Shape Memory Alloy (SMA) actuators were used to position 12 interlocking panels at the nozzle exit. The actuator design and operation took advantage of Boeing's significant experience with full-scale testing of SMA based actuation systems to vary the fan nozzle geometry of a GE115B engine. The antagonistic design of the scale model nozzle features a system of opposing SMA beam actuators that allows forces to be actively applied to expand or constrict the nozzle diameter. The system

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does not rely on passive devices such as springs or aero loading to control the nozzle diameter. The nozzle was tested in Boeing's Quiet Air Facility in Seattle. Fully expanded Mach number was varied up to 1.1. A simple closed loop PID control system was used to maintain a range of constant diameters with varying Mach numbers and mass flow rates and to vary the nozzle diameter under constant flow conditions. Acoustic data by side line microphones and flow field measurements at several cross-sections using PIV was collected at each condition.

In this paper the variable area nozzle's design is described including the integration of the SMA beam actuators. The control system performance is shown for both constant diameter under varying conditions and varying diameter area under constant flow conditions. The effect of the nozzle's diameter on its acoustic performance is presented for a range of Mach numbers and mass flow rates. Flow field data is shown including the effects of the joints between the interlocking panels.

6930-30, Session 7

New configurations of oscillatory flow pumps using bimorph piezoelectric actuators

S. L. Vatanabe, R. F. Pires, INOVEO Automação de Sistemas (Brazil); E. C. N. Silva, Escola Politécnica da Univ. de São Paulo (Brazil)

Precision flow pumps have been widely studied over the last three decades. They have been applied in the areas of Biology, Pharmacy and Medicine in applications usually related to the dosage of medicine and chemical reagents. In addition, thermal management solutions for electronic devices have also been recently developed using these kinds of pumps offering better performance with low noise and low power consumption. In previous works, it was presented the working principle of a pump based on the use of a bimorph piezoelectric actuator inserted in a fluid channel to generate flow. The flow direction observed in some prototypes was inverted when compared with two-dimension computational simulations. By performing three-dimensional CFD simulations it was possible to realize that the flow direction was inverted due to the vortex generated around the actuator and its aspect ratio. Thus, in this work we propose the study of novel configurations of piezoelectric flow pumps using bimorph piezoelectric actuators with different aspect ratio. The complete cycle of pump development consists in designing, manufacturing, and experimental characterization steps. The prototype built allowed changing the channel geometric dimensions, such as width and height. Flow rate characterization experimental tests are conducted, providing data that allows analyzing the influence of geometric dimensions in the pump performance. Comparisons among numerical and experimental results are made to validate the computational models and improve the accuracy.

6930-31, Session 7

Study of oscillatory piezoelectric flow pumps using bimorph actuators with different tip geometries

R. F. Pires, S. L. Vatanabe, INOVEO Automação de Sistemas (Brazil); E. C. N. Silva, Escola Politécnica da Univ. de São Paulo (Brazil)

Precision flow pumps have been widely studied over the last three decades. They have been applied in the areas of Biology, Pharmacy and Medicine in applications usually related to the dosage of medicine and chemical reagents. In addition, thermal management solutions for electronic devices have also been recently developed using these kinds of pumps offering better performance with low noise and low power consumption.

In a previous work, the working principle of a pump based on the use of bimorph piezoelectric actuators inserted in a fluid channel to generate flow was presented. The present work aims at the development of novel configurations of piezoelectric flow pumps based on the use of bimorph actuators with different tip geometries that were inspired in fish caudal fin shapes, such as ostraciiform, subcarangiform, carangiform and thunniform. The pump development consisted in designing, manufacturing and experimental characterization steps.

In the design step, computational models of pump configurations are built to perform sensitivity studies and to apply optimization techniques using

ANSYS® finite element analysis software. The sensitivity study analyzes the effect of parameter changes in the flow rate giving information that guides the design of pump electronic control modules. This allows the achievement of a desired flow rate by varying the frequency and amplitude of the applied voltage.

The prototype manufacturing is guided by the computational simulations. The piezoelectric pumps are built using a CNC machine tool and a ceramic cutting tool. Electronic circuits for pump electrical excitation and control are developed and implemented. They include a signal generator that works as a source of a sinusoidal wave with controlled amplitude and frequency, and an amplifier to raise excitation voltage levels to the desired values.

Comparisons among numerical and experimental results are also made to validate the computational results and improve the accuracy of the implemented models.

6930-32, Session 7

Experimental investigation of waveguide dynamics for the medical invasion treatment

A. Bubulis, A. Palevicius, V. Jurenas, R. Bansevicius, A. Rinkevicius, Kaunas Univ. of Technology (Lithuania)

The aim of this article is to provide methods that allow investigating the vibrations of the stainless steel waveguide by combining non-contact techniques with the state-of-the-art multiphysics software. The vibrations of the stainless steel waveguide, used in nowadays surgery, are examined by the aids of the holographic interferometry technique, vibrometer based on Doppler shift of backscattered laser light and the virtual model of the waveguide is created by the Comsol Multiphysics software.

6930-33, Session 7

Temperature-pressure characteristics of SMH actuator using a Peltier module

K. Kim, K. Hong, T. Kwon, D. Kim, N. Kim, Chonbuk National Univ. (South Korea)

This paper presents the temperature-pressure characteristics of a new SMH actuator using a peltier module. The SMH actuator is characterized by its small size, low weight, noiseless operation, and compliance similar to that of the human body. The simple SMH actuator, consisting of the hydrogen-absorbing alloys of copper-pipes type as a power source, Peltier elements as a heat source, and a cylinder with metal bellows as a functioning part has been developed. Peltier effect is heat pumping phenomena by electric energy as one of the thermoelectric effect. So if current is asserted to peltier element, it absorbs heat from low temperature side and emits to high temperature side. In this experiment, Peltier element is used to control the temperature of small aluminum plate with ON/OFF control scheme and fan ON/OFF. To improve the thermal conductivity of the hydrogen-absorbing alloy, an assembly of copper pipes has been used. It is well known that hydrogen-absorbing alloys can reversibly absorb and desorb a large amount of hydrogen, more than about 1000 times of their own volume. The hydrogen equilibrium pressure increases when hydrogen is desorbed by heating of the hydrogen-absorbing alloys, whereas by cooling the alloys, the hydrogen equilibrium pressure decreases and hydrogen is absorbed. The new special metal hydride (SMH) actuator uses the reversible reaction between the heat energy and mechanical energy of a hydrogen absorbing alloys. As the result of experiments, it is proper to act fan only while cooling duration and there exist a proper cooling current to drop temperature rapidly. It takes about 100sec to increase to 70,°f and drop to 35,°f of aluminium plate temperature and about 90sec to increase to 70,°f and drop to 40,°f in ambient temperature 30,°f while fan is on only in cooling duration. The desirable characteristics of SMH actuator, which makes it suitable for the uses in medical and rehabilitation applications, have been also studied.

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6930-34, Session 7

High-resolution interrogator system for fiber grating sensor

S. X. Dong, AT Photonics, Inc.; T. Li, H. Liu, X. Wei, P. Ye, G. Xu, Daqing Oilfield Corp. (China); F. Meng, AT Photonics, Inc.; B. Xu, W. Hao, Daqing Oilfield Corp. (China)

Fiber strain sensor using fiber Bragg grating are poised to play a major Optical role in structural health from military to civil engineering. Fiber Bragg Grating sensor is a practical type of fiber optic sensors. Its measurement is encoded with the wavelength of the optical signal reflected from fiber Bragg grating. The method of measuring the absolute optical wavelength is a critical component of the fiber optic sensing system. To reliably detect very small changes in the environment at the sensor, the interrogation system must provide accurate and repeatable wavelength measurements. This work shows results obtained from the application of an interrogation system with a demodulator system which consist two fiber gratings; one is an extremely narrow bandwidth phase shift fiber grating; the other is normal Bragg grating. Two gratings have same center wavelength and connected by an optical circulator. This demodulator module is controlled by Max1978 which is most accurate complete single-chip temperature controller for Peltier thermoelectric cooler module. The sensing head is an extremely narrow bandwidth Side hole single-mode phase shift fiber Bragg grating. Temperature range is from -40°C to 85°C . A linear response of the sensors was observed. The interrogation system has 0.1 pm resolution.

6930-35, Session 7

A piezoelectric deformable mirror for intra-cavity laser adaptive optics

P. W. Loveday, C. S. Long, A. Forbes, Council for Scientific and Industrial Research (South Africa)

Adaptive optics is used to improve the capabilities of large telescopes by compensating for the effects of air turbulence. The use of adaptive optics inside lasers, to improve the quality of the laser beam, is currently being researched. Intra-cavity adaptive optics is complex due to the build up of transverse optical modes. This paper describes the development of a deformable mirror to be used in conjunction with diffractive optical elements inside a laser cavity. The adaptive mirror will be used to correct for time dependent phase aberrations to the laser beam, such as those caused by thermal expansion of materials.

Deformable mirrors actuated by numerous piezoelectric stack actuators have been developed for telescopes, but this approach is too bulky and expensive for the laser application. MEMS mirror arrays are capable of high spatial resolution but do not provide sufficient deformation for this application. Piezoelectric unimorph mirrors offer simplicity, compactness, low cost and good displacement amplitude and were therefore selected for development.

The unimorph consists of a piezoelectric disc bonded to the back surface of the mirror, which could be aluminium, glass or copper. The rear electrode of the piezoelectric ceramic disc is divided into segments so that a number of different control voltages can be applied to deform the mirror in a desired displacement distribution. The mirror is required to be able to deform in the shape of each of the lower order Zernike polynomials - a set of orthogonal functions that are used to describe aberrations in optical systems. The ability of the mirror to deform in a particular polynomial is dependent on the number and layout of the electrode segments used.

A numerical model of the device will be used to optimise the electrode configuration in order to achieve accurate representation of certain desired shapes. Finally, the device will be constructed and tested. Displacement distributions will be measured with a laser vibrometer during development and finally the Zernike polynomials will be measured using a Shack-Hartman wavefront sensor. This will allow the voltage ratios for displacing an individual polynomial to be determined and to be compared to the numerical predictions.

6930-36, Session 7

High-power piezoelectric acoustic-electric power feedthru for metal walls

X. Bao, W. Biederman, S. Sherrit, M. Badescu, Y. Bar-Cohen, C. M. Jones, J. B. Aldrich, Z. Chang, Jet Propulsion Lab.

Piezoelectric acoustic-electric power feedthru devices transfer electric power wirelessly through a solid wall by using elastic or acoustic waves. This approach allows for the removal of holes through structures. The technology is applicable to power supply for electric equipment inside sealed containers, vacuum or pressure vessels, etc where the holes on the wall are prohibitive or result in significant performance degrade or complex designs. This technology may also be used to realize "plugless" charging for batteries in cell phones or other electronic devices. In the author's previous work, 100-W electric power was transferred through a metal wall by a small, simple-structure feedthru device. To meet requirements of higher power applications, the feasibility to transfer kilowatts level power was investigated. Pre-stressed longitudinal piezoelectric feedthru devices were analyzed by finite element model and an equivalent circuit model was developed to predict the power transfer characteristics to different electric loads. Based on the analysis results, a prototype device was designed, fabricated and a demonstration of the transmission of electric power up to 1-kW was successfully conducted. The methods to minimize the plate wave excitation on the wall were also analyzed. Both model analysis and experimental results will be presented in detail in this presentation.

6930-37, Poster Session

Design, development, and testing of a transonic missile fin employing PBP/DEAS actuators

R. M. Barrett, R. Vos, The Univ. of Kansas; R. De Breuker, Technische Univ. Delft (Netherlands)

This paper describes the design, development and testing of a new class of flight control surface for use on missiles operating from subsonic through transonic flight regimes. At the core of this fin is a new class of driving actuator element which uses the latest techniques to enhance deflection and moment generation capabilities of piezoelectric actuators simultaneously. This Post-Buckled Precompressed (PBP) actuator class employs methods of buckling induction which enhance deflections as the axial forces on piezoelectric bender elements are brought up close to the first buckling mode. Although deflections are increased significantly, actuator blocked force and moment generation levels are maintained through the entire deflection range. Because in-plane tension on the convex actuator face is a notorious problem for ultra-high-deflection PBP-class actuators, Dynamic Elastic Axis Shifting (DEAS) techniques are used to keep the convex face in compression, thereby preserving structural integrity and poling direction. The DEAS system was designed to shift the elastic axis of the actuator element approximately 31mils (787 μm) off the convex actuator face at limit conditions. A set of 7.5mil (191 μm) thick piezoelectric sheets were built into PBP actuators to drive the control surface at deflections up to $\pm 8^{\circ}$, generating moment levels compatible with transonic air loads. The actuators were built into a 6" (15cm) square fin which was tested through maximum velocity in the 3' x 4' (91 x 122cm) subsonic wind tunnel at the University of Kansas. Quasi-static testing in the wind tunnel showed no adverse aeroelastic tendencies. Because the control surface was mass balanced along an appropriately placed pivot line, no dynamic aeroelastic characteristics were noted as a 28Hz bandwidth was verified. Closed form analytical modeling and numerical simulation showed good correlation between theory and experiment.

6930-38, Poster Session

The application of thermally induced multistable composites to morphing aircraft structures

F. Mattioni, P. M. Weaver, K. D. Potter, M. I. Friswell, Univ. of Bristol (United Kingdom)

The always present need for better aircraft performance is increasingly prompting designers towards the realization of morphing or shape-

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adaptable structural systems. Such systems should simultaneously fulfil the contradictory requirements of flexibility and stiffness. So far the solutions adopted consist of complex assemblies of rigid bodies hinged to the main structure and actuated. To enhance the performance of the aircraft as a system, multistable composites could provide an interesting alternative to traditional designs, thanks to their multiple equilibrium configurations. In this paper thermally induced bi-stable composites will be considered for the realisation of morphing structures. This type of structures consists of unsymmetric laminates that are cured flat at high temperature but, when cooled down to room temperature, deform because of a mismatch of thermal properties of the constituent layers.

An approximation of the process may be described as follows: The differences in coefficients of thermal expansion between layers produce a residual stress field during the cooling process. Due to the unsymmetric stacking sequence the neutral axis is shifted away from the middle plane. As a result, at room temperature, the thermal stresses are locked-in and produce twisting and bending moments that lead to out-of-plane displacements. If the geometry meets appropriate requirements, the structure will have more than one equilibrium configuration.

The main characteristic of multi-stable structures is that they can be at the same time flexible and stiff eliminating (in principle) the need for joints and complex mechanical system. If the technology proves feasible, a considerable reduction in weight and complexity is possible. In this paper two possible applications for morphing structures realised with bi-stable composites will be presented. The first is aimed at the realisation of a high-lift device in the form of a bi-stable blended winglet. The key idea is to mount a bi-stable panel, appropriately tailored, on the tip of a traditional wing. The winglet will possess two configurations: an extended configuration that extends the wing-span thus increasing the lift and a deployed configuration when the panel works as a winglet optimising the performance for cruise flight. The second application is aimed at realizing a trailing-edge-mounted device to change the camber of an airfoil by morphing its geometry. This concept relies on unsymmetric lay-up patches whose bi-stability drives the shape change, thus obtaining 2^N stable configurations (where N is the number of unsymmetric patches).

The results obtained from the numerical analysis and from experimental models will be presented.

6930-39, Poster Session

A comparative study of ultrasonic micro-motors based on single-crystal PMN-PT and polycrystalline PZT ceramics

S. A. Wilson, P. Rayner, Cranfield Univ. (United Kingdom); R. C. McBride, J. G. Gore, A. R. Bowles, QinetiQ Ltd. (United Kingdom); N. C. Jones, The Univ. of Exeter (United Kingdom)

A comparative study has been performed to explore the potential benefits of newly available single-crystal ferroelectric materials when used in a practical device, in this case an ultrasonic micro-motor. This type of micro-motor exhibits exceptional power-to-weight characteristics, which could be exploited beneficially, for example, in unmanned air-vehicle (UAV) systems. The operating principles of a range of commercial and experimental motor designs were evaluated objectively in order to identify areas of performance that can potentially be enhanced using PMN-PT single-crystal piezoelectric ceramics. Based on this analysis a practical motor design was selected for construction and experimentation. Detailed numerical analysis indicated that a motor constructed from single crystal PMN-PT could be expected to provide an improvement in motor stall-torque by up to a factor of 2.8 and a no-load speed improvement by a factor of 1.5 when compared with pre-existing motors based on standard polycrystalline lead-zirconate-titanate (PZT) ceramics. This conclusion had the significant proviso that the increased energy of the stator vibrations could be efficiently coupled into rotor motion. Additionally, no allowance was taken in these calculations for non-linearities due to strain-rate or heating effects that may accrue from using the new materials. In practice single-crystal versions of the motor were found to produce double the power output of their polycrystalline counterparts. Overall efficiency was also found to be improved two-fold. There were significant discrepancies between the numerical predictions for the single-crystal devices and their measured performance, whereas the polycrystalline devices were found to perform closely in line with predictions.

6930-40, Poster Session

Design and evaluation of bimorph and sandwich tunable frequency power harvesting devices

W. Wu, Y. Chen, National Taiwan Univ. (Taiwan); C. Lai, Y. Chu, C. Hsu, Industrial Technology Research Institute (Taiwan)

Over the past years, there are growing interests on scavenging energy from ambience for portable and low-power electronic devices. Among these low-power electronic devices, wireless sensor networks combined with piezoelectric power harvesting devices are the most convincing scenario which using piezoelectric cantilever beam structure excited by ambient vibrations to convert mechanical vibration power to electric power and power the wireless sensors. It is known that the environmental excitation frequency will not be always the same as the resonant frequency of the cantilever beam. However, the cantilever beam excited under resonant frequency will have the highest energy output. In this paper, bimorph and sandwich type structure of tunable resonant frequency devices is proposed to shift the resonant frequency of the piezoelectric cantilever beam in real-time to match the environmental excitation frequency in order to increase the power efficiency and harvest more energy. For the bimorph and sandwich structure of laminated PZT cantilever beam, there will be 2 layers and 3 layers of PZT layers, and one for the PZT layers will be used to control the beam resonant frequency by connecting to different electrical loading impedance. The exciting frequency will be monitored by a low-power micro-processor usually used on wireless sensors. The design and fabrication of the bimorph and sandwich beam structure with and without frequency tuning will all be evaluated and detailed in this paper.

6930-41, Poster Session

Quantifying the performance of piezoelectric optical switches

M. Leung, E. Haemmerle, J. Yue, K. A. Razak, M. A. Hodgson, W. Gao, The Univ. of Auckland (New Zealand)

Piezoelectric optical switch prototypes have been successfully built at the University of Auckland. This paper presents the design and fabrication of these optical switch prototypes. Also, the switches' performances are quantified and compared with commercial products. The New Zealand Government New Economy Research Fund (Nerf) project - Piezoelectric Switches for Optical Fibers aims to develop the piezoelectric switching concept into a new commercial product.

The optical switch prototypes are developed based on the new concept that the input fiber is directly moved by the deflection of a piezoelectric tube actuator. The piezoelectric tube actuators used in the switch prototypes are manufactured by an electrophoretic deposition process. The tubes are low cost and compact in size with an inner diameter of less than 1mm. They have a maximum deflection of 30 μm which is adequate to actuate the input fiber for switching.

The multimode and single-mode 1x2 fiber optical switches have been built. To reduce the misalignment loss between the fibers, the output fibers are precisely aligned in silicon v-grooves. As for the single-mode fibre switch, thermally-diffusion expanded core (TEC) fibers are used such that the use of index-matching oil or collimators can be avoided. The prototypes show an insertion loss of <1.5 dB, crosstalk of -47 dB and switching time from 5 to 15 ms. Polarization dependant loss and return loss will also be presented. The switches have been tested in a real world optical network and good reliability. The success in the prototype development will lead to a new optical switch which can be used in communication, optical sensing and testing applications.

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6930-42, Poster Session

Realization and Testing of an Active System for Structure-Borne Noise Control within a Car Chassis

H. Hanselka, M. Thomaier, T. Melz, Fraunhofer-Institut für Betriebsfestigkeit und Systemzuverlässigkeit (Germany)

No abstract available

6930-43, Poster Session

Adaptive structures for manipulation in clean room

C. Lira, F. Scarpal, Univ. of Bristol (United Kingdom)

No abstract available

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6931-24, Poster Session

Study of a low-frequency vibration-to-electricity energy harvester

M. Zhang, K. Lian, P. K. Ajmera, Louisiana State Univ.

As the power consumption of modern electronics and wireless circuits decreases to a few hundred microwatts, it becomes possible to power these electronic devices by using ambient energy harvested from the environment. Among the various available environmental energy forms, mechanical vibration is among the more pervasive energy forms. Recent work in these vibration-to-electricity energy harvesters have been centered on high frequency vibration applications. Although high-frequency mechanical vibrations are more energy rich, for some situations the local ambient environmental vibrations tend to occur at lower-frequencies. For example, the highway vibration frequencies are mainly between 10 ~ 20 Hz and tend to be centered around 15 Hz. This paper discusses the development of a miniature vibration-to-electricity energy harvester based on electromagnetic methods using MEMS technology, targeted on the low vibration frequency regime in the 15 ~ 20 Hz range for potential use in highway health monitoring purposes or in certain biological applications. Innovative design considerations need to be addressed to achieve this goal in a miniature package. For example, a highly pliant material and a heavy seismic mass are needed. In our design, SU-8 is chosen as a part of the composite material for the cantilever beam and seismic mass fabrication. The micro-copper coils are fabricated by an innovative multilayer copper electroplating technique. The mechanical characteristics of the energy harvester are simulated using the finite element method. The power generation capability of the designed energy harvester is reported.

6931-25, Poster Session

Controlled release of salicylic acid from polyacrylamide hydrogel by electric field stimulation

A. Sirivat, S. Niamlang, Chulalongkorn Univ. (Thailand)

The release mechanisms and the diffusion coefficients of salicylic acid - loaded polyacrylamide hydrogels were investigated experimentally by using a modified Franz-Diffusion cell at the temperature of 37°C to determine the effects of crosslinking ratio and electric field strength. The fabricated hydrogels retain their physical shapes and sizes during the experiments along with data reproducibility. A significant amount of salicylic acid is released within 48 hours from the hydrogels of various crosslinking ratios, with and without electric field. The release profile found follows Q vs. $t^{1/2}$ linear relationship. Diffusion coefficient, as determined from the Higuchi equation, increases with electric field strength and reaches the maximum value at electric field strength of 0.1 V due to the electrophoresis force on the drug and it becomes saturated at electric field strengths between 0.5 - 10 V.

6931-26, Poster Session

Nanocrystalline NiZn ferrite for bio-medical applications

S. Thakur, S. C. Katyal, Jaypee Univ. of Information Technology (India); M. Singh, Himachal Pradesh Univ. (India)

Highly uniform, spherical shape, narrow particle distribution, chemical stable with average grain size of 9 nm behaving superparamagnetic at room temperature have been synthesized using reverse micelle technique. Blocking temperature of Ni_{0.58}Zn_{0.42}Fe₂O₄ nanoparticle is about 147 K and shows negligible hysteresis at low temperature. Also Fe²⁺ ions are resist up to a temperature of 473 K. Superparamagnetic behavior and control of Fe²⁺ ions make this ferrite highly suitable for biomedical application such as drug delivery system as a magnetic fluid carrier.

6931-01, Session 1

Innovative smart microsensors for Army weaponry applications (Keynote Presentation)

P. B. Ruffin, U.S. Army Aviation and Missile Research, Development and Engineering Ctr.; C. L. Brantley, U.S. Army Research, Development and Engineering Command; E. Edwards, U.S. Army Aviation and Missile Research, Development and Engineering Ctr.

No abstract available

6931-02, Session 2

Hierarchical nanostructures of bioceramics for new therapeutics

Z. R. Tian, V. K. Varadan, Univ. of Arkansas

No abstract available

6931-03, Session 2

Development of an IrO_x micro pH sensor array on flexible polymer substrate

W. D. Huang, J. Chiao, J. Wang, T. Ativanichayaphong, The Univ. of Texas at Arlington

pH sensor is an essential component used in many chemicals, food, and bio-material industries. Conventional glass electrodes have been used to construct pH sensors, however, have some disadvantages in specific applications. It is difficult to use glass electrodes for in vivo biomedical and food monitoring applications due to size limitation and no deformability. Glass substrates require complicated processes and may be eroded by HF or alkaline solutions. In order to build an integratable sensor array for biomedical applications, we proposed new micro-scale solid-state metal oxide pH electrodes on flexible substrates.

In this paper, we present design and fabrication processes of a miniature pH sensor array on flexible polymer substrates called "smart litmus papers". Polymer substrates provide advantages of low fabrication and material costs, light weights, chemical resistance and bio compatibility.

A sol-gel dip-coating process is used to deposit iridium oxide thin film on flexible polymer substrate. The heating profile has been characterized to compose amorphous iridium oxide thin film. Reference electrodes of Ag/AgCl are formed by electroplating processes. To maintain equilibrium potential of Ag/AgCl, the electrode is immersed in a saturated KCl solution for at least 24 hours. The electrodes are patterned by standard photolithography processes. A near super-Nernstian response has been measured on each sensor of the array with a slope -71.6 +/- 3 mv / pH at 25 degree C within a pH range between 2.8 and 11.4.

Dynamic real-time experiments have been performed in random solutions with pH values from 1.5 to 12.0. The measurements show good sensitivity, stability, and a wide sensing range. The small size, low costs and simple fabrication processes demonstrate great potentials for biomedical applications.

6931-04, Session 2

Screen-printed carbon electrodes for amperometric glucose sensing

L. L. Aryasomayajula, J. Xie, V. K. Varadan, Univ. of Arkansas

The paper describes a disposable electrochemical biosensor for glucose monitoring. The sensor is based on carbon paste immobilized with glucose oxidase and upon screen printed electrodes. The sensor has been tested effectively for the abnormal blood glucose levels->6.9 mM or < 3.5 mM which are the prediabetic and diabetic glucose levels respectively which are seen in the calibration curves. These results are compared with a similar sensor based on Multiwalled Carbon Nano Tubes (MWCNT). The Signal to noise ration was comparatively high apart from the response

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time. The performance of the biosensor was also tested with common interference chemicals (ascorbic acid, uric acids etc.).

Keywords: Glucose, Biosensor, Screen Printed Electrodes, MWCNT

6931-05, Session 3

Nanoscale materials for engineering and medicine (Keynote Presentation)

M. Schulz, V. N. Shanov, Y. Yun, Univ. of Cincinnati

This talk will discuss synthesis, processing, and application of nanoscale materials for engineering and medicine. Materials with nanoscale features are important because almost all solid matter with nanoscale size has new or improved properties compared to bulk materials. These properties depend on the composition, size, and shape of the material, and include high specific strength and modulus, low melting point, high electrical and thermal conductivity, a large surface area to volume ratio, nearly defect-free structure, magnetic and optical properties, and sensing and actuation properties.

Recent advances in nanoparticle synthesis will be presented. A major advance is the development of "Black Cotton™" which is centimeter long carbon nanotube (CNT) arrays grown on large substrates. Another advance is development of carbon nanosphere chain (CNSC) material which has the morphology of carbon onions chained together. CNSC has several advantages compared to carbon nanotubes. CNSC is low cost, catalyst-free, highly electrically conductive, and it has magnetic properties. Nanowires are also interesting for designing new smart materials. Nickel nanowires are metallic and have strong magnetic properties and can be oriented in fluids.

Processing and integration of nanomaterials and their intermediate components into different matrix materials is challenging. Several approaches for post-processing of nanomaterials will be discussed including acid treatment, plasma processing, and approaches for thermal annealing. Biofunctionalization of nanotubes for biosensor applications and approaches for electrochemical analysis will also be outlined.

Applications of nanotechnology under development in our lab include spinning Black Cotton into thread to produce a new smart material with reinforcement, sensing, and actuation properties, use of CNT arrays for electrode and biosensor development, and use of CNSC to make smart composites. Smart composites can be based on almost any combination of nanoparticles and any matrix material. We are developing nano-epoxy, nano-elastomers, and nano-cement that have piezoresistive and piezomagnetic self-sensing properties. The materials are black in color and are electrically conductive.

Future ambitions of our lab include developing a CNT ribbon material that is strong enough to form a cable for the space elevator, tiny biosensors that can work inside the body to monitor important physiological variables, and producing carbon power electronics. Our group believes that "Nanoizing" materials and structures is becoming a new technological science and the smart structures community should take the lead putting nanoscale materials and their devices into our lives.

6931-06, Session 4

Multifunctional low-cost bioceramic nanowires for water filtration

Z. R. Tian, V. K. Varadan, Univ. of Arkansas

No abstract available

6931-07, Session 4

Microwave applications of carbon nanotubes: nano-antennas and nano-switches

A. Ziaei, Thales Research & Technology (France)

This paper provides an overview of potential applications of carbon nanotube devices in microwave technology. The main structural, mechanical, thermal and electronic properties of carbon nanotubes are briefly reviewed. Then, the possibilities offered by metallic carbon nanotubes as nano-antennas

in the E- and W- bands and further are investigated: comparison with macroscopic wire antennas is made, major advantages brought by nanotubes but also technical issues to be addressed are discussed. Finally, the integration of carbon nanotubes in nano-electro-mechanical systems (NEMS) is studied through nano-switches: the contribution of carbon nanotubes is detailed, state-of-the-art is described, as well as our approach of such future nano devices

6931-08, Session 4

Current transport modeling in carbon-nanotube field-effect transistors (CNT-FETs) and biosensing applications

J. M. Marulanda, A. Srivastava, Louisiana State Univ.; A. K. Sharma, Air Force Research Lab.

During the past decade carbon nanotubes have been a subject of extensive research for applications ranging to bio- and chemical sensing, and material for nano-CMOS technology of the future. Their properties and performance are remarkable, surpassing current CMOS technology. This has motivated researchers to examine carbon nanotubes as a substitute material for silicon, and carbon nanotube field-effect transistors (CNT-FETs) as an alternative to CMOS transistors. Although current transport models have already been developed, these are still numerically-based and require a mathematical software realization, which increases the complexity and time of simulation, eliminating as a result, any possibility of SPICE modeling compatibility. It is mainly the complexity and implicit mathematical relationships between the terminal voltages and the charge inside the carbon nanotube that make SPICE compatibility very difficult. In current models, in order to find the charge density in a carbon nanotube for a given gate and drain-source voltage, numerical integration and even iteration are necessary to find the respective voltage inside the carbon nanotube. In an effort to implement a model that is SPICE compatible, this work has partitioned the CNT-FET into three regions of operations. Each region specified by its appropriate limit depending only on the terminal voltages of the device. These regions allow the derivation of explicit-dependency solutions for the equations that describe the charge inside the carbon nanotube. Using these equations, it is possible to predict the charge and voltage values inside the carbon nanotube for any given terminal voltage combination, thus allowing the derivation of a current transport equation, analytically solved, for CNT-FETs. In addition, these current transport characteristics can be used for electrical sensing in bio-materials since carbon nanotubes have dimensions comparable to typical bio-molecules such as DNA.

6931-09, Session 5

Conductive nanoparticles in electro-activated shape-memory polymer sensor and actuator

J. Leng, H. Lv, Y. Liu, S. Du, Harbin Institute of Technology (China)

There is a strong interest in the use of conductive shape memory polymer (SMP) for shape recovery or actuation by passing an electrical current. This presentation will cover the fabrication, characterization and potential electronic application of both multi-walled carbon nanotubes (MWCNTs) and its synergistic effect with short carbon fiber (SCF) on the electro activate shape memory polymer (SMP). Over the past several years Carbon Nanotubes (CNTs) have been touted as being one of the most promising materials for future electronic applications. CNTs are a unique form of carbon filament/fiber in which sheets of sp² bonded graphite with no surface broken bonds roll up to form tubes. Multi-wall CNTs exhibits metallic-like behaviour. Their future application in the electronics industry is based upon several unique properties which the CNTs possess, e.g. they have the highest thermal conductivity, and they can exhibit ballistic electron transport and do not suffer from electron migration. Firstly, the fabrication and characterization of styrene-based SMP filled with MWCNTs was investigated. It is found that MWNTs can incorporate very well with resin after being treated by nitrohydrochloric acid at even higher than 100°C at which the MWNT has the maximum reaction activity, to form sulphonyl on its surface. The glass transition temperature (T_g) of the composite filled with 2, 5 and 8 wt.-% MWNTs measured by differential scanning calorimetry (DSC) is 51.33, 49.57, 49.45°C respectively which

are lower than that of the pure polymer of which is 530C. The resistivity of 8 wt.-% MWNTs sample is 80 ohm•cm with dimension of 8.0_2.0_0.2 cm3 rectangle sheet, it can be triggered by passing an electrical current with a constant voltage of 200 to 500 V.

The second is focused on the synergistic effect of MWNTs and fibrous fillers on the electrical property of composite. It was shown that the particulate additives are dispersed homogeneously within matrix and served as interconnections between the fibers, while the fibrous additives act as long distance charge transporter by forming local conductive paths observed from ZEISS microscope. The existing of short carbon fiber may be considered as a rigid long aggregate of carbon, leading to easy formation of continuous conductive networks, and the amount of the networks generally determines the effectiveness of electrical conductivity. The electrical conductivity of the 5 wt.-% MWNTs and 2 wt.-% SCF composites achieves 3 S/cm. Their shape recovery can be activated by passing an electrical current of 25 V voltages through them, and an insulator-to-conductor transition is evidenced. Then temperature-dependent resistivity test is done to investigate the thermo-sensitive effects in conducting polymer composite, and the composites containing SCF show a classical negative temperature coefficient (NTC) effect ranged from 70°C to 90°C, show a positive temperature coefficient (PTC) effect at the other temperature. So the above characterization of SMP composite is similar with that of pure carbon fiber. Thus smart thermal sensor using conducting SMP composite can be realized through both shape and resistivity change.

6931-10, Session 5

Schottky diode made on cellulose paper with PEDOT:PSS and pentacene

J. Kim, H. K. Lim, S. Y. Yang, K. S. Kang, Inha Univ. (South Korea)

Electro-active paper (EAPap) composed with cellulose has been discovered as a smart material with an interesting actuation phenomenon. Microwave driven actuation of the EAPap actuator is interesting to open the remote controlled robotics. However, commercial Schottky diode can not be utilized for this application due to the heavy weight for the cellulose based actuator. For this reason, we will develop to fabricate micro patterned Schottky diode on EAPap using poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate) (PEDOT:PSS) having high hole mobility. Aluminum (Al) electrode having work function of 4.25eV will be fabricated on the cellulose paper by thermal evaporation, and PEDOT:PSS semiconductor layer will be spin-coated to the Al electrode. Then gold electrode will be fabricated to the semiconductor layer. The semiconductor layer will be modified with organic molecule. After that, the device output current will be measured using probe station.

6931-11, Session 5

Pre- and post-machining and release residual stresses in microelectromechanical systems (MEMS)

M. E. Vechery, Univ. of Maryland/College Park; A. J. Dick, Rice Univ.; B. Balachandran, Univ. of Maryland/College Park; M. Dubey, Army Research Lab.

Microelectromechanical systems (MEMS) are used in a wide variety of industrial and military applications. A major concern in the development of MEMS systems is the presence of residual stress. Residual stress, which is produced during the fabrication of multi-layer thin-film structures, can significantly affect the performance of micro-scale devices. Though experimental measurement techniques are accurate, actual stress measurements can vary dramatically from run to run and wafer to wafer. For this reason, the modeling of this stress can be a challenging task. Past work has often focused on experimental, static techniques for determining residual stress levels in single-layer and bi-layer structures. In addition, these past studies have concentrated on residual stress measurements in thin films as they are being deposited and prior to the release of a particular device.

In this effort, residual stresses in MEMS structures are characterized pre and post micro-machining and release of the structure in question. This

is accomplished by using wafer bow techniques and two techniques based on parameter identification. For one of the parameter identification schemes, frequency-response data are used. For the other scheme, static displacement data are used. The wafer bow technique is suited for determining the residual stresses in thin film layers as they are being deposited and before any micro-machining or release process occurs. On the other hand, the parameter identification technique can be used to determine the average residual stress in a thin film structure after a device has been released. The results obtained by using the different techniques are used to understand how polarization affects the stress state in a piezoelectric device after release and how geometry influences the stress state. The results, which show that the stress levels can be quite different after a device has been released and poled, point to the importance of considering parameter identification schemes such as those described in this effort for identifying residual stresses in multi-layer micro-structures.

6931-12, Session 5

Microcontact printing method for metal micro-patterning with polyurethane mold

J. Kim, K. Han, K. S. Kang, Inha Univ. (South Korea)

The cellulose films can be used as a biodegradable and flexible MEMS due to its electro-active properties. However, it is difficult to apply conventional lithography to fabricate MEMS device due to its nature. So, we applied unconventional lithography. Since PDMS has a modulus less than 10MPa, it is not good for high aspect ratio mold. Therefore, PUA mold with a modulus of 200MPa was used for micro-contact printing. Gold and MPTMS SAM layer were deposited onto the mold. The gold was transferred to the cellulose film. The characteristics of the transferred gold on the film were investigated using FESEM.

6931-13, Session 5

Study on shape recovery speed of SMP, SMP composite, and SMP foam

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Abstract: Shape memory polymer (SMP) receives increasing attention along with its derivants, i.e., SMP composite and SMP foam in recent years. These SMP materials have high potential of engineering applications as actuators attributed to their shape memory effect. So further characterization and comparison on shape recovery speed (SRS) of SMP materials will be required. In this article, after fabricating thermoset styrene-based SMP, SMP/CB (carbon black) composite and SMP foam, we studied their SRS in bending. In addition, we proposed a newly noncontact approach, i.e., using infrared light in vacuum, for actuating these SMP materials for shape recovery. Test temperature is set according to glass transition temperature (T_g) of materials which is obtained from the Differential Scanning Calorimetry (DSC) curves: the T_g is 48 for pure SMP, 65 for SMP/CB composite and 47 for SMP foam. It is shown that SRS of SMP/CB composite is not uniform during the overall recovery process: SRS in angle range 30° -150° is approximate (1.04o/s) and is more quick than that in angle range 0° -30° (0.53o/s) and angle range 150° -180° (0.43o/s) at 90°, and it is the same trend with pure SMP but not so prominent with SMP foam. The results could be attributed to different recovery stress corresponding to different recovery angle for the three kinds of SMP materials. Repeatability of SRS of the three kinds of SMP materials is investigated (at 90°, five times) respectively because macromolecular material is liable to be fatigue in application. It reveal that repeatability of SRS of pure SMP and SMP/CB composite are similarly stable and the former is the better, but it is worse for SMP foam. Temperature-dependent SRS is done to investigate the thermo-sensitive effects of pure SMP and SMP/CB composite only. It is found that higher temperature increases SRS and makes it going uniform during the overall recovery process for the two kinds of SMP materials. In addition, change of temperature has less effect on SMP/CB composite than that on pure SMP. These results are explained preliminarily from the combined action of mechanical losses and elastic modular. Finally comparisons of SRS of the three kinds of SMP materials were done for different angle ranges within a temperature range from 80 to 120, and the results show that SRS of SMP/CB composite is the most quick among them. So, compared with

pure SMP and SMP foam, SMP/CB composite has better stable and quick shape recovery speed. These results are significant for the application of SMP materials as actuators in scientific and technological fields.

6931-14, Session 6

Implantable wireless microsensors for gastroesophageal reflux disease diagnosis and pain management (Keynote Presentation)

J. Chiao, The Univ. of Texas at Arlington

Microsensors have been widely used in medical diagnostic instrumentation. Conventional sensor electrodes or electrode arrays are mostly tethered with wires making them bulky and uncomfortable for long-term in vivo uses. Our research focuses on the development of micro-electro-sensors, utilizing batch-fashion micromachining fabrication techniques, with device architectures suitable for telemetry integration. The goals are to develop miniature implantable wireless sensors for long-term diagnostic and therapeutic medical applications. Two examples of our research projects will be discussed in this presentation.

Gastroesophageal reflux disease (GERD) affects approximately 15% of the adult population in the United States and is one of the most prevalent clinical conditions afflicting the gastrointestinal tract. Precise diagnosis of acid and nonacid reflux episodes helps determine potential treatment approaches. Currently available transnasal multichannel intraluminal impedance probes utilize electrodes positioned along a catheter in one's esophagus to sense the passing reflux. It is uncomfortable for long term uses and therefore produces inaccuracy in measurement.

Aiming for disposable implants that are comfortable to wear and accurate to detect real-time reflux episodes for large-population screening, we have developed a new method to detect gastroesophageal reflux with a microsensor implant based on passive telemetry. The prototype has a size of a capsule consisting of inductive coils, circuitry and planar electrodes. The implant does not require a battery and can be attached to patient's esophagus wall by applying endoscopy. With an external radio-frequency reader, the impedance of the refluxates on the electrodes can be determined by the frequency generated from the circuit. In vitro and in vivo experiments have been conducted and the sensor is capable to distinguish air, drinking water, soft drinks, vinegar and simulated stomach acid.

Clinical studies have shown that neurostimulation at one's spinal cord or brain could significantly inhibit chronic pain. Neurostimulation have also been studied for depression management, Parkinson's Disease tremor control and incontinence management. However, the lack of a feedback mechanism in neurostimulation prevents optimization and quantitative documentation of neuroactivities. We have developed an integrative sensor and stimulator system consisting of a miniature wireless action potential sensor to record neuronal signals and a waveform generator to stimulate designated brain areas. A wearable prototype has been developed allowing simultaneous recording and stimulating. In anesthetized rats, lumbar spinal cord dorsal horn neurons are recorded in responses to various types of peripheral graded mechanical stimuli. Neurostimulation at various parts of the brain with various combinations of electrical parameters shows a comparable inhibition of spinal cord dorsal horns in response to peripheral mechanical stimuli. Compared to those in the control periods, averaged action potential rate decreases significantly for pain stimuli.

In this presentation, we will discuss design consideration and constraints, sensor principles, fabrication, communication methods and experimental results of the GERD sensor and pain management systems.

6931-15, Session 6

Effects of magnetic properties and geometrical structures of magnetic nanotubes on neuron growth

L. Chen, J. Xie, Univ. of Arkansas; M. Srivatsan, Arkansas State Univ.; V. K. Varadan, Univ. of Arkansas

It has been confirmed that functionalized iron oxide magnetic nanotubes are non-toxic and biocompatible for neurons, and they could be used in

regulating neuron growth and activities. In our previous work, we found that both the magnetic properties and the geometrical structures of magnetic nanotubes affect neuron growth. As the magnetic properties of magnetic nanotubes are closely related to their geometrical structures, usually the magnetic properties and the geometrical structures of magnetic nanotubes affect neuron growth and activities in combination, and it is difficult to clearly distinguish the effects of geometrical structures from the effects of magnetic properties. In this work, we will investigate the effects of magnetic properties and the effects of structural properties of magnetic nanotubes, independently.

In this work, two groups of magnetic nanotubes will be synthesized. One group of magnetic nanotubes have the same geometrical structures but with different magnetic properties, while the other group of magnetic nanotubes have close magnetic properties but with different geometrical structures. The control of the geometrical structures will be mainly achieved by using templates with suitable thicknesses and pore diameters, and the control of magnetic properties will be achieved mainly by synthesizing suitable types of iron oxides, such as hematite, magnetite and maghemite. In particular, two special samples will be synthesized. One is the non-magnetic nanotubes which have the same geometrical structures with those of magnetic nanotubes, and the other is the magnetic nanowires which have magnetic properties similar to those of magnetic nanotubes. These two samples will be used to investigate two extreme conditions in neuron culture. In our experiments, the geometrical structures of magnetic nanotubes will be characterized by scanning electron microscopy (SEM) and transmission electron microscopy (TEM); and the magnetic properties of magnetic nanotubes will be characterized using vibrating sample magneto meter (VSM) at room temperature.

The fabricated magnetic nanotubes will be functionalized, and neuron cells will be cultivated on magnetic nanotube mats. The growth of neurons will be observed using an optical microscope and SEM. The effects of the saturate magnetization, remanent magnetization, and coercivity force of the magnetic nanotubes to neuron growth will be investigated, and the effects of length, diameter, aspect ratio, and the void structure of the magnetic nanotubes to neuron growth will be analyzed. This work is important for the optimization of magnetic nanotubes for their applications in neuron science.

6931-16, Session 7

Feasibility of e-paper made with cellulose

J. Kim, K. Cho, K. S. Kang, Inha Univ. (South Korea)

Cellulose is a beneficial material that has low cost, lightweight, high compatibility and biodegradability. Recently electro-active paper (EAPap) composed with cellulose is discovered as a smart material. It also exhibit actuator property through ion migration and piezoelectric effect. Since cellulose acetate (CA) has optically transparent, we focus on optical field application, such as electronic paper, prismsheet, and polarizer film application. Acetone is utilized as a solvent to dissolve CA. Various shape and height patterns, such as circle, honeycomb, and rectangular patterns are fabricated using 12% cellulose acetate solution. The fabricated CA films are stretched put into the sodium methoxide solution in methanol to desubstitute the acetate group. Various saponification (SA) process times are applied to the samples. These regenerated cellulose films have larger mechanical strength than CA films. Although the UV-visible transmittance is decreased as increasing SAP time, the transmittance of the further SAP and stretched film back up near untreated CA film. Most of the compositions are one directional ordered nanofibers. The nanofiber diameter is about 30nm.

6931-17, Session 7

Biomimetic approach to develop electronic sensing cilia for flow velocity sensing in mesoscale vessels

H. Yoon, V. Ramachandran, V. K. Varadan, Univ. of Arkansas

This paper presents a new approach to measure fluid velocity in mesoscale vessels, such as renal tubule or coronary artery for biomedical applications, based on biomimetic architectures of vertically aligned nanowires. By taking advantage of cilia sensing structures, we can find a way to overcome the sensing limit which current engineering technology

faces. According to literature survey, primary cilium on kidney cells can sense luminal flow rate with high sensitivity (10-15 nl/min) in renal tubules. In order to develop biomimetic electric sensing cilia, we introduce a new design and fabrication methods of bottom-up nanostructures on a flexible polyimide substrate. This research has been performed on our existing knowledge base of biological and chemical sensor development with nanowire array on flexible substrates. With the advantage of bottom-up fabrication technology on a thin polyimide substrate, nanostructured flow sensors can provide superior fluid sensing performances without disturbing flow condition. Parallel arrays of "electronic cilium" with the size of few micrometers in length and few hundreds nanometers in diameter has been vertically formed on a thin flexible film, which is comparable size to biological cilium.

In this paper, we present a prototype microelectrode array that utilizes biomimetic sensing cilia on a polyimide substrate. For the fabrication of sensing structure, gold electroplating is applied in a polycarbonate membrane. An applied voltage of -650 mV is used to obtain a growth rate of 2.5 $\mu\text{m/hr}$ for Au nanowires. Vertically aligned nanowires of Au are grown over 90% of pores and mean distance between nanowires is around 0.3 μm for 200 nm diameter nanowires.

The advantages of nanoscale sensing cilia approach are many. First, using mechanical flexibility of nanowires, it will be more sensitive to small flow change. Second, this is direct flow sensing method measuring mechanical bending caused by flow condition. Third, because of small size, it will allow spatial resolution to understand flow evolution in mesoscale vessels. Fourth, scaling the size of fluid sensing structures down to few micrometers long from bottom-up nanofabrication technology on polyimide thin film substrate will measure fluid flow in mesoscale vessels without interrupting original flow in mesoscale vessels. Finally the advantages include low cost development of highly sensitive electronic cilia and their integration with signal processing. With the advantages of biomimetic approach, electronic sensing nanocilia will provide unprecedented opportunities for various biomedical and electronic applications, including diagnostics of cardiovascular disease and monitoring of urine flow in renal tubule.

6931-18, Session 7

Ion-sensitive field effect transistors for pH and potassium ion concentration sensing, towards detection of myocardial ischemia

P. Rai, S. Jung, T. Ji, V. K. Varadan, Univ. of Arkansas

Ion Sensitive Field Effect Transistors (ISFETs) for sensing change in ionic concentration in biological systems can be used for detecting critical conditions like Myocardial Ischemia. Having the ability to yield steady signal characteristics ISFETs can be used to observe the ionic concentration gradients which mark the onset of ischemia. Two ionic concentrations, pH and $[\text{K}^+]$, have been considered as the indicator for Myocardial Ischemia in this study. The ISFETs in this study have an organic semi-conductor film as the electronically active component. Poly-3 hexylthiophene was chosen for its compatibility to the solution processing, which is a simple and economical method of thin film fabrication. The gate electrode, which regulates the current in the active layer, has been employed as the sensor element. Also, the possibility of using a high κ dielectric metal oxide as the gate dielectric was explored. The devices under study here were fabricated on a flexible substrate PEN.

The pH sensor was designed with the Tantalum Oxide gate dielectric as the ion selective component. The charge accumulated on the surface of the metal oxide acts as the source of the effective electric field. The device was tested for pH values between 6.5 and 7.5, which comprises the variation observed during ischemic attack. The potassium ion sensor has got a floating gate electrode which is functionalized to be selective to potassium ion. The device was tested for potassium ion concentration between 0.15 and 6.5 mM, which constitutes the variation in extra cellular potassium ion concentration during ischemic attack. The device incorporated a monolayer of Valinomycin, a potassium specific ionophore, on top of the gate electrode. Solution casting technique was employed for Valinomycin monolayer formation. Preliminary studies of Valinomycin layer formation on the electrode surface were conducted to conclude the optimum concentration of Valinomycin in the solution and the pretreatment to be done to obtain the desired effects.

6931-19, Session 7

Respiration sensors based on carbon nanotube films

J. K. Abraham, L. L. Aryasomayajula, A. K. Whitchurch, V. K. Varadan, Univ. of Arkansas

One of the approaches for the unobtrusive monitoring of respiration rate of sleep apnea patients is the design of meshed-transducers that are wearable with the fabric system. This paper presents the design and development of a yarn-based resistive sensor for the design of a wireless respiration sensor. This sensor uses carbon nanotube nanofilm integrated resistive yarns that could be able to monitor any minute changes in respiratory movement. Since it is integrated to a wearable suit, wireless respiration monitoring could be done using this sensor without any discomfort to a patient.

6931-20, Session 8

Development of a high-performance peristaltic micropump

M. Pham, N. S. Goo, Konkuk Univ. (South Korea)

In this work, we tried to develop a high performance peristaltic micropump and characterize its pumping performance. The micropump has three cylinder chambers which are connected through micro-channels. A circular-shaped mini LIPCA has been designed such that a 0.1mm thickness PZT is used as an active layer. As the results, the actuator has shown to produce large out of plane deflection and consume low energy which can be appropriately employed for medical application like drug delivery system or lab-on-chip devices.

During design process, we performed a coupled field analysis to predict the actuating behavior of a diaphragm and pumping performance. In order to fabricate the optimally designed peristaltic micropump, we used MEMS technique. We evaluated the pumping performance of the present peristaltic micropump and compared it with simulation results. We could show that the present peristaltic micropump has higher performance than those which had been developed before.

6931-21, Session 8

Study on microwave power via rectenna for airship application

K. D. Song, Norfolk State Univ.

Flexible dipole rectenna devices offer an attractive source for the delivery of power to high altitude airships, MAVs (Micro-Aero Vehicles), and smart robots. The power converted by the rectenna can vary due to the distance and receiving angle of the source. Regulating the voltage and current delivered to the system will be critical to the proper operation of the remote device. There are many different methods for the regulation of the power received and, in this paper, their applicability will be presented. Simple to complex regulators are explored including: Zener diodes, series pass regulators, three terminal regulators and switching mode regulators. Moreover, in this work, these systems were tested to determine which produced the best performance for the application of powering a remote controlled airship. This paper presents power regulation under varying loads, and effectiveness and efficiency under various power loads. In addition, a method for providing stable voltage and current delivered by an array of rectenna on to an airship will be detailed.

6931-22, Session 8

2D fiberoptic scanning microdisplay system

W. Wang, Univ. of Washington

In recent years, head mounted displays (HMD) have been widely used in areas such as virtual reality, augmented reality [1-2], medical imaging [3], and heads up displays [4]. Most of the commercially available HMD systems use cathode ray tube (CRT) or liquid crystal display (LCD) technologies. All of these have a common principal that an image that is generated electronically is viewed with the optical system of an eye. The image a person sees is subject not only to the quality of the optical system

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of their eyes, but also to the quality of the display and the environment in which the display is located.

More recently at University of Washington Microtechnology lab, our research team has developed a MEMS based on a 2D micro image display device that can potentially overcome the size reduction limits while maintaining the high image resolution and field of view obtained by mirror based display systems. The basic design of the optical scanner includes a micro-fabricated polymer based cantilever waveguide that is electromechanically deflected by a 2D piezoelectric actuator [6-7]. From the distal tip of the cantilever waveguide, a light beam is emitted and the direction of propagation is displaced along two orthogonal directions. The waveforms for the X-Y actuators and the LED light modulation are controlled using a field programmable gate array (FPGA).

In this paper, we are looking to improve the image quality of our previous piezo-electric driven 2D Optical Display system using an optical fiber scanner. The current display system is able to produce a desired image (FPGA input) via the oscillation an microfabricated cantilever waveguide or optical fiber "pixel" driven by two piezos in perpendicular arrangements; however, the image produced is slightly blurred and unstable. To sharpen the image, a more refined output "pixel" is needed.

To obtain such a "pixel", optical fibers with a tapered tip is to be used on the output end. The use of tapered fibers reduces the light that was misguided by the cladding of the fiber, thus producing a finer "pixel" at each point of the image, reducing the blurriness of the displayed image.

We will be testing optical fibers tapered with two different methods and compare the resulting output image from the system.

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6931-23, Session 8

Millimeter wave identification: concept, applications, and demonstrations

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Radio frequency identification (RFID) systems have already been transferred from research laboratories to industrial applications successfully. The RFID systems operate typically in frequency bands between 125 KHz and 2.4 GHz. This paper presents millimeter wave identification (MMID) concept, which extends the RFID concept to millimeter wave frequencies (30-300 GHz). The MMID system is described as well as experimental demonstrations are presented.

Several unlicensed frequency bands are available at millimeter wave frequencies. Frequency bands around 60 GHz and 77 GHz are interesting for commercial application because of commercially available components and circuits. Millimeter wave frequencies allow new functionalities for MMID systems compared to existing RFID systems, and these are possible mostly because of shorter wave length and wide frequency bands available at millimeter waves. The possible new MMID functionalities include high data rate transfer possibility, miniaturized tags, electrically steerable narrow beam antennas for readers, and pointing capability. The size of a tag antenna is in the range of few millimeters by millimeters below 100 GHz being considerably smaller compared to RFID tag antennas.

Application areas of MMID include bio-sensor networks, where micro sensors can be connected to miniaturized tags. Also, sensors close by each other can be separated and pointed by having a reader with directive antenna/antenna array. Other potential applications include road and transport, telecommunication/gigabit data transfer, as well as wireless identification and monitoring in general.

The MMID concept has been demonstrated both at 60 GHz and 77 GHz. Monolithically integrated tag with Schottky diodes were realized for 60 GHz and heterogeneously integrated tag with Schottky for 77 GHz frequency range, respectively. Figure 1 shows SEM images of the tags. Figure 2 presents measured radiation patterns for the 60 GHz tag. The system demonstrations were carried at both frequencies. Measured backscattering from the 77 GHz tag to reader is shown in Figure 3, when the distance between the tag and 77 GHz reader was over one meter with Ptx ~34 dBm EIRP, and resolution bandwidth of 10 kHz. These are the first MMID demonstrations and the experiments are described more in detail in the full-length paper.

6931-27, Session 8

MEMS-based liquid lens for capsule endoscope

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6932-06, Session 2

Structural health monitoring method for curved concrete bridge box girders

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Curved concrete bridge girders, although subject mainly to vertical loads, have very complex internal forces, stress and strain distribution. As a consequence of horizontal curvature, not only the usual bending moments and shear forces are generated, but also important tensional moments are created. These moments "rotate" the axes of principal tensional stresses increasing the risk of cracking. Post-tensioning can prevent the cracks, but the added compression forces introduced in different directions increase the complexity of stress and strain field. Therefore, the curved post-tensioned concrete girders must be particularly designed and carefully constructed. However, the real structural behavior should be verified, and risks and uncertainties related to structural design and quality of construction minimized. Structural health monitoring is a natural solution for these issues. Structural health monitoring method, based on the use of long-gage fiber optic interferometric sensors and compatible fiber optic interferometric inclinometers, is presented in this paper. A 36 meters long curved post-tensioned bridge box girder is equipped with so-called parallel and so-called crossed sensor topologies, and inclinometers, in order to monitor axial strain, both horizontal and vertical curvature changes, torsion, average shear strain and rotations in both vertical plans. Important parts of structure life such as early age, post-tensioning and first years of service are registered, analyzed and presented.

6932-07, Session 2

Innovative non-contact impedance-based structural health monitoring method

J. Wang, The Univ. of Alabama at Tuscaloosa

This article presents an innovative structural health monitoring scheme using magnetostrictive materials. A magnetostrictive patch is externally bonded on the surface of a host beam. An alternating magnetic field is applied to the magnetostrictive patch by a coil to vibrate the MS patch which excites the host beam. The vibration of the MS patch is constrained by the host structure. The constraining force exerted by the host beam changes the magnetization of the MS patch. This change of magnetization modulates the magnetic flux connecting the coil and the magnetostrictive patch, which leads to the change of the electric impedance of the coil. An analytical dynamic model is established to describe the interaction between the coil, the magnetostrictive patch, and the host beam. Analytical solutions obtained in this study show that the electric impedance of the coil is a function of the mechanical impedance of the host structure. Damage in the host structure changes the mechanical impedance of the host structure, which eventually leads to the change of the electric impedance of the coil. Therefore, changes in the impedance signature are indicative of the presence of structural damage. To evaluate the integrity of the health structure, one only needs to measure the frequency-dependent electric impedance signature of the coil and compare it with the baseline signature taken at the undamaged state of the structure. In this method, the giant magnetostrictive patch is used not only as an actuator, but also as a sensor, and is therefore a collated active sensor. Since no hardwiring is needed to connect the magnetostrictive active sensor to the out power source, this new method provides a non-contact impedance-based damage detection scheme. Compared with the electromechanical impedance method using piezoelectric materials, this new method enjoys the following advantages: a) MS sensors are more rugged and durable than piezoelectric sensors because no electrode or hard wiring are needed; b) EMMI can be easily implemented in rotating and moving parts of a structure whereas EMI has difficulty because hard wire connections between the sensor and power source are often difficult to implement; and c) MS sensors can be fully embedded into the host structure.

6932-08, Session 2

Cement-matrix magnetostrictive smart composites

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Recently, there have been significant advances in using magnetostrictive (MS) particles in a polymer matrix to form magnetostrictive particulate composite (MPC). This composite can be used as sensors, actuators, and passive dampers in intelligent structural systems. Compared with other available smart sensors, MPC sensor enjoys the following advantages: a) distributed sensory properties, b) non-contact detection, and c) straightforward manufacturing implementation. However, the available MPC technology is not suitable to be used in concrete structures of which most civil infrastructure are made due to distinct materials mismatches between them. Such mismatches of materials properties lead to poor compatibility between sensors and structures and raise serious concern about the long-term structural integrity. To increase the compatibility with concrete structures, an innovative MS composite material using cement as matrix is developed in this study, based on which, new sensors/actuators can be fabricated. The new composite material consists of two major components, i.e., Terfenol-D (a magnetic anisotropy-compensated alloy $TbxDy_{1-x}Fe_2$ which shows a strong MS behavior) powder and Portland cement. The new composite can be manufactured in a straightforward way, which is very similar to making cement paste. Quasi-static and dynamic tests are conducted to evaluate the smart properties of this new smart material. Testing results suggest that the potential applications of this new smart material in civil structures are very promising.

6932-09, Session 2

**Distributed structural sensing by carbon nanotube-based thin film skins

K. J. Loh, T. Hou, J. P. Lynch, N. A. Kotov, Univ. of Michigan

Traditionally, accurate local structural damage identification over large structural surfaces necessitates the use of massive amounts of densely distributed sensors. However, realistic dense sensor networks are only capable of resolving large localized damage. In this study, a high-performance carbon nanotube (CNT)-polymer composite thin film sensing skin is demonstrated for corrosion monitoring (i.e. to identify progressive corrosion byproduct formation, pitting, and stress corrosion cracks) of metallic structures (e.g. steel and aluminum). As opposed to installing individual sensors at discrete locations, the proposed homogeneous nanocomposite sensing skin uniformly coats and covers the entire structural surface. Fabricated using a layer-by-layer self-assembly technique, the CNT-based sensing skin is designed to undergo conductivity change due to corrosion. By simply taking the skin's boundary electrical measurements and combined with an electrical impedance tomography (EIT) spatial conductivity mapping technique, the EIT algorithm solves the inverse problem to determine the two-dimensional skin conductivity map. Accelerated corrosion tests are conducted on sensing skin-coated steel and aluminum plates while the skin's EIT conductivity maps are obtained periodically to monitor and characterize corrosion progression.

6932-10, Session 2

Concrete structure monitoring based on built-in piezoelectric ceramic transducers

X. Zhao, Dalian Univ. of Technology (China)

Self-developing piezoelectric ceramic transducers were made and embedded in concrete structures in order to monitor cracks under static load in this paper. In the experiment, the components were made in plain concrete and with rebars. The transducers were used as sensors according to the direct piezoelectric effect and actuators according to the indirect

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piezoelectric effect. During the experiment, sine pulse signals are applied on the transducer to generate elastic wave to scan the area between the transducers. As being electronic device, signals of piezoelectric material will be disturbed by electromagnetic wave in environment. Wavelet analysis with its good ability both in time and frequency domain was adopted in filtering the interfering signal. Then damage index was established based on wavelet package entropy. From the change of the damage index, the information of crack occurring and developing has been acquired. And the trend of the index also has a good correlation with that of the strain gauges and optical fiber displacement sensor used in the experiment. Results have shown that the method has the advantages that do not require sensors placed on the point of damage occurring and protect sensors from damage and can be used in the monitoring of civil structure.

6932-05, Session 3

Study on data acquisition system for living environmental information using robots for biofication of living spaces

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"Biofication of Living Spaces" represents our research target to make living spaces safe and comfort by autonomous mechanisms embedded in the living spaces. The key technologies for biofication are sensor networks for acquisition of information and information technologies for effective utilization of information. As a first step toward the target, we tested the feasibility of using cameras, smart sensor networks and robots in gathering information on environments relevant to living spaces. The robots are used as moving sensors and active sensors. In various tools for gathering information, cameras and sensors loaded onto the robots are promising as they can gather a lot of information from various viewpoints and places

In this research, we examine algorithms to distinguish whether the data taken by cameras or measured by smart sensors on the robots are informative or not. Especially we take cognizance of restriction in image processing and sensing by using cameras and sensors loaded onto robots.

We use the mechanisms in the biological systems such as genes or immune systems to distinguish this information. The uniqueness of the biological systems we are interested in is their adaptability to unknown environments in multi-dimensional scales in time and space. The biological systems such as genes or immune systems monitor and attack the foreign intruders and they cook information in such a way the genetic information will be useful to adapt to the unknown environment. The suggested algorithm is adaptable to environmental changes by emulating the mechanisms embedded in biological systems.

6932-11, Session 3

Load monitoring in multiwire strands by interwire ultrasonic measurements

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UCSD, in collaboration with Caltrans, is investigating the combination of ultrasonic guided waves and embedded sensors as an approach to provide prestress level monitoring and defect detection capabilities in concrete-embedded PS tendons.

This work will focus on the prestress level monitoring by first discussing the behavior of ultrasonic guided waves propagating in seven-wire, 0.6-in diameter twisted strands typically used in post-tensioned concrete structures. A semi-analytical finite element analysis is used to predict modal and forced wave solutions in order to isolate features sensitive to the prestress level. In order to monitor such features, low-profile piezoelectric sensors are used to probe the individual, 0.2-in wires comprising the strand. Results of load monitoring in free and embedded strands during laboratory tests will be presented along with recommendations for the transition of the technology to the field.

6932-12, Session 3

Experimental investigation of fatigue behavior of smart CFRP cables embedded fiber Bragg grating sensors

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Carbon Fiber Reinforced Polymer (CFRP) is a new material with properties of high tensile strength, low weight and excellent chemical resistance which make these materials more attractive for stay cables or suspenders of bridges. The smart cables consisting of CFRP reinforced bars through embedding with Fiber Bragg Grating (FBG) strain and temperature sensors have self-sensing properties, as well as good mechanical properties. The fatigue behavior of the smart cables as well as FBG sensors is not fully understood so far.

In this paper, the fatigue behavior of smart cables is experimentally investigated. Three stress levels of 0.6, 0.5 and 0.4 are adopted in the fatigue tests and average stress is kept constant. The loading profile is as follows: upper and lower load range 60% to 70% and 20% to 10% of the theoretical failure load, respectively. An acoustic emission (AE) system is employed to monitor damage initiation and progression of CFRP cables in the static tests and fatigue tests. The two of three narrowband AE piezoelectric transducers are attached at the upper and lower anchorages, respectively; the other is placed at the polyethylene (PE) sheath of the CFRP cables. The signals are continuously measured during the whole test process. The results show that all the CFRP cables exhibit acoustic events. The AE signal is a good indicator of degree of fatigue damage. The signal measured by piezoelectric ceramics patches is also used as an index of degree of fatigue damage. Additionally, the test results indicate that the fatigue resistant capability of the smart cables is much better than the steel cables. Finally, the fatigue modulus degradation model is employed to predict the fatigue damage progression of the CFRP cables and its prediction accuracy is verified.

6932-13, Session 3

Miniaturized long period grating sensor interrogator based on a thermally tunable arrayed-waveguide grating demultiplexer

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Long period grating (LPG) fiber optical sensors are compact, highly sensitive to ambient environmental changes and immune to electromagnetic field. They have shown great application potentials in bio-chemical detection, structural health monitoring and industrial process monitoring. The interrogations of LPG sensors, however, are usually performed by an optical spectrum analyzer (OSA), a type of bulky and expensive lab equipment. This has significantly limited the practical applications of LPG sensors. In this paper, we report a novel miniaturized interrogator for LPG sensors based on a thermally tunable arrayed-waveguide-grating (AWG) demultiplexer. An AWG is a device consisting of micron or nano sized optical waveguides fabricated on a semiconductor chip. Both theoretical simulation and experimental results have shown that the transmission wavelengths of an AWG demultiplexer shift monotonically with the chip temperature. Assuming that the center wavelength of Channel X of an AWG is shorter than the center wavelength of the selected resonant dip of an LPG at temperature T_0 , the light intensity from Channel X is measured as P_0 by a photodiode. When increasing the temperature of the AWG, the center wavelength of Channel X shifts. At temperature T_1 , the center wavelength of Channel X overlaps with the center wavelength of the selected resonant dip of an LPG with the light intensity of P_1 . Obviously, from temperature T_0 to T_1 , the measured light intensity will decrease and reach the minimum value at temperature T_1 . If continuously heating the AWG, the center wavelength of Channel X becomes larger than the center wavelength of the LPG. Meanwhile, the measured light intensity from Channel X increases. Thus, by choosing the right transmission channel of an AWG and knowing the AWG temperature corresponding to the minimum value of measured light intensity, we are able to precisely obtain the center wavelength of the selected resonant dip of an LPG. The experimental

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results have demonstrated that the wavelength dependency of the AWG used in our experiment was $11.7 \text{ pm}/^\circ\text{C}$. The temperature resolution of the heater available in our experiment was $0.05 \text{ }^\circ\text{C}$, which makes that an interrogated wavelength resolution of 0.5 pm was achieved with this novel interrogation scheme. In the lab condition, a temperature resolution of $0.01 \text{ }^\circ\text{C}$ can be achieved for controlling the heater, which can increase the interrogated wavelength resolution better than 0.1 pm . In addition, a state-of-the-art thin-film heater and advanced patterning techniques can be employed to only heat the array waveguides of an AWG, which avoids heating the whole AWG device. In this case, we can save energy and improve the response time to approximately 2 ms , which makes this interrogation scheme feasible to be applied in the dynamic measurements. Furthermore, it is feasible to integrate an AWG demultiplexer, a photodiode detector array, a signal processing module and an electronic controlling module into a palm-size LPG sensor interrogator.

6932-14, Session 3

Structure monitor system by use of optical fiber sensor and watching camera in utility tunnel in urban area

M. Nakano, Osaka Sangyo Univ. (Japan)

Utility Tunnel measurement system^{1/4}_

This construction is a behavior of underground tunnel structure according to the adjacent construction measurement. The excavating work including the SMW(underground piling) construction was executed in the range of about 350m in total length. There is an inner displacement sensor to measure it the transformation of the top and bottom of the utility tunnel right and left in axial in displacement of the tunnel. The optical fiber sensor used four line tape for the communication that arranged a stainless steel wire. Moreover, the amount of the compression warp of 0.15% can be given beforehand, and the warp up to 0.7% be measured.

Measurement result and watch result of surveillance camera^{1/4}_

In the electric power and the communication tunnel axis direction sensor show the entire tunnel and the tendency to the seasonal variation. It was changeable within the range of $\mu\pm 50\sim 60\mu$. This change is thought the error margin of the measurement equipment, and seems to influence by construction more than this change.

Next, it shows in the result of the inner displacement sensor in the communication tunnel. After construction of the SMW installation, digging was executed. The tunnel side load acted after setting up SMW and the tunnel was transformed into the vertical direction. Afterwards, the ground transformation was steady. In addition, because an upper load had been removed by digging, the tunnel was transformed into the vertical direction. The tunnel did not have the problem though the tunnel was transformed by the adjacent construction, and construction was executed safely.

The example of the delivery image by the surveillance camera is shown. The network camera has Internet Protocol address one, and can display image (animation) display with an arbitrary camera and two or more camera images at a time. Moreover, the camera control like an expansion, a right and left rotation, and an upper and lower rotation, etc. can be done on a browser. In addition, the still picture with the network camera can be preserved in the FTP server every hour, and it inspect it on the Internet.

Consequently, the tunnel behavior grasp is made adequate by using together about optical fiber sensor and the network camera watch.

6932-15, Session 3

Current developments in fiber Bragg grating sensors and their applications

V. G. M. Annamdas, Y. Yang, Nanyang Technological Univ. (Singapore)

Whatever may be the material used to build the engineering structures, they are bound to undergo damage at some point in their lifetime. The damage could develop because of continuous usage, degradation, environmental factors, earthquakes or terror strikes. Structural health monitoring (SHM) has emerged as an important area that the modern world is looking into in the recent time. Smart materials like piezoceramics and fibre optical sensors (FOSs) based effective SHM tools are rapidly developing. Especially, the FOSs offer great potentials as monitoring sensors due to

their small size, immunity to electromagnetic interference, robustness and survivability in harsh environment. Conventional FOSs use phase modulation techniques for sensing. In spite of the above advantages, they are dependent heavily on source intensity fluctuations and coupling losses. However the Fibre Bragg grating (FBG) sensors developed from FOSs are immune to source intensity fluctuations, thus addressing some potential problems of the conventional FOSs. This paper presents a review on the current developments of FBG based monitoring techniques and their applications.

6932-16, Session 3

Local strain monitoring study of offshore platform T-shape tubular joint using fiber Bragg grating sensors

X. Zhao, Dalian Univ. of Technology (China); Z. Duan, J. Ou, Harbin Institute of Technology (China)

As one of the most important fiber optic sensor, significant amount of interest in Fiber Bragg Grating (FBG) sensing techniques has been generated in a variety of fields. Since the photosensitivity of Germanium doped fiber was discovered by Hill (1978), and transverse holographic method using UV illumination was invented by Meltz(1989), Fiber Bragg Grating received extensive attentions from research organizations around the world. FBG, as a novel type of sensor, was initially applied to military fields such as aviation. Lots of measurands such as stress, vibration, pressure, magnetic field can be measured by FBG sensor through the two basic measurands, strain and temperature. Because of distinct advantages (EMI immunity, high sensitivity, multiplexing capabilities, durability etc) over traditional sensors, FBG sensor is regarded as one of the most promising candidates for applications in structure health monitoring.

Offshore platform is one kind of important structure for marine oil industry, which will suffer the hush environmental influences during the long service period, such as wind load, tide load, erosion and current load. Deterioration of the whole structure is inevitable. It is important to establish one FBG sensing network for offshore platform to monitoring the local strain in key structural elements, and then evaluate the local health condition. A series of problems have been studied in this paper to test the feasibility of FBG sensor's application in offshore platform health monitoring. Complex stress monitoring test of big scale offshore platform T-shape tubular joint is designed, manufactured and accomplished. To assist this study, a finite element model of the T-shape tubular joint is established to predict the complex strain distribution in the hot point of the joint. Installation principle and scheme of FBG sensors are proposed. The right angle FBG strain rosette is developed to measure the principle strain, along with the strain distribution of the hot point, in comparison with results from strain gages. The results show that FBG rosette can monitor the principle strain precisely, and single FBG sensor is acceptable for the hot point strain monitoring. A method is proposed to correct the FBG sensor measurement for its relatively long sensing gauge. Further experimental results show that a single FBG sensor with data correction can monitor the hot point strain of the model. Static test and ice force loading test using FBG sensors and strain gages were designed and conducted, respectively. Results show that FBG sensors can precisely measure the axial force, the hot point strain, and the local strain of the tubular joint model.

6932-17, Session 4

A geometrically nonlinear mixed finite element formulation for the simulation of piezoelectric shell structures

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Smart materials and structures play an important role for sensor and actuator applications. For the simulation of such systems it is essential to predict the material and system behavior as precisely as possible. A reliable simulation may provide an easier, faster and cheaper development of such devices.

Hence, this paper is concerned with a geometrically nonlinear most accurate finite element formulation to analyze piezoelectric shell like sensor devices. Therefore the classical shell assumptions are extended

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to the electromechanical coupled field problem. The consideration of geometrical nonlinearity includes the analysis of stability problems and other nonlinear effects and leads to a reliable simulation of structures with large deformations.

The formulation is based on the mixed field functional of Hu-Washizu. The first variation provides the weak forms of the relevant balance laws of the electromechanical coupled field problem. Within this variational principle the independent fields are displacements, electric potential, strains, electric field, stresses and dielectric displacements. The mixed formulation allows an interpolation of the strains and the electric field through the shell thickness, which is an essential advantage when using a three-dimensional material law. Thus, the formulation allows the consideration of arbitrary nonlinear constitutive relations. Here, a linear constitutive relation is employed. It is remarked that no simplification regarding the constitutive law is assumed. The normal zero stress condition, which is a common assumption in shell theories, and the normal zero dielectric displacement condition are enforced by the independent resultant stress and resultant dielectric displacement fields.

With respect to the numerical approximation an arbitrary reference surface of the shell structure is modeled with a four node element. Each node possesses six mechanical degrees of freedom, three displacements and three rotations, and one electrical degree of freedom, which is the difference of the electric potential through the shell thickness. An appropriate interpolation of the independent stress, strain, dielectric displacement and electric field are discussed and presented.

The present shell element fulfills the important patch tests: the in-plane, bending and shear test. Some numerical examples demonstrate the applicability of the present piezoelectric shell element. Furthermore some practical devices, a smart antenna and a cylindrical telescope actuator, are analyzed.

6932-18, Session 4

Comparison of shape reconstruction strategies in a complex flexible structure

Z. Mao, M. D. Todd, Univ. of California/San Diego

Current requirements for large aperture deployable structures call for precise displacement control, with some tolerances approaching micron levels. Given that strain gages are one of the most economically-deployed sensor architectures, we explored two methods for reconstructing displacement from a distributed sensing array. One method linearly maps displacement fields to local strains in a supervised learning mode. After loading the system with sufficient cases, a matrix can be established to approach the approximate displacement-strain relationship. The other method is based on linear regression of generalized basis function projections, typically mode shapes. Results of these two approaches are compared. The second method has higher accuracy due to natural modal behaviors, while the first method is feasible for large amount of training cases and measuring points if scientifically picked. Both methods are compared for accuracy, robustness, training time, and real-time capability.

6932-19, Session 4

Damage identifying algorithm for concrete structures based on smart piezoelectric transducer array

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Concrete structures will be damaged in various types and degrees during service lives due to factors such as ageing of material, excessive use, overloading, environmental conditions and deficient maintenance. However, the unique features of large size and complexity of most concrete structures renders visual inspection very tedious, expensive, and sometimes unreliable, especially for the micro cracks hiding in the inner of structures. Once meeting the condition of damages, the cracks will occur and extend until the structure is failure. So it is necessary to develop an automated, quick and real time health monitoring technique which can be performed throughout the service life of structure. Such technique is useful not only to improve reliability but also to reduce maintenance and inspection cost of structure.

Smart piezoelectric (such as lead zirconate titanate, PZT) transducer is a kind of powerful tool for detecting inner cracks of structure. It has dual functions of sensor and actuator, and is sensitive to the micro cracks by applying high working frequencies. Being embedded in structure, the transducer can diagnose structural damages by analyzing changes of signals which mainly include decline of energy and mode changes of waves, etc. However, many researches are focused on identification of locations and widths of the cracks using single PZT transducer. The locations and degree of the damage are not easy being effectively found with numbers of independent transducers and a qualified method for the random features of concrete.

In this paper, a structure damage identifying algorithm based on transducer array was proposed to evaluate the complex damage mode of concrete structures. It was a unified approach for damage location and degree evaluation. The basic idea of this algorithm was placing a PZT transducer array in the structure and dividing artificially the detected structure into some sub-domains where the damage detection was completed. According to the root-mean-square-deviation (RMSD) index of the received signals before and after damage appearances, the damage degree in every sub-domain was evaluated. Because of the damage RMSD index reflecting damage degree, the more it was, the more damages of this sub-domain had, which could help us determine approximate damage scale. Putting the RMSD damage indexes of every sub-domain into a weighting formation, the damage index for the whole structure was derived. To validate the effectiveness of proposed method, a structure health monitoring experiment for a reinforced concrete beam with a PZT transducer array was carried out in the lab. The experiment results showed that the unified method proposed in this paper for evaluations of the damage location and degree was very effective to health monitoring of large scale civil structure. Some problems and suggestions on the proposed method were also given for further application of the smart piezoelectric transducer in health monitoring of other type of concrete structures.

6932-20, Session 4

Structural health monitoring using PZT sensors, comprehensive study, and applications

V. G. M. Annamdas, Nanyang Technological Univ. (Singapore); A. K. Harish, T. Radhika, Jawaharlal Nehru Technological Univ. (India)

Structural health monitoring (SHM) and security monitoring (SM) are two important challenges for the modern world in recent time. The monitoring of existing aero, civil and mechanical (ACM) structures has become a regular feature after the world witnessed the various recent deadly failures and damages, due to natural calamities (like earth quakes) or continuous usage of structures causing wear and tear or terror attacks. These include the infamous Tsunami in South East Asia (2004), space shuttle Columbia's explosion (2003) and the September 11, 2001, New York world trade centre terror attack. SHM has attracted the effort of many engineers throughout the world and is fast emerging as a pioneering field. It is helping to improve world economy in two ways. First directly, by providing longevity to all the structures and secondly, by saving millions of dollars via prevention of untimely failure. The field of SHM is very vast, consisting of traditional monitoring methods (such as visual inspection, static/ dynamic structural response methods) as well as smart system based methods. The last few years have witnessed rapid development in the areas of non-destructive evaluation (NDE) by the emergence of the electromechanical impedance (EMI) technique. This technique employs piezoelectric-ceramic (PZT) transducers for the prediction of structural response known as electromechanical (EM) admittance. This paper summarizes some of the key developments in the area of PZT based SHM.

6932-21, Session 4

Ultrasonic actuator/sensor placement strategies for active sensing in structural health monitoring

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Active sensing studies involving the use of piezoelectric actuator-sensor pairs for ultrasonic damage detection have become commonplace in recent years in the field of structural health monitoring. In active sensing

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paradigms, energy is added to the system of interest, usually by means of an electromechanical transducer, in order to excite a measurable response. Discrepancies in features extracted from the measured response, when compared to an experimental or model baseline, are used as indicators of damage. Arrays of actuator-sensor pairs further enable the prediction of both the extent and location of the potential damage within some level of certainty.

Here we present and compare approaches for actuator/sensor array placement with the objective of maximizing the damage prediction certainty. We further investigate strategies for non-stationary optimal actuation-sensing scheduling for the parallel minimization of detection uncertainty and power consumption. This study focused on the arrangement and scheduling of arrays of isotropic PZT discs, where each disc can serve as both actuator and sensor.

Primarily, evolutionary algorithms were utilized for searching the sensor arrangement solution space for optimums. These techniques have the advantage of requiring little formal understanding of how the optimization parameters affect the performance metric. Instead, an intelligent search is performed by joining and rejoining high performing sets of parameter values until a sufficiently optimal set is found. Evolutionary algorithms are useful in systems where an accurate model is difficult to develop. This is often the case in sensor optimization problems, where a particular arrangement's damage detection performance can be driven by difficult-to-model structural dynamics and complicated signal processing routines. Prediction certainty was minimized both directly, by using the prediction error as a performance metric, and indirectly, through maximization of a measure of information entropy.

A variety of literature-established features were used to construct several damage metrics and their corresponding optimal sensor/actuator arrangements are compared. Models for uncertainty were developed through exhaustive feature extraction using damaged and undamaged conditions. Experimental verification was performed through the selection and scheduling of an optimal subset of a dense sensor array for the detection of simulated damage of varying size and location. Experimental results demonstrate an improvement over random and evenly spaced grid placement approaches.

6932-22, Session 5

Tunable mechanical monolithic sensor with interferometric readout for low-frequency seismic noise measurement

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This paper describes a mechanical monolithic sensor for environmental and civil applications developed at the University of Salerno. The instrument is basically a monolithic tunable folded pendulum, shaped with precision machining and electric-discharge-machining, that can be used both as seismometer and, in a force-feedback configuration, as accelerometer. The monolithic mechanical design and the introduction of laser interferometric techniques for the readout implementation make it a very compact instrument, very sensitive in the low-frequency seismic noise band, with a very good immunity to environmental noises. Many changes have been produced since last version (2007), mainly aimed to the improvement of the mechanics and of the optical readout of the instrument. In fact, we have developed and tested a prototype with elliptical hinges and mechanical tuning of the resonance frequency together with a new laser optical lever and laser interferometer readout system. The theoretical sensitivity curve both for both laser optical lever and laser interferometric readouts, evaluated on the basis of suitable theoretical models, shows a very good agreement with the experimental measurements. Very interesting scientific result, for example, is that the measured natural resonance frequency of the instrument is 70 mHz with a $Q = 140$ in air without thermal stabilization, demonstrating the feasibility of a monolithic FP sensor with a natural resonance frequency of the order of mHz with a more refined mechanical tuning. Results on a new prototype of small dimensions with thermal stabilization are also presented and discussed.

6932-23, Session 5

Laser interferometric sensor for seismic waves measurement

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Laser interferometry is a very sensitive technique for small displacement measurement for scientific and industrial applications. Interferometric techniques have been already successfully applied also to the design and implementation of very sensitive sensors for environmental and civil applications. In this paper we describe the architecture and the expected theoretical performances of a laser interferometric sensor for seismic waves and tilts measurement. We analyze and discuss the experimental performances of the interferometric system, comparing the experimental results with the theoretical predictions and with the performances of state-of-the-art seismic sensors and tiltmeters.

6932-24, Session 5

**A new sensor for web flutter measurement

A. Seshadri, P. R. Pagilla, Oklahoma State Univ.

A "web" is any material which is manufactured and processed in a flexible, continuous strip form. Web materials cover a broad spectrum from plastic, paper, textile, metals and composites. Web materials are transported in the processing machinery where several operations like printing, coating, lamination, etc., are carried out. The processed web quality is dependent on the way in which the web is handled in these processing machines. As the web is transported on rollers in processing machinery it experiences motion in all three dimensions; longitudinal motion which is in the direction of web transport, lateral motion which is the direction perpendicular to longitudinal motion of the web and in the plane of the web, and flutter which is in the transverse direction perpendicular to both lateral and longitudinal motion. For efficiently transporting webs without defects such as wrinkles, tears, web behavior in all three directions must be monitored and controlled. Currently sensors are available to measure the longitudinal and lateral movement of the web. At present there is no sensor that can measure web flutter.

A new sensor for web flutter measurement is proposed in this paper. The sensor is based on the principle of scattering of light and directional properties of optical fibers. A collimated beam of light is incident on the web edge and the light scattered from the web edge is collected using a linear array of optical fibers. As the web flutters the point of scattering moves. The optical fiber in the array, due to their directional property, collects light scattered from a point exactly below them. The other end of the fiber array is terminated onto a linear array of photodiodes (pixels). Based on the amount of light received by the fibers in the array, the transverse motion of the web can be determined. This paper describes the construction and working of this new sensor for web flutter measurement. Experiments were conducted on a web handling platform to observe the performance of the sensor and results show that the sensor is effective in determining the web flutter accurately. The frequency response of the sensor is limited only by the scanning rate of the pixel array and not by the method by which flutter is measured. A dedicated signal processing circuit can be used to obtain a desired scanning rate, thus, a desired frequency response.

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6932-25, Session 5

**Investigation of nonlinear effects of coupling materials in sonic IR imaging

X. Han, Y. Song, G. Godfrey, Wayne State Univ.

We have presented our preliminary results on studying the effect of two different coupling materials in Sonic infrared (IR) imaging in the Smart Structures and NDE in San Diego in March 2007. Sonic IR Imaging is a hybrid ultrasonic/infrared NDE technology, which can detect defects

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in materials and structures by detecting the changes of IR radiation of defective objects through sensors during an ultrasound excitation pulse which can be a fraction of a second. Those two coupling materials produced different results in the sense of producing different IR signal levels. We have been further investigating the non-linear phenomena of different coupling materials in Sonic IR Imaging because this non-linear effect appears to play a very important role in Sonic IR Imaging technology. We focus our study on the effect of the level of coupling mechanical energy from the ultrasound transducer to the target, and the level of infrared signals produced around the defects. We will present our results from those aspects in this paper.

6932-26, Session 5

A novel shear stress sensor based on the electric double layer

C. J. Weiland, D. J. Griffiths, Virginia Polytechnic Institute and State Univ.; B. J. Akle, Lebanese American Univ. (Lebanon) and Virginia Polytechnic Institute and State Univ.; P. P. Vlachos, D. J. Leo, Virginia Polytechnic Institute and State Univ.

The concept of the electric double layer has been studied extensively in the past. The phenomenon was first studied by Hermann von Helmholtz in 1879. Later Gouy and Chapman furthered the concept by developing a model to characterize the potential given by an electrode surface. Stern advanced the Gouy-Chapman model to its current form. The Gouy-Chapman-Stern model characterizes the electric double layer using two regions: the Stern (fixed) layer and a diffuse (mobile) layer. Due to the difficulties of measuring the Stern layer, and given its significance in the Gouy-Chapman-Stern model, a measurement technique was developed to overcome this difficulty. Measuring the zeta potential allows for an empirical estimation of the shear plane strength, and is based on an electro-osmotic or streaming potential measurement. The streaming potential is a by-product of the electric double layer formation. Previous studies have shown the streaming potential and streaming current are proportional to the zeta potential, fluid velocity, kinematic viscosity, electrical permittivity of free space and the dielectric constant of the fluid.

In this paper, we introduce a sensor to directly measure wall shear stress utilizing the concept of the streaming potential. Analytic and experimental methods were used to develop a semi-empirical equation relating the measured streaming potential to wall shear stress. The sensors were calibrated using a gravity feed parallel plate flow channel at varying Reynolds numbers. The sensor measurements were compared to the analytic solutions and Digital Particle Image Velocimetry (DPIV) was employed to experimentally verify the wall shear stress in the channel. The calibrated sensors were used to measure the laminar and turbulent wall shear stresses exerted on a flat plate in a water tunnel facility with simultaneous time resolved DPIV measurements to validate the data.

6932-27, Session 5

****Characterization of the mechanical properties and sensing behavior of iron-gallium nanowire arrays**

P. R. Downey, A. B. Flatau, Univ. of Maryland/College Park; P. D. McGary, B. J. H. Stadler, Univ. of Minnesota

This study experimentally investigates the capabilities of iron-gallium nanowire arrays as artificial cilia transducers. This alloy has distinctive properties that should allow these nanowires to display the large deformations observed in biological cilia, but coupled with a strong magneto-mechanical sensing behavior. The goal of this research is to identify and model the characteristics of these nanowire arrays in order to incorporate them into underwater acoustic sensors.

The experiments are conducted with a custom manipulator device incorporated into the stage of a scanning electron microscope (SEM) for observation. Individual nanowires of varying size (20 - 200 nm in diameter) and composition are loaded in tension to determine the elastic properties and failure modes. This data is also measured dynamically by exciting the fundamental resonance of cantilevered nanowires and calculating the material parameters. Results reveal properties very similar to those of the bulk material, but with a significant improvement in tensile strength at the

nanowire scale. Entire arrays of close packed wires are mounted onto giant magnetoresistive (GMR) sensors to measure the coupled magnetic induction response resulting from bending the array statically and dynamically. This data is compared with empirical and simulated results from previous macroscale research.

6932-29, Session 6

****Crack detection methods for concrete and steel using radio frequency identification and electrically conductive materials**

K. Morita, Building Research Institute (Japan)

Radio Frequency Identification (RFID) tag is a promising device for the management of products at a very low cost. Huge number of such low-cost sensors can be installed to the structure beforehand, after a disaster we can access to these sensors wirelessly and very easily. In this system, an electrically conductive paint or printed sheet is applied to a part of structure in which crack will occur. Copper wire is connected to the attachment on the structure and a RFID tag. When a crack occurs, the paint or printed sheet is broken, resulting in an increase in resistance. Crack width can be estimated by the ability of an RFID transmitter to communicate with the tag. By bending tests of concrete specimens, the relationships between concrete crack width and conductivity of the materials are examined. It is shown that the level of concrete crack width can be related to the ability of the paint or printed sheet to conduct electricity or not. This printed sheet is also applied for steel crack. By fatigue test of steel specimen with a notch, very small steel crack can be detected by this sensor.

6932-30, Session 6

Colloidal dampers for semi-active isolation and suspension systems

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Smart colloidal dampers are developed with on-demand controllable damping curves, based on multi-scale damping mechanisms and ferro-fluid nano-flow governed by applied magnetic fields. At nanometer scale, nano-flow in the channels of porous particles dominates damping effects; while, at micro-scale, the specific deformation of porous-particle-formed chain-like structures dissipates external mechanical energy. Compared to current existing hydraulic dampers such as magnetorheological fluid dampers, the colloidal dampers possess the characteristics of low heat generation yet high damping efficiency. Meanwhile, due to the giant compression ratio of the damping medium, the proposed dampers provide a considerable large stroke together with a high damping force. The magnetic field dependent dampers together with on-demand controllable damping curves would benefit the adaptable vibration reduction for ride, handling, and NVH improvements of high performance vehicles.

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6932-31, Session 6

Integrated design method of MR damper and electromagnetic induction system for structural control

H. Lee, H. Jung, Korea Advanced Institute of Science and Technology (South Korea); S. Moon, Korea Institute of Machinery & Materials (South Korea); K. Choi, Korea Advanced Institute of Science and Technology (South Korea)

Magnetorheological (MR) dampers are one of the most advantageous control devices for civil engineering applications to natural hazard mitigation due to many good features such as small power requirement, reliability, and low price to manufacture. To reduce the responses of a structural system by using MR dampers, a control system including a power supply, control algorithm, and sensors is needed. The control system becomes complex, however, when a lot of MR dampers are applied to large-scale civil structures, such as cable-stayed bridges and

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high-rise buildings. Thus, it is difficult to install and/or maintain the MR damper-based control system.

To overcome the above difficulties, a smart passive system was proposed, which is based on an MR damper system. The smart passive system consists of an MR damper and an electromagnetic induction (EMI) system that uses a permanent magnet and a coil. According to the Faraday law of induction, the EMI system that is attached to the MR damper can produce electric energy and the produced energy is applied to the MR damper to vary the damping characteristics of the damper. Thus, the smart passive system does not require any power at all. Besides the output of electric energy is proportional to input loads such as earthquakes, which means the smart passive system has adaptability by itself without any controller or sensors.

In this paper, the integrated design method of a large-scale MR damper and Electromagnetic Induction (EMI) system is presented. Since the force of an MR damper is controllable by altering the input current generated from an EMI part, it is necessary to design an MR damper and an EMI part simultaneously. To do this, design parameters of an EMI part consisting of permanent magnet and coil as well as those of an MR damper consisting of a hydraulic-type cylinder and a magnetic circuit that controls the magnetic flux density in a fluid-flow path are considered in the integrated design procedure.

To verify the effectiveness of the proposed integrated design method, an MR damper-based control system with EMI system for reducing stay cable response is designed and fabricated. Furthermore, its characteristics are tested through experiment.

6932-32, Session 7

Large-scale smart passive system for civil engineering applications

H. Jung, H. Lee, D. Jang, Korea Advanced Institute of Science and Technology (South Korea); S. Cho, Samsung Heavy Industries (South Korea)

The smart passive system consisting of a magnetorheological (MR) damper and an electromagnetic induction (EMI) part has been recently proposed. An EMI part can generate the input current for an MR damper from vibration of a structure according to Faraday's law of electromagnetic induction. The control performance of the smart passive system has been demonstrated mainly by numerical simulations. It was verified from the numerical results that the system could be effective to reduce the structural responses in the cases of civil engineering structures such as buildings and bridges. On the other hand, the experimental validation of the system is not sufficiently conducted yet.

In this paper, the feasibility of the smart passive system to real-scale structures is thoroughly investigated. To do this, the large-scale smart passive system is designed, manufactured, and tested. The system consists of the large-capacity MR damper, which has a maximum force level of approximately $\pm 10,000\text{N}$, a maximum stroke level of $\pm 35\text{mm}$ and the maximum current level of 3 A, and the large-scale EMI part, which is specially designed to generate sufficient induced current for the damper.

The applicability of the smart passive system to large real-scale structures is examined through a series of shaking table tests. The magnitudes of the induced current of the EMI part with various sinusoidal and random excitation inputs are measured. Also, the damping forces from the MR damper and the electromagnetic damping forces from the EMI part are measured, respectively. All the measured values are compared with those from the analytical approach. According to the test results, the large-scale EMI part could generate the sufficient current or power for changing the damping characteristics of the large-capacity MR damper without any difficulty. Therefore, the large-scale smart passive system could be considered as one promising control devices for civil engineering applications.

6932-33, Session 7

Semi-active control of floor isolation system using MR damper

P. Lin, National Ctr. for Research on Earthquake Engineering (Taiwan); C. Loh, National Taiwan Univ. (Taiwan)

This paper presents the performance evaluation of a semi-active controlled floor isolation system for earthquake reduction. The floor isolation system consists of a rolling pendulum system and a semi-active controlled MR damper. The modified Bouc-Wen model is used to represent the behavior of the MR damper. A series of performance test of the MR damper is made and been used for system identification. Two contrasting control methods including LQR with continuous-optimal control and Fuzzy Logic control are experimentally investigated as potential algorithms and comparisons are made from the results. Unlike the clipped-optimal control, LQR with continuous-optimal control can output the continuous command voltage to control the MR damper, and get smoother control effect. A three-story steel structure with the floor isolation system on the 2nd floor is tested on the shake table. Scaled historical near- and far-field seismic records are employed to examine controller performance with respect to frequency content and PGA level. Experimental results show that both control algorithms can suppress the acceleration of the isolated floor during small and large PGA levels, and alleviate both displacement and acceleration simultaneously in larger, near-field events. Both control algorithms are adaptive and robust to various intensity of excitation. This investigation demonstrates the feasibility and capabilities of a smart semi-active controlled floor-isolation system.

6932-34, Session 7

Decentralized sliding mode control of building using MR-dampers

K. Lu, C. Loh, National Taiwan Univ. (Taiwan); J. N. Yang, Univ. of California/Irvine; P. Lin, National Ctr. for Research on Earthquake Engineering

This paper presents the structural control results of shaking table tests for a steel frame structure in order to evaluate the performance of a number of proposed semi-active control algorithms using multiple magnetorheological (MR) dampers. The test structure is a six-story steel frame equipped with MR-dampers on the 1st, 3rd and 5th floors. In experimental tests, an EL Centro earthquake, a Kobe earthquake and a Chi-Chi earthquake (station TCU067) are used as ground excitations. Various control algorithms are used for this semi-active control studies, including the Decentralized Sliding Mode Control (DSMC), LQR-H2, LQR-H ∞ control, LQG control, and passive-on and passive-off control. Each algorithm is formulated specifically for the use of MR-dampers. Additionally, each algorithm uses measurements of the absolute acceleration and the device velocity for the determination of the control action to ensure that the algorithm can be implemented on a physical structure. The performance of each algorithm is evaluated based on the results of shaking table tests, and the advantages of each algorithm is compared and discussed. The reduction of the story drift and acceleration throughout the structure is examined.

6932-35, Session 7

Performance evaluation of semi-active equipment isolation system using MR-dampers

Y. Fan, National Taiwan Univ. (Taiwan); P. Lin, National Ctr. for Research on Earthquake Engineering (Taiwan); C. Loh, National Taiwan Univ. (Taiwan); J. N. Yang, Univ. of California/Irvine

This paper presents the performance evaluation of passive and semi-active control in the equipment isolation system for earthquake protection. Through shaking table tests of a 3-story steel frame with an equipment on the 2nd floor, a MR-damper together with a sliding friction pendulum isolation system is placed between the equipment and floor to reduce the vibration of the equipment. A decentralized sliding mode control (DSMC) algorithm and the LQR control method have been used. The control performance measures are the peak acceleration sustained by the equipment and the peak displacement of the isolation system. A parametric study on the selection of the suitable values for the feedback control constants for the semi-active equipment isolation is investigated. The reliability of the passive and semi-active equipment isolation system is assessed using three historical earthquakes. Both DSMC and LQR control methods as well as the passive-on and passive-off for semi-active control are also examined for the comparison of respective control effectiveness. Experimental results illustrate the performance of a decentralized sliding

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mode control in protecting the vibration-sensitive equipments from earthquakes. Correlations between the design variables of the isolation system and the responses provide guidance for improving the equipment behavior.

6932-36, Session 7

Monitoring and evaluation of self-sensing concrete-filled FRP/FRP-steel composite tube columns under earthquake loading

X. Yan, H. Li, J. Ou, Harbin Institute of Technology (China)

Two concrete-filled fiber reinforced polymer (FRP) tube (CFFT) columns and two concrete-filled FRP-steel composite tube (CFST) columns, as well as a control reinforced concrete column, were prepared to investigate the seismic behavior of them as bridge piers. The columns were subjected to a constant axial load and a pseudostatic lateral load. To monitor the axial deformation of the inner concrete under the cyclic loading, two optic fiber Bragg grating (FBG) strain sensors were pre-embedded in the top of every CFFT and CFST columns. They were arranged parallel to the longitudinal axis of the column and at the two ends of the horizontal axis along the direction of the lateral load. Moreover, each column also included one FBG strain sensor and one electric resistance (ER) strain gauge embedded in the inter-ply of FRP for CFFT or the interface between FRP and steel for CFST. They were arranged at the middle height of the column in the hoop direction and the horizontal axis along the direction of the lateral load, to monitor the hoop deformation of the tube. The embedded sensors made the column have the ability of self-sensing, and the deformations of the column under the combined axial and lateral loads were recorded in real time. Using the monitoring data, the deteriorations of the column at different stages, such as the cracking of the inner concrete, the delamination of the FRP and the damage of the interface between the FRP and steel, were detected. A seismic damage evaluation method was presented based on the monitoring information.

6932-161, Session 7

Verification of real-time hybrid tests of response control of base isolation system by MR damper comparing shaking table tests

H. Fujitani, H. Sakae, R. Kaswasaki, Kobe Univ. (Japan); H. Fujii, Daiwa House Industry Co., LTD (Japan); T. Hiwatashi, TOA Corp. (Japan)

No abstract available

6932-37, Session 8

Shape memory polymer composite and its application in deployable hinge for space structure

Y. Liu, X. Wang, H. Lv, J. Leng, Harbin Institute of Technology (China)

This paper is concerned about the basic properties of deployment for shape memory polymer composite (SMPC) and its application in deployable hinge for space structure. Shape-memory polymers (SMP) are an emerging class of active polymers that have dual-shape capability. They can change their shape in a predefine way from shape A to shape B when exposed to an appropriate stimulus. While shape B is given by the initial processing step, shape A is determined by applying a process called programming. One of the advantages, compared with other traditional material hinge, the SMPC carpenter type hinge is that it will not produce a large shock when it spring into the deployed position. There are several kinds of shape memory polymer composite (fiber reinforced, powder reinforced, etc.). Shape memory polymer used in this study is a thermosetting styrene-based shape memory resin in contrast to normal epoxy SMPs, carbon fibre fabric reinforced SMPC. In order to investigate the basic performances of deployment for SMPC hinge, the experimental and simulation methods are used as follows: dynamic mechanical analysis (DMA), three point bending test, deployment tests and the stiffness analysis using ANSYS. Results indicate that the glass transition temperature (T_g) of SMPC is approximate to 63°C and it has a higher

storage modulus than that of pure SMP. The storage modulus of SMPC falls precipitously within the glass transition region of about 40~80°C (from $T_g-20^\circ\text{C}$ to $T_g+20^\circ\text{C}$). The peak value of tangent delta is defined as the glass transition temperature (T_g). SMPC shows typical linear elasticity and high bending modulus before T_g , while exhibits apparent nonlinear viscoelasticity and low bending modulus above T_g . The shape recovery ratio of SMPC is above 90% at/above T_g , while drops sharply at/below T_g . The deployable properties of SMPC depend strongly on the number of thermomechanical cycles, which become relatively stable after some packaging/deployment cycles. Moreover, deployment velocity and shape recovery ratio rise remarkably with the increase of temperature which ranged from T_g to $T_g+30^\circ\text{C}$. The ANSYS stiffness analysis show that the carpenter type hinge is low strains during packaging of the hinge. In the end, the structure of the carpenter type hinge is introduced. The carpenter type hinge is one mechanism that has the advantage of high-reliability of the deployment, lightweighted, and low cost. The solar array actuated by SMPC carpenter hinge, which is heated by passing an electrical current, deploys from about 180° to 0° in one minute. This SMPC carpenter type hinge performs good deployment performances during numerous thermomechanical cycles. So the potential applications for such materials as active medical devices are highlighted.

6932-38, Session 8

SMA to control the deployment of a space hinge

G. Akhras, Royal Military College of Canada (Canada)

A tape spring rolamite (TSR) hinge controlled by a shape memory alloy (SMA) actuator is proposed as a deployment mechanism for a high packaging efficiency satellite SAR (synthetic aperture radar) membrane antenna. The TSR exploits the stored elastic energy of curved spring steel strips placed in such a way that the hinge self-deploys and self-locks into a final stiff straight configuration. The hinge is composed of two tape springs, two motion guide wheels and pins, a motion control escapement mechanism and the SMA actuator.

The paper describes the hinge design and its working conditions. The theoretical analysis alongside the experimental program are presented and compared. Finite element analysis is performed to find the moment rotation behaviour of the hinge and compare it with the experimental hinge behaviour. Finally, keeping in mind that the device should be compact, space qualified, lightweight and able to actuate the complete lateral deployment of a large antenna, suggestions to improve the overall functionality of the prototype are recommended.

6932-39, Session 8

Reflexive composites: self-healing composite structures

T. W. Margraf, Jr., D. E. Havens, C. D. Hemmelgarn, Cornerstone Research Group, Inc.

Cornerstone Research Group Inc. has developed a Reflexive Composites system achieving increased vehicle survivability through increased structural awareness and responsiveness to damage. Reflexive Composites can sense damage through integrated piezoelectric sensing networks and respond to damage by heating discrete locations to activate the healable polymer matrix in areas of damage. The polymer matrix is a modified thermoset shape memory polymer (SMP). The SMP is modified with the addition of unique long polymer chains within the thermoset matrix, that heal based on a phenomena known as reptation.

In theory, the reptation healing phenomena according to the reptation model should occur in microseconds; however during experimentation it has been observed that to maximize healing and restore up to 90% of mechanical properties a healing cycle of at least 3 minutes is required. To fully understand this variance in time to heal, heat transfer analysis of a polymer matrix composite was conducted to determine the amount of time and energy needed to obtain steady-state temperatures above the matrix activation temperature. The time to steady-state is the theoretical minimum healing cycle for the Reflexive Composites. This paper will focus on work conducted to determine the healing mechanisms at work in CRG's Reflexive Composites, optimal healing cycles, and an explanation of the difference between the reptation model and actual healing times.

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6932-40, Session 8

Self repairing composites for airplane components

C. M. Dry, Natural Process Design, Inc.

Durability and damage tolerance criteria drives the design of most composite structures. Those criteria could be altered by developing structure that repairs itself from impact damage.

Protection techniques and technologies for improving damage tolerance of composite structures that suffer damage due to impact effects fits into both sustainment and the vulnerability reduction of damage tolerance improvement. This is a technology for increasing damage tolerance by quantum leaps for impact damage. It does not only increase resistance to damage once but multiple times.

Repaired damage would enable continued function and prevent further degradation to catastrophic failure in the case of an aircraft application. Further, repaired damage would enable uavs/missile applications to be utilized without reduction in performance due to impacts.

Self repairing structures are designed to incorporate hollow fibers, which will release a repairing agent when the structure is impacted, so that the repairing agent will fill delaminations, voids and cracks in less than one minute, thus healing matrix voids. The intent is to modify the durability and damage tolerance criteria by incorporation of self-healing technologies to reduce overall weight: A 30% increase in weight associated with structure capable of withstanding just hammer-shock can be largely eliminated whereas <1% weight associated with the incorporation of a self-healing system will be added. The structure will actually remain lighter than current conventional design procedures allow.

Research objective(s) were: Prove that damage can be repaired to within 80-90% of original flexural strength in less than one minute, in laminates that are processed at 300- 350F typical for aircraft composites.. These were successfully met.

The approach was to set parameters for impact resistance and then do lab work on self repair to assure these are met. The main focus was on testing of elements in compression after impact and a larger component in shear at Natural Process Design, Inc. Based on these results the advantages purposes are assessed. The results shows potential that with self repairing composites, compressive strength is maintained sufficiently so that less material can be used as per durability and damage tolerance, yielding a lighter structure and that self repair adds performance and therefore the grade and related cost of the prepreg could be reduced

6932-41, Session 8

Infrared laser-activated shape memory polymer

D. Zhang, Y. Liu, J. Leng, Harbin Institute of Technology (China)

This paper is concerned about the drive of shape memory styrene-based copolymer through infrared optical fiber carrying infrared laser and the influence of cross-linking degree on its shape memory effect. As one of most novel actuators in smart materials, shape memory polymers (SMP) have been investigated widely. Proper cross-linking of styrene copolymer can exhibit shape memory effect (SME). In this article, the influence of cross-linking degree on shape memory effect of styrene copolymer was investigated through changing dosage of cross-linking agent in order to change the cross-linking degree. The cross-linking degree was determined by measuring the gel content in the polymer. The effect of cross-linking degree which influences the glass transition temperature (T_g) of the styrene copolymer was measured by Dynamic Mechanical Analysis (DMA) and Differential scanning calorimetry (DSC). The performance of SME was measured as the following. The banding specimens (50mm x 10mm x 2mm) with different cross-linking degree were heated above the melting point, then these specimens were elongated up to 200% length, followed by cooling down to room temperature with the constant constraint of external force. The stretched specimens were put on the table with ruler, heated with constant ramp and the deformation was recorded per 5°C. The infrared laser was chose to drive the SMP through the optical fiber embedded into the SMP. The wavelength of infrared laser was installed at 2μm, 3.3μm, the working band of optical fiber was 2-5μm. An optical fiber

was embedded into the SMP for delivery of 3-6μm laser light for heating activation. The surface of the optical fiber was etched by the hydrofluoric acid in order to increase transmission efficiency of the optical fiber, which increased the total area of sending laser. The polymer absorbed the power of the infrared laser to change the bond length and bond angle of covalent bond. Results indicated that the SMP copolymer networks with different cross-linking degree was synthesized successfully with T_g from 35°C to 70°C, which experienced excellent SME. Moreover, the T_g can be adjusted through the alternation of the gel content of the copolymer, and the T_g increased with increasing gel content. The copolymer with less gel content showed faster recovery speed than the copolymer with more gel content at the same recovery temperature. When the recovery temperature was at T_g+30°C, the copolymer with higher gel content performed faster recovery speed. The largest reversible strain of the SMP reached as high as 150% and the reversible strain of the copolymer decreased with increasing the gel content. The shape recovery speed of SMP was faster in 3.3μm than in 2μm.

6932-03, Session 9

Intelligent tires for improved tire safety using wireless strain measurement

R. Matsuzaki, A. Todoroki, Tokyo Institute of Technology (Japan)

From a traffic safety point-of-view, there is urgent need for intelligent tires as a warning system of road conditions, for optimized braking control on poor road surfaces and as a tire fault detection system. Intelligent tires, equipped with sensors for monitoring applied strain, are effective in improving reliability and control systems, such as anti-lock braking systems (ABSs). However, conventional strain gages, with their high stiffness and lead wires, are unsuitable for strain measurement in tires.

The present paper examines the feasibility of a direct in-service strain measurement system for automobile tires. Three main technologies are investigated: sensing, wireless transmission and strain utilization. As strain sensors, we presented the patch-type flexible sensor using ultra-flexible resin. The sensor is made from flexible polyimide substrates and ultra-flexible epoxy resin, which makes the whole structure low in stiffness and high in elongation. The sensor was applied to an automobile tire and compression tests performed. The capacitance of the proposed flexible sensor decreases monotonously due to tensile strain, and there is no hysteresis due to loading or unloading. Using an amplitude modulation corresponding to the sensor capacitance, the proposed sensor is feasible for wireless strain measurement in tires. Although it is not suitable for strain measurement as the capacitance of the sensor increases with temperature, temperature compensation is possible using a dummy sensor.

Measured capacitance changes are transmitted to a receiver, wirelessly, without batteries. The method comprises a tire sensor (or tuning circuit), external transmitter and external receiver. Since the tuning circuit performs as a frequency filter, the tuning frequency of the sensor can be wirelessly measured without any batteries to the sensor circuit. The method was demonstrated experimentally with static tension and cyclic loading tests. The tuning frequency of the sensor circuit decreases with increased tensile loading, even at a high stroke frequency of 10 Hz. Using spectral features of the tuning frequency, the peak power spectrum and quality factor, tire strain was estimated accurately using a response surface method. Wireless communication using tuning frequency is preferable in that it is: battery-less, has a high sampling frequency, low cost and is practical to manufacture.

Finally, we showed the utilization model of strain data for the optimized braking control and road condition warning system. The relationships between strain sensor outputs and tire mechanical parameters, including braking torque, effective radius and contact patch length, were calculated using finite element analysis. The optimized braking control and road condition warning systems are also suggested, using strain data. Optimized braking control can be achieved by keeping the slip ratio constant. The road condition warning would be actuated if the recorded friction coefficient at a certain slip ratio is lower than a reference value for safe road condition.

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6932-42, Session 9

****Improved reading techniques for electronic structural surveillance tags**

P. Pasupathy, D. P. Neikirk, S. L. Wood, The Univ. of Texas at Austin

Results from our efforts to improve the performance of low-cost, unpowered, wireless, resistance based electronic structural surveillance tags (ESS) will be presented. The ESS tags operate using inductive coupling between an unpowered embedded sensor and an external reader. An inductive reader coil is used to measure impedance data from which information pertaining to the state of the sensor is extracted. The read range is influenced by the signal strength, noise and the method of data extraction. We have identified that the maximum distance at which a reliable signal can be obtained is largely dependent on the strength of inductive coupling which in turn depends on the relative shape and size of the coils. Thus various configurations of coils are being studied to find optimum coil geometries to extend the read range. We have also found that the method of impedance analysis influences the types of information that can be extracted from the sensor. In particular, an enhanced circuit model for data extraction provides more information than a purely numerical fit. The advantages of this approach will be demonstrated as applied to a corrosion sensor for steel reinforced concrete. The circuit values extracted by the model provide insight into environmental perturbations of the system, such as proximity to reinforcement bars. The extension of read range through optimized coil design when used together with circuit model based data extraction methods can improve the reliability in reading the sensor at greater distances. In addition to improving the performance of the corrosion sensor, recommendations for design and analysis resulting from this study can be extended to optimize other electronic structural surveillance tag sensors. This work was sponsored in part by the National Science Foundation.

6932-43, Session 9

Development of smart sensor for hybrid health monitoring on PSC girders

J. Park, D. Hong, J. Kim, Pukyong National Univ. (South Korea); M. D. Todd, D. D. L. Mascarenas, Univ. of California/San Diego

Major damage-types of prestressed concrete (PSC) girder bridges include prestress-loss, flexural crack and support failure. Over the past two decades, many researchers have attempted to detect the damages in PSC girder bridges by using changes of vibration characteristics. However, the following problems still remain to be solved for successful damage detection in PSC girder bridges: (1) the damage types of PSC girder bridges cannot be easily recognized from the vibration-based approaches, (2) current mainly systems need to employ wires for data transfer are on-line between on-site loggers and a centralized server, so the costs associated with installation and maintenance can be high, (3) data repositories of high capacity are needed for on-line engineering decision process, and (4) techniques related to wireless sensing and embedded software algorithms is also needed for the realization of real-time damage monitoring in PSC girder bridges

In this study, a smart sensor that can monitor damage in PSC girder bridges by using wireless sensing and embedded software algorithms is newly developed. In order to achieve the objective, the following approaches are implemented. Firstly, a hybrid damage monitoring scheme for PSC girder bridges is designed. Secondly, a wireless sensor platform embedded with the hybrid damage monitoring algorithm is designed. Finally, the performance of the developed wireless sensor platform is evaluated using a large-scale PSC girder bridge model for which vibration and impedance signatures are measured for a series of damage scenarios.

6932-44, Session 9

Wireless inclinometer acquisition system for reducing swing movement control module experiment of hook model

Y. Yu, J. Ou, Dalian Univ. of Technology (China); C. Zhang, Harbin Institute of Technology (China)

Lagrange Scale Heavy Derrick Lay Barge is very important for sea work. Under

intense wind and wave load, the hook on the Barge will vibrate so large that in some cases it can not work. Through installing the TMD on the hook, the vibration will be reduced to a certain range to meet the demand on sea work, which is also important for increasing the efficiency of sea work. To design the suitable TMD for the hook, the dynamical parameters should be specified beforehand. Generally, the related dynamical parameters such as inclinometer and acceleration are measured by wire sensors. But due to the restriction of the actual condition, the wire sensors are very hard to implement. Recently, the wireless sensor has been presented to overcome the shortcoming of wire sensor. It is more suitable and also convenient to utilize wireless sensor to acquire the useful data of large scale heavy derrick lay barge.

In this paper, the hook reducing Swing movement control module is designed for large scale heavy derrick lay barge. Secondly, wireless inclinometer sensor system is integrated using the technique of MEMS, sensing and wireless communication. Finally, the hook reducing Swing movement control module is validated by the developed wireless inclinometer data acquisition system. The research shows that the wireless inclinometer sensor has the following characteristics: Precise, the MEMS inclinometer with inner temperature unit can measure more accurately; Stable, the wireless sensor system is put in an airtight box, this improves the capability of anti-jamming; More far, using high-plus antenna, the developed wireless sensor system transmits data more far. The wireless inclinometer sensor can be used not only in swing monitoring for large scale heavy derrick lay barge's Hook, but also in vibration monitoring for TV tower, large crane. In general, it has great application foreground.

6932-45, Session 9

An embedded wireless system for remote monitoring of bridges

T. J. Harms, F. Bastianini, S. Sedigh, Univ. of Missouri/Rolla

This paper describes an autonomous embedded system for remote monitoring of bridges. Salient features of the system include ultra-low power consumption, wireless communication of data and alerts, and incorporation of embedded sensors that monitor various indicators of the structural health of a bridge, while capturing the state of its surrounding environment. Examples include water level, temperature, vibration, and acoustic emissions.

Ease of installation, physical robustness, remote maintenance and calibration, and autonomous data communication make the device a self-contained solution for remote monitoring of structural health. The system addresses shortcomings present in centralized structural health monitoring systems, particularly their reliance on a laptop or handheld computer. The system has been field-tested to verify the accuracy of the collected data and dependability of communication. The sheer volume of data collected, and the regularity of its collection can enable accurate and precise assessment of the health of a bridge, guiding maintenance efforts and providing early warning of potentially dangerous events.

6932-46, Session 9

Damage detection for crane girder using wireless MEMS

S. Lee, K. Shin, W. Kim, H. Seo, Kyungpook National Univ. (South Korea)

The objective of this research is to identify the damage of crane girder using wireless MEMS monitoring system. The damage detection methodology is first evaluated experimentally using a simply supported beam. The beam is a wide flange beam (H-400 x200x8x13) of 6000mm span length and has a bolted splice at the center. The bolted splice is composed of 20 bolts, 8 bolts at the web and 12 bolts at the bottom flange only. An impact load and a moving load test were performed for the damage detection. An impact load using Schmidt hammer is applied at the distance 200mm from the center of beam, and the moving mass of 800N at constant speed 200mm/sec is applied as a source of moving load. Next the methodology is applied to a crane girder. The crane girder, which is installed at the structural laboratory of Kyungpook National University, is an over-head crane with maximum capacity of 100kN. The crane girder is assumed to be damaged when the bolts on the splice are loosened. For the system identification of the crane, the acceleration responses are measured using

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wireless MEMS accelerometers. MEMS is a small integrated device or system that combines electrical and mechanical components. It ranges in size from the sub micrometer level to the millimeter level. The use of MEMS and wireless communication can reduce system cost and simplify the installation for the structural health monitoring. MEMS sensor used for this research is the ADXL103 from Analog Devices. It has a measuring range of $\pm 1.7g$, and can measure both static and dynamic accelerations. The output is analog voltage proportional to acceleration with a nominal scale factor of 1V/g and the dimension of MEMS sensor is 5mm x 5mm x 2mm. The experiment results indicate that the wireless MEMS is applicable for damage detection of crane girder based on the impact loading and moving load responses.

6932-47, Session 9

****Full-scale field evaluation of wireless MEMS monitoring system**

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The objective of this research is to develop and verify the wireless micro-electro-mechanical system (MEMS) monitoring system for the health monitoring of high rise buildings. MEMS is a small integrated device or system that combines electrical and mechanical components. It ranges in size from the sub micrometer level to the millimeter level. For MEMS, the term micro suggests a literally small system, electro suggests electricity and/or electronics, and mechanical suggests moving parts of some kind. Examples of MEMS device applications range over sensors for airbag system, miniature robots, microengines, inertial sensors, and chemical, pressure and flow sensors. These systems can be utilized for sensor, control, or actuator technology in micro-scale. The MEMS accelerometer has advantages of small size, low-cost, and low power consumption, and thereby is suitable for wireless monitoring. Consequently, the use of advanced technology of MEMS and wireless communication can reduce system cost and simplify the installation for the structural health monitoring. To assess the applicability, the wireless MEMS monitoring system is examined in the laboratory test and full-scale field evaluation. In the laboratory test, the accuracy, the propensity for data loss, and the delay for the wireless communication are examined. MEMS sensor evaluated for this research is the ADXL103 from Analog Devices. It has a measuring range of $\pm 1.7g$, and can measure both static and dynamic accelerations. The output is analog voltage proportional to acceleration with a nominal scale factor of 1 V/g and the dimension of MEMS sensor is 5 mm x 5 mm x 2 mm. A simple cantilever steel beam with a varying lumped mass is used for the experiment. Then the monitoring system is applied to a full-scale building structure with HTMD system. The building is a 5-story steel building and the HTMD is mounted on the top floor to vibrate the building. Both in the laboratory and field test, the data measured with MEMS accelerometer is compared with one measured with piezoelectric accelerometers. The laboratory and field evaluation results indicate that the wireless MEMS monitoring system is reliable and robust for the health monitoring of buildings.

6932-48, Session 10

****FEA model and theoretical analysis of a novel triaxial optical tactile sensing system**

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The development of intelligent robots requires more and more advanced sensors, which help robots acquire environmental information. For a robot to perform the assigned tasks in a satisfactory manner, a large amount of tactile information is required. Among them, the triaxial force is closely related to the tasks such as walking, grasping objects, and so on. However, it is difficult to accurately measure the triaxial force using traditional techniques. A promising method based on a novel triaxial optical tactile sensing system has been studied in this paper.

According to the theory of wave guide, the total internal reflection condition is spoiled with an external force. The symmetrical plane waveguide is converted into asymmetrical plane waveguide, which leads to light leakage. The frequency of the leaked light is between the cutoff frequency of symmetrical plane waveguide and the cutoff frequency of asymmetrical plane waveguide.

The optical tactile sensing system consisted of a sensor head (silicone rubber material) and a waveguide plate. One side of the silicone rubber sheet was a cylindrical contact array, while the other side was a hemispherical contact array. For a single tactile cell, under each cylindrical contact, there were four hemispherical contacts, acting as a four-part optical tactile sensing unit. When a force is applied on a cylindrical contact, the total reflection condition of the guided wave will be violated, which induces optical leakage. Moreover, the deformation of the four hemispherical contacts will result in four optical spots with different sizes under the waveguide plate. That is to say, there must be some kind of relationship between the applied force and the areas of four leaked optical spots. And the applied force can be calculated by the areas of four optical spots once we obtain the relationship.

Although the final research object is an array of cylindrical and hemisphere contacts, only a cylindrical contact and its corresponding four hemisphere contacts are studied in this paper considering that the interaction force is negligible because it is generally small. Triaxial FEA model is set up to simulate the deformation of the sensor head, and a mathematical formula is brought forward to describe the relationship between the applied triaxial force and the areas of leaked optical spots.

A novel triaxial optical tactile sensing system is set up to perform the experiments, and the results considerably conform with the mathematical model, then the triaxial force can be calculated by observing the areas of leaked optical spots. It is expected that this formula should benefit the design and fabrication of new tactile sensing systems.

6932-49, Session 10

Real-time damage detection using self-sensing E-glass composites

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It is generally appreciated that the interfacial and general mechanical properties of the reinforcing fibres can influence the overall mechanical properties of advanced fibre reinforced composites (AFRCs). In the case of glass fibre composites, coupling agents are applied to enhance the chemical compatibility between the fibres and the matrix. The authors have demonstrated recently that evanescent wave spectroscopy via E-glass fibres can be used to assess the influence of the concentration of the coupling agent on the cure kinetics of a thermosetting resin. The focus of the current publication is to report on efforts directed at real-time fibre damage detection using high-speed photograph and image analysis where the E-glass fibres act as light guides. In other words, the end of a reinforcing fibre bundle or composite is imaged and the fibre fracture sequence is monitored using a high speed camera. It is now possible to relate fibre fracture and the overall mechanical properties of E-glass composites to surface-treatments and the processing conditions that were used to produce the composite.

The first part of this paper reports on the development of the techniques for producing the self-sensing composites and the procedures for imaging the end of the fibre bundle and composite. The failure modes of the neat-resin (matrix) and the un-impregnate E-glass fibre bundles were also studied. Conventional acoustic emission was used to trigger the high-speed camera. Surface-mounted fibre Bragg gratings were used to measure the applied strain during tensile testing of the self-sensing composites. The second part of the paper reports on the effect of silane pre-treatment on the fracture behaviour of E-glass fibre reinforced composites.

6932-50, Session 10

Sensor fusion for machine condition monitoring

X. Xue, V. Sundararajan, Univ. of California/Riverside

Machinery maintenance accounts for a large proportion of plant operating costs. Compared with the conventional scheduled maintenance strategy which is to stop the machine at pre-determined intervals, modern condition-based maintenance strategy stops the machine only before there is evidence of impending failure. With the development of cheaper sensors, more and more sensors are designed for machine condition monitoring. It is now possible to use multi-modal sensor input to monitor

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machine condition in a collaborative and distributed manner. In this paper, three categories of methods for condition monitoring are reviewed - 1. knowledge based, 2. model based 3. data based methods. Knowledge-based systems are derivations from expert systems that use rules and inference engines to determine failures and their causes. Data-driven methods use machine fault data, typically derived during experiments to train a monitoring system. Pattern recognition algorithms then attempt to classify actual sensor data using the results of the training phase. However it is often impractical to obtain data for every type of fault. Model-based techniques on the other hand use mathematical models to predict machine performance. We propose to combine the model based and data based method for machine condition monitoring. The data is used to train the model and derive its parameters. The various fault modes are then identified and simulated. The output is then input to the classification schemes that can be then used to identify and classify real-time data. A three phase induction motor system is set up to verify the method. The sensors used are current probes, wireless accelerometers, microphones and thermocouples. The experimental results validate the effectiveness of the method.

6932-51, Session 11

****Surface layer measurements of early age mortar investigated by ultrasonic guided waves and finite element analysis**

H. L. Reis, J. L. Borgerson, Univ. of Illinois at Urbana-Champaign

A pulse-echo guided wave approach to monitor mortar setting and hardening is presented. The method monitors both the end- and the entry-reflection of the fundamental torsional mode in a cylindrical steel rod partially embedded in mortar. The development of the material mechanical properties during hydration is related to the change in signal strength of these reflections. However, the entry-reflection is essentially a surface measurement. It is also known that concrete material properties vary with depth. To shed light into these differences, a finite element analysis was performed. The analysis shows that at early stages, it takes longer for the surface layer material to achieve the same properties as the material at the specimen core. However, after the mortar has achieved measurable strength (e.g. 12-14 hours), the material properties of the surface layer can reasonably approximate those properties of the core material.

6932-52, Session 11

****Monitoring uniform and localized corrosion in reinforced mortar using high-frequency guided longitudinal waves**

H. L. Reis, B. L. Ervin, J. T. Bernhard, D. A. Kuchma, Univ. of Illinois at Urbana-Champaign

High-frequency (up to 9 MHz) guided longitudinal waves have been used in a through-transmission arrangement to monitor reinforced mortar specimens undergoing both accelerated uniform and localized corrosion. High-frequency guided longitudinal waves were chosen because they have the fastest propagation velocity and lowest theoretical attenuation for the rebar/mortar system. This makes the modes easily discernible and gives them the ability to travel over longer distances. The energy of the high-frequency longitudinal waves is located primarily in the center of the rebar, leading to less leakage into the surrounding mortar. The results indicate that the guided mechanical waves are sensitive to both forms of corrosion attack in the form of attenuation, with less sensitivity at higher frequencies. Also promising is the ability to discern uniform corrosion from localized corrosion in a through-transmission arrangement by examination of the frequency domain.

6932-53, Session 11

Impact detection using ultrasonic waves based on case-based reasoning

T. Otsuka, A. Mita, Keio Univ. (Japan)

Recently, Structural Health Monitoring (SHM) has become the key measure to assure the safety and saving maintenance cost for many structures such as infrastructures, buildings, airplanes and so on. Smart

structures in which the SHM systems are embedded are promising and further evolving to include self-repairing capability. However, most of the technologies are still under research. The part of the reason is that the robustness of the system is not satisfactory in using the system in the field. For resolving this issue, the case based reasoning mechanism is introduced in the impact detection system using ultrasonic waves.

The Case Based Reasoning (CBR) is a learning algorithm. In this method, when a new problem, called a case, occurs, the past cases that are similar to the new case are retrieved from the database and reused for solving the new case. Then the solved case is revised and retained in the database to solve future cases easily. In this sense, the learning mechanism can be embedded in the system.

6932-54, Session 11

****Crack detection with wireless inductively-coupled transducers**

P. Zheng, D. W. Greve, I. J. Oppenheim, Carnegie Mellon Univ.

In prior work we developed inductive coupling for surface-mounted Lamb wave transducers, showing analytical predictions confirmed by experimental observations. Those transducers were piezoceramic wafers, roughly 1 cm square and 1 mm thick, operated at relatively low frequencies, such as 300 kHz; they were tested on thin plates at frequency-thickness products, fd , associated with only the lowest symmetrical and antisymmetrical Lamb wave modes. We now report on the performance of similar inductively-coupled transducers operating at higher (multiple MHz) frequencies, showing new theoretical predictions once again confirmed by experimental measurements.

Our investigation was motivated by a particular application, to perform an ultrasonic examination of a box girder top flange, under tension stress in a negative moment region, using transducers mounted along the flange edge. In the prototype structure the flange width and thickness are approximately 1 m and 2 cm, respectively, and our experiments confirm that ultrasonic waves propagate effectively across the width of the flange. Our crack detection experiments are performed on a laboratory steel plate specimen at 55% of full scale, in which we seek to detect a through-thickness slot, approximately 3 cm long, located interior from the edges and oriented transversely.

The wafer-type transducers are mounted on the steel plate edge, are excited at frequencies (in the MHz range), and show a peak response associated with the thickness mode in the piezoceramic; we study the use of a backing material for better inertial coupling, and we show the radiation field associated with such edge-mounted transducers. We first employ a pair of transducers in pitch-catch mode, offset longitudinally to create a diagonal path, and show that a shadow (a relative null) is detected when the path is intercepted by the crack. We compare results obtained using conventionally wired transducers and using inductively-coupled transducers, showing that effective performance can be achieved with wireless (inductively-coupled) operation.

Superior performance is obtained if a narrower radiation field, centered along the diagonal path, is employed. This can be achieved using plexiglass wedges, and we show experimental results for laboratory-built wedges bonded to the plate edge and for commercial wedges fluid-coupled to the plate edge. Reflection from the crack is evident, as is the shadow effect along the direct diagonal path. In all cases successful crack detection can be demonstrated.

6932-55, Session 11

****Lamb waves and nearly longitudinal waves in thick plates**

D. W. Greve, I. J. Oppenheim, P. Zheng, Carnegie Mellon Univ.

Extensive research has been directed at the detection of defects in plate-like structures using Lamb waves, motivated by the fact that pulses formed from Lamb waves propagate with low attenuation for considerable distances in plates. However, the existence of multiple Lamb wave modes presents a significant complication for flaw detection. Lamb waves, which are most often excited by transducers mounted on the surface of the plate, have numerous dispersive modes when the frequency-thickness product fd exceeds, say, 3 MHz-mm in metals such as steel or aluminum.

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Therefore, this condition is frequently encountered when working with thick plates. Mode conversion occurs when wave modes reflect and transmit at boundaries and at flaw locations, further increasing the number of wave modes that would be detected by a sensor. It is typically a great challenge to distinguish a flaw reflection from the many other responses in a signal. Limiting operation to low frequencies, to restrict the number of Lamb wave modes, is not a completely satisfactory solution because scattering becomes weaker and the resolution is degraded when the wavelength is large compared to the defect size.

We consider waves created in relatively thick plates by edge excitation at fd products that correspond, in principle, to multiple Lamb wave modes. For relatively low values of the fd product it is clear that Lamb wave modes will be generated, while at large values of the fd product we observe a bulk (longitudinal wave) in the solid, but influenced by reflections from the plate surfaces. We show that for a range of intermediate fd products a train of regularly spaced nearly-longitudinal waves is generated. This development of a lead pulse and trailing pulses, all traveling at the longitudinal (bulk) wave speed, is well known and has been explained in the literature. In this paper we describe the transition from Lamb wave generation to the formation of nearly-longitudinal waves with their trailing pulses. We report experimental results and theoretical results, with good correspondence between them. We also examine the transfer of energy from leading to trailing pulses, which means that such nearly-longitudinal waves will not propagate indefinitely; however, we show that they retain ample energy for flaw detection at distances of several meters, and are very practical for flaw detection in civil structures such as bridge members and in representative aerospace components. Most importantly, we study the interaction of these trailing pulses with cracks, again showing experimental results and theoretical predictions that are consistent with one another. The results suggest that these nearly-longitudinal waves are an attractive option for flaw detection because of their shorter wavelength (as compared to Lamb waves at low fd products) and because they preserve their pulse train characteristics after scattering.

6932-56, Session 11

Noncontact local and global damage detection with integrated ultrasonic transducers

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The continued requirement for increased air safety, life extension of aging aircraft fleets, increased aircraft availability and reduced operational costs, suggests the adoption of structural health monitoring technologies (SHM) by the aerospace industry. The ultimate objective of such technologies is to employ structurally integrated sensors to perform local and global in-service component inspection; thus increasing platform availability and reducing associated maintenance costs. In this investigation we present and demonstrate the development of miniaturized light weight integrated ultrasonic transducers (IUTs) for bulk (BAW), plate (PAW) and surface acoustic waves (SAWs) propagation. The unique and distinct advantages of these IUTs are that they can be fabricated, using sol-gel based technique, directly onto simple and complex structures including curved surfaces and require no couplant for operation. In addition, these can operate at temperatures up to 150°C, at center frequencies ranging from 1 to 20 MHz, and provide damage detection range of tens of centimeters in metallic structures.

Thick films (>40µm) piezoelectric ultrasonic transducers were directly deposited onto metallic planar and curved surfaces as longitudinal BAW IUTs by a sol-gel based technique. Top electrodes of these IUT were made by silver paste or colloidal silver spray method. Experimental results demonstrated that longitudinal and shear waves can be excited and detected efficiently and simultaneously in metallic structures using mode conversion methods. These can be used for localized damage detection through component thickness. The experimental results agreed well with those obtained by a finite difference based method.

The piezoelectric thick films and top electrodes were also deposited at the end edges of metallic plates of about 2 mm thickness as PAW IUTs. With novel mode conversion techniques these IUTs were able to efficiently generate and receive symmetric, anti-symmetric or shear horizontal PAWs

with proper mode conversion angles. These proper angles were obtained by the 3D finite difference based method. The propagation lengths of these PAWs reached more than one meter with frequencies of several MHz along aluminum plates. Line defects of several depths and widths were clearly detected.

To demonstrate the effectiveness of the sol-gel spray technology to fabricate SAW IUT onto curved surfaces, a hollow steel tube with 102mm outer diameter and 28mm thickness was used as a sample. An 89µm thick piezoelectric film and interdigital transducer (IDT) electrode were deposited on the outer surface of this tube as SAW IUT. The IDT fingers were perpendicular to the circumferential direction. It was shown that SAW, with center frequency of 1.5MHz, traveled a total distance of more than 1.9 m at temperature of 150°C.

For SHM, an induction based non-contact approach has been developed to generate and receive all above discussed BAW, PAW and SAW IUTs to eliminate the need for direct electrical connections. Electrical analysis is carried out to optimize the inductive coil design and the gap between the probe coil and IUTs. Effects of number of the turns of coil, choices of ferrites and associated sizes and locations on the performance of different IUTs will be discussed.

6932-57, Session 12

Self sealing tanks and pressure vessels

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This paper will discuss the technology of self-sealing fluid-carrying tanks and pressure vessels. The intent is to apply these active material techniques to build better performing pressure vessels, such as those required for high pressure lightweight hydrogen fuel storage onboard motorized vehicles. Leaks are the bane of many fluid containment vessels. Autonomous leak sealing systems can significantly improve the performance and reduce the maintenance costs of these vessels. Leak-induced swelling and sealing is one of the primary self-sealing techniques. Some of these technologies date back to antiquity. Notable early examples include wooden vessels, boats and pipes. Water leaking through the seams caused the wood to swell and to seal the leak. Leak stoppage technology developed considerably further with regard to fuel tanks in both World Wars. The more sophisticated variants used separate layers of material for structural containment and leak sealing. Gasoline-induced swelling of rubber was the primary sealing mechanism. Pressure vessels pose additional challenges due to the mechanical forces exerted by the escaping fluid and due to fail-safe leak-before-burst design requirements. Additional self-sealing methods for pressure vessels include the use of sealing particulates in the fluid and stored elastic energy in specific layers of a multilayer tank structure. Ginger root is a standard sealing particulate for automobile radiators. Elastic precompression of inner layers can prevent crack formation, especially in high pressure vessels. More aggressive active configurations with sensing and controlled responses are possible, but have not been heavily developed to date. Design configurations for self-sealing high-pressure lightweight tanks will be presented along with an analysis of the performance of the tanks.

6932-58, Session 12

**Mechanics of surface stress generation during SAM formation of alkanethiol

P. Shrotriya, K. Kang, Iowa State Univ.

Micro-machined cantilevers coated with self-assembled monolayers (SAM) of alkanethiols are being utilized as sensing elements for new generation of high-sensitivity chemical and biological sensors. Presence of chemical species is detected by resolving the surface stress change associated with absorption/adsorption of analyte molecules on the sensitized cantilever. Challenges to widespread use of micromechanical cantilever sensors are: susceptibility to vibrations, integration in a single device and understanding the mechanism governing surface stress generation. We aim to overcome these limitations by developing a novel sensing approach based on high-resolution differential surface stress sensor reinforced with multi-scale models of surface stress generation. In order to demonstrate the feasibility of our approach, we characterized the

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surface stress development associated with formation of self-assembled-monolayers of alkanethiols. Specifically, we developed a proof-of-concept for our sensing approach by investigating the development of surface stress during the formation of self-assembled-monolayers (SAM) of alkanethiols on a gold-coated cleaved mica strip. In order to understand the molecular mechanism underlying the surface stress generation, a multi-scale model is developed to predict the surface stress generated during absorption of the alkanethiols on a gold film. Atomistic simulations are performed to investigate the formation of self-assembled monolayers of Dodecanthiol on Au(111) surface. The results of the molecular simulations are incorporated into the multi-scale framework to understand the surface stress generation and curvature change observed during experiments at continuum scale.

6932-60, Session 12

Use of spatiotemporal response information from sorption-based cross-reactive sensor arrays to identify and quantify the composition of analyte mixtures

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Linear sensor arrays made from small molecule/carbon black composite chemiresistors placed in a low headspace volume chamber, with vapor delivered at low flow rates, allowed for the extraction of chemical information that significantly increased the ability of the sensor arrays to identify vapor mixture components and to quantify their concentrations. Each sensor sorbed vapors from the gas stream, and thereby, as in gas chromatography, separated species having high vapor pressures from species having low vapor pressures. Instead of producing equilibrium-based sensor responses that were representative of the thermodynamic equilibrium partitioning of analyte between each sensor and the initial vapor phase, the sensor responses varied depending on the position of the sensor in the chamber and the time since the beginning of the analyte exposure, creating a concomitant spatiotemporal (ST) response. The responses to pure analytes and to multi-component analyte mixtures comprised of hexane, decane, ethyl acetate, chlorobenzene, ethanol, and/or butanol, were recorded along each of the sensor arrays. Use of a non-negative least squares (NNLS) method for analysis of the ST data using only four chemically different sorbent films trained against the pure test analytes enabled the correct identification and quantification of the composition of 2-, 3-, 4- and 5-component mixtures. In contrast, when traditional time- and position-independent sensor response information was used, these same mixtures could not be identified or quantified robustly. A model for sensor array responses is developed and applied over a wide range of experimental conditions, ranging from macro- to micro-scale chamber geometries and vapor flowrates. Responses and mixture analyses are characterized according to two dimensionless numbers, and an optimal operational regime is defined which provides maximum array performance. The ability to correctly identify and quantify constituent components of vapor mixtures through the use of such ST information significantly expands the capabilities of such broadly cross-reactive arrays of sensors.

6932-61, Session 12

**A large area multifunctional flexible stretchable network for smart structures

G. Lanzara, F. Chang, Stanford Univ.

Structural Health Monitoring (SHM) systems are candidate to improve the reliability and durability of a structure during its in-service life. They have the capability to detect the location of damage and its extent by means of a sensors/actuators network. Even though these techniques are quite promising several issues still need to be solved to be able to implement them into real-world practical applications. In order to effectively monitor the health of a structure in terms of damage detection and digital imaging, a network that can cover large areas and is integrated with a high-density of high-performance sensors is required. Recently the authors have proposed a cost-effective, large-area stretchable network approach based on monolithic silicon. The advantage of the technique is that the network is fabricated directly on a silicon wafer with standard CMOS processes and then stretched to a desired size and shape. The stretchability is achieved

by interconnecting the nodes that house the sensors or actuators, with conductive rotational microsprings. With this approach the network area can be stretched by several orders of magnitude and be bonded to the structure to be monitored. The electronics, processors and data memory could be manufactured together with the network.

Even though this approach is quite promising, several challenges still need to be solved. These challenges are linked to the specific design and to the mechanical properties of silicon which is rigid and brittle and is shaped in the form of microsprings. The consequence is that special handling is needed to avoid damaging of the network.

In this study we show the design, fabrication and testing of a low-cost, multifunctional, "flexible" stretchable network capable to survive extreme temperature conditions and deformations. This new approach is ideal for the realization of the next generation of Smart Structures and Materials.

A conductive flexible mesh that can host thousands of multifunctional nodes is built at the microscale in a polymer sheet, cut from the sheet, stretched manually up to the macroscale and bonded in/to a structure. The flexible mesh works as electrical and mechanical support for the sensor network. The nodes of the mesh are electrically interconnected with folded, conductive polymer microwires which can be unfolded up to the macroscale in the direction of an applied load. Moreover, the polymer nodes can be the housing for sensors, actuators, switches, amplifiers etc.

This approach will ultimately lead to low-power, high-performance, low-cost smart structures with embedded sensor networks that can sense structural parameters on a very fine scale (millimetres).

6932-04, Session 13

Design of integrated IPMC/PVDF sensory actuator and its application to feedback control

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Ionic polymer metal composites (IPMCs) form an important class of electroactive polymers with promising applications in biomedical devices, biomimetic robotics, and nano/micro manipulation. In most of these applications, both position and force feedback controls are needed for IPMC actuators to ensure precise and safe operation. Since dedicated bulky sensors are not easy to be embedded into bio-, micro-, or nano-systems, compact sensing schemes are desirable for feedback control of IPMC actuators. However, the design of reliable and robust compact sensors has been reported as a great challenge in the literature due to actuation-induced feedthrough coupling, thermal fluctuation, and other environmental noises.

In this paper, a novel integrated sensory actuator with both position and force feedback is designed by combining IPMC with polyvinylidene fluoride (PVDF) films. The design adopts differential configurations for both the sensor-actuator structure and the sensing circuit, and thus enables excellent immunity to thermal and electromagnetic noises. Closed-loop position control of the IPMC output is demonstrated together with simultaneous tip force measurement, based upon the integrated PVDF position and force sensors. This work brings the IPMC actuators much closer to their targeted biomedical and micromanipulation applications. The following further elaborates on the contributions.

Two PVDF films are bonded to an IPMC actuator in a sandwich configuration to sense the bending output of the actuator. For the force measurement, a relatively rigid elastic beam sandwiched by two PVDF films is attached to the actuator tip. The stiffness of the force-sensing beam enables direct inference of effector tip position from the position sensor reading, effectively decoupling the two sensors. A differential configuration is used for both sensors, which has proven critical for ensuring consistent and effective actuation and sensing performance for the following reasons: 1) it allows shielding of capacitive coupling between IPMC and PVDF, and eliminates fictitious sensing signal induced directly by the actuation signal (instead of bending); 2) it minimizes the internal stress at bonding interfaces, which would cause delamination of layers or spontaneous creep of the composite beam structure; 3) it removes the influence of thermal fluctuation and other environmental noises, which is often the most challenging problem for PVDF sensors; and 4) it compensates for asymmetric sensing responses of a single PVDF

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film during contraction and extension. A conductive black box is used to house the sensory actuator and the sensing circuits to further reduce electromagnetic interference and other disturbances.

Feedback control experiments based on integrated sensing have been conducted to demonstrate the effectiveness of the proposed sensory actuator. A proportional and integral (PI) controller is designed to achieve precise position tracking. A laser distance sensor is used to measure the bending displacement as an independent observer. Experimental results show that the position output measured by the integrated PVDF sensor agrees well with that measured by the laser sensor, and that both track the reference trajectory closely. In the mean time, the tip force sensor can capture interaction force as low as micro Newton.

6932-63, Session 13

**Design and testing of a MEMS acoustic emission sensor system

D. W. Greve, I. J. Oppenheim, A. P. Wright, W. Wu, Carnegie Mellon Univ.

We present four new findings pertaining to MEMS sensors for acoustic emission detection. Our sensors are resonant-type capacitive transducers, operating with a frequency between 100 kHz and 500 kHz, fabricated in the PolyMUMPS process. The sensitivity of a resonant transducer is related to the sharpness of its resonance, measured by the quality factor Q , and operating in a coarse vacuum will increase Q . We describe a practical laboratory method for sealing and evacuating our MEMS sensor, and present measurements showing Q in the evacuated packages to be 2.4 to 3.6 times greater than under atmospheric pressure. Pencil lead break tests confirm the expected improvement in transducer sensitivity. We also describe our theoretical analysis of noise sources in the electromechanical behavior of a resonant, capacitive-type transducer sensitive to out-of-plane motion, with particular interest in noise resulting from mechanical excitation of the moving plate by air molecule impact. Whereas the signal is predicted to increase in direct proportion to Q , the noise is predicted to be independent of Q , which is consistent with our noise measurements.

We report on another transducer design to sense out-of-plane motion. The new design features a moving plate constructed as an open grill rather than as a plate perforated by etch holes. Experimental measurements, and underlying theoretical predictions, identify two advantages to this new design. Measurements show that the capacitance between the two electrodes is closely approximated by the gross area of a whole plate, rather than the net area of the open grill; that is, the cutouts in the open grill do not diminish the capacitance. This measurement confirms a result predicted by finite element simulation. Moreover, admittance measurements show the open grill design to have a higher Q (lower damping) than a similar transducer constructed as a perforated plate; these measurements confirm results predicted by analysis of the viscous forces associated with the movement of air from the gap between the open grill and the stationary electrode.

We then report on another novel transducer, designed to sense in-plane motion. Most commercial acoustic emission transducers are sensitive only to out-of-plane motion, and this new capability will enable the collocation of three transducers on one MEMS chip to sample particle motion in 3-D. The in-plane sensor is a comb finger capacitive transducer with a design frequency of 250 kHz. (Earlier MEMS accelerometers capable of sensing in-plane motion operate at much lower frequencies, and would not be suitable for acoustic emission sensing.) The predicted Q for this device is much higher than for the out-of-plane sensors, because the in-plane motion produces only a direct shearing of the air gap. At the same time, the predicted Q for out-of-plane motion of this sensor is significantly lower, which is highly beneficial because it effectively isolates the unwanted out-of-plane motion from the desired in-plane motion. We show measurements confirming these design characteristics, and we show results from pencil lead break experiments and from testing of structural components

6932-64, Session 13

**Evaluation of a LPFG-based whitelight interferometric distance sensor for near-field surface profiling

H. Huang, A. Majumdar, The Univ. of Texas at Arlington

The development of an in-fiber whitelight interferometric distance sensor based on the mode coupling effect of a Long Period Fiber Grating (LPFG) for absolute distance measurement and Near-Field Surface Profiling (NSOM) has been investigated. Unlike the conventional whitelight interferometric distance sensor that uses a regular single mode fiber as the sensor probe, the LPFG-based distance sensor employs a special sensor probe that is fabricated from a single mode fiber whose cladding region is coated with a reflective film and having a LPFG located at a distance from the cleaved fiber end. The LPFG serves as a beam splitter that separates the light into a core mode and a cladding mode and recombines the two light waves to generate interference, from which the absolute distance can be deduced. Because the optical path difference of the interferometric distance sensor is contributed by both the free-space cavity distance and the distance between the LPFG and the fiber end, it does not have a limit on the minimum measurable distance. Therefore, it can be employed as a NSOM by providing nanometer-scale distance measurement for distance feedback and surface profiling simultaneously. The LPFG is mechanically induced by pressing the fiber between a spring and a metal plate. It adds to the flexibility of the sensor since it enables us to place the grating at a desired distance from the fiber end, which helps increasing or reducing the phase sensitivity of the sensor. The data interrogation algorithm uses a variation of the two fringe matching technique. First a rough estimate of the distance from two fringe locations is obtained based upon which an estimated fringe pattern is calculated. The phase shift is calculated from the position difference between one fringe in the measured and the estimated fringe spectrum. Updating the estimated spectrum with the new phase shift essentially shifts the spectrum and aligns one fringe in the estimated fringe spectrum with one fringe in the measured spectrum but it doesn't still achieve the correct cavity distance and phase shift estimation. The correctional terms for cavity distance and the phase shift can then be calculated by linear fitting the envelope of the difference between the measured and estimated fringe spectra. The cavity distance and phase shift are updated iteratively until a predetermined root-mean-square of the fringe difference is obtained. The implementation of the LPFG-based whitelight interferometric sensor for absolute distance measurement is discussed in detail. Its application for Near-Field Surface profiling has also been investigated.

6932-65, Session 13

Time domain reflectometry as a distributed strain sensor

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Structures deteriorate with time due to aging of the materials, excessive use, overloading, climatic conditions and lack of sufficient maintenance. Appropriate sensing and monitoring methods are required to quantify these deteriorations or defects in the critical components of the structures. Strain gages are widely used to measure local strains from a few discrete locations, while Time Domain Reflectometry (TDR) can interrogate distributed changes along the entire length of the sensor line. TDR is a method of sending an electric pulse down a transmission line and monitoring the reflection signal returning back from impedance changes along the line. The transmission line can be embedded within a target structure or surface-mounted on the structure to monitor the changes in material spatial properties, which result in attenuation/increase in the reflection signal as well as propagation delay. Therefore, investigating reflection signals provides useful information on the structural health status such as crack initiation, and propagation and failure locations. In addition, adequately designing TDR sensors will improve the sensitivity and coverage of monitoring areas and provide reliable input data to a structural health monitoring system for proactive structural maintenance. The present study investigates feasible applications of a new technique using TDR as a distributed strain sensor for an advanced structural health monitoring system.

First, two types of sensors (two parallel flat ribbon cables and magnetic

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wires) were used as a TDR sensor by being wound spirally around three types of cylinders: Aluminum and PVC cylinders, and a commercial fire extinguisher tank. The tanks were filled with hydraulic oil and increasingly pressurized with a hydraulic pump until they failed. Bi-axial strain gages were surface mounted to measure the longitudinal and circumferential strains of the tanks. All the TDR sensors have not only measured the circumferential strain and thus the internal pressure of the tanks but also detected the failure locations on the tank surfaces in the real time basis. Depending on the sensor configuration and material, the sensor failed before or after the crack initiation in the cylinders. Therefore, the TDR sensor can be used as a health alerting sensor of a pressurized tank.

Second, two types of TDR sensor patterns were tested: two parallel and two interlocking comb-shaped conductors. The sensor patterns were laid out on two substrates: fiberglass/epoxy and polycarbonate plates on which a notch was made in order to provide different strain levels along the sensor line. The sensor having two parallel conductors could not find the localized strain at the notch. However, it successfully measured the failure locations and the averaged strain over the whole sensor. Meanwhile, the sensor having interlocking comb-shaped conductors not only measured the distributed strains but also detected the failure locations successfully when the samples were under increasing tensile loads (over the strain level of 3%).

Finally, noise levels in the TDR signal were tested with respect to the different sensor lengths and different locations in a sensor and the minimum detectable strain levels were identified on each condition. As the impedance change was located farther from the TDR pulse generator, the signal to noise ratio decreased. A special sensor length was found that showed a higher noise level, which seemed to be related to the antenna effects of the transmission line.

Future work includes developing mathematical models to estimate the relationship between the damage types and measured TDR signals, so as to inversely identify the changes in local physical or chemical properties quantitatively from measured TDR signals. The developed TDR monitoring technique shows great potential for real-time health monitoring of various critical structures such as bridge, aircraft, and aerospace applications.

6932-66, Session 13

Design of an integrated piezoelectric wafer phased array for structural health monitoring

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Design study of an integrated piezoelectric wafer phased array bonded to a plate for SHM is reported in this paper. Development of Piezoelectric Wafer Array Sensor (PWAS) type array system has already been reported in the published literature. In the proposed design, we explore the possibility of phase conjugation in the normal induced stress. The main advantage here is the amplification of certain frequency-geometry factors and resonant mass effects. SAW and Lamb wave steering features here are similar to those observed in the PWAS. The energy transfer into the structure for symmetric Lamb wave modes are much higher in this new design, which is useful for application in composite plates. A one-dimensional element of the array and their electromechanical characteristics are obtained in terms of stress transfer and impedance. Effects of geometry are then analyzed by analytical approximations and also by finite element simulations. We study the effects of resonant mass on the tunability of the lobe details.

6932-68, Session 13

Usage of fiber Bragg grating sensors in low-earth orbit space environment

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It is widely known that any materials exposed to the severe low earth orbit (LEO) space environment undergo degradations. For the reliability of fiber Bragg grating (FBG) sensors in LEO environment, the tensile strength of FBG sensors were tested and the reflective spectrum changes of FBG sensors were measured after aging cycles simulated the LEO environment. The LEO space environment was simulated by high vacuum (~10⁻⁵ Torr), ultraviolet (UV) radiation (<200nm wavelength), temperature

cycling (-70°C~100°C), and atomic oxygen atmosphere (AO flux of ~1016 atoms/cm²•s and kinetic energy of ~0.04 eV). The tensile tests of FBG sensors followed the international standard IEC 60793-1-31. The tensile properties and spectral characteristics of FBG sensors exposed to the LEO environment were investigated.

6932-129, Poster Session

A damage classification technique for impedance-based health monitoring of helicopter blades

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One of the most sensitive problems regarding the application of SHM (Structural Health Monitoring) is found in the aeronautical segment. This field presents the necessity of monitoring small structural changes representing damage, due both to economic aspects and safety. In this contribution two helicopter blade structures (pertaining to a civil and a military helicopter) are studied. In both cases, two types of damage are inserted, namely holes and cracks. Through the impedance-based structural health monitoring method, an identification procedure using cluster analysis techniques was performed aiming at distinguishing these two types of damage. Then, a meta-model was built for fault position identification.

6932-142, Poster Session

Adaptive optics system prototype for the automatic control of geometrical fluctuations in a laser beam in air

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In this paper we present a prototype of an adaptive optics system developed for the control of geometrical fluctuations in a laser beam in air and based on the interferometric detection of the beam phase front. We show that this technique is very effective also when high sensitivity and high band-pass are required for correction of small perturbations. The working principle is also very simple and direct. In fact, the laser beam is made to interfere with a reference beam, properly obtained, and the phase difference is read by means of an array of photodiodes. A digital control system acquires the output signal from the array, computes the error signals and generate the correction signal, sent to the deformable mirror. In the paper we discuss some experimental results, the limits of the prototype and future developments and improvements.

6932-144, Poster Session

Long period grating-based ocean PH sensor in a SMS fiber

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A long period grating-based PH sensor is developed for ocean monitoring. The sensor consists of single mode-multimode-single mode (SMS) fibers where the sensing fiber (multimode fiber) is led in and out by two single mode fibers. The long period grating is written in the multimode fiber. The grating structure makes the fiber as a microbending sensor. In case of a multimode fiber, the grating couples light from the fundamental mode to higher order modes or even cladding modes. Only energy detection is needed at the receivers' end. The PH-sensitive hydrogel is made of PVA/PAA. The hydrogel swells its volume according to the PH change in sea water. The sensor is designed in such a way that when the hydrogel swells, a force is acted on the grating portion of the fiber therefore, the mode distribution in the multimode fiber has been changed. Because only fundamental mode is launched into and delivered out of the sensing fiber by the single mode fibers, energy redistribution between the fundamental mode and higher order modes can be detected.

The PH sensor has been tested in the chemostat, which changes the PH in the sea water by absorbing CO₂ gas and the sensor response has been obtained.

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6932-145, Poster Session

Damage detection of structures by acoustic emission technique

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Damage detection is the core technique of structural health monitoring systems. Lots of studies have been done in this field. As a powerful nondestructive tool, acoustic emission (AE) technique was employed to detect the pre-existing defects or evaluate damage conditions of structure. Moreover, AE have capacity of detecting damage which occurs inside the structure and monitoring the structure on-line, so the AE technique has a bright prospect in applications.

In order to determinate damage location of structure by AE, several methods have been developed. These sound source location techniques are based on the wave mode or time arrival method. However, in an actual test, the AE signals mixed with lots of test noise. This noise can infect the location precise greatly. In this paper, wavelet analysis is adopted to deal with the received AE signals before the correlation analysis. By this time-frequency analysis tool, the noise can be effective filtered and an accuracy sound source location is available. The results show that the proposed analyzing method should be a progress for detecting the damage of structures.

6932-146, Poster Session

A sensitivity-based method for sensor placement optimization of bridges

S. Yu, Y. Lei, H. Jin, Xiamen Univ. (China)

Damage detection is the core technique of bridge health monitoring systems. Mostly, the detection is based on comparison of initial signatures (frequency, mode shapes and so on) of intact bridge with that of damaged bridge. The damage identification technique for bridge structure by vibration mode analysis is based on the precision of modal experiment. In order to identify the damage in time, the problem of sensor placement is very important. The number of the sensors and their settled locations determine the accuracy of test results. So how to distribute sensors reasonably to get the appropriate information about the changes of structure state of the bridge is the key for the health monitoring to large span bridges.

Taking an actual long span Bridge as an example and calculating the modal date by the finite element model, a method based on the eigenvector sensitivity is presented in this paper. The numerical example shows that this is an effective method for optimal sensor placement to identify vibration characteristics of the bridges.

6932-147, Poster Session

A distributed damage detection strategy employing smart sensor technology

W. S. Lee, K. Park, B. C. Joo, Y. Hwang, Korea Institute of Construction Technology (South Korea)

The rapid growth in the smart sensor technology (SST) has enabled easier and more economic construction of the structural health monitoring system (SHM). Nevertheless, there is no distributed damage detection algorithm for efficient usage of the computation power of the SST. Therefore, this study aims at developing a new distributed damage detection algorithm suitable for the smart sensor system for the SHM. The algorithm suggested in this study utilizes the damping ratio of a structure, using the structure's energy dissipation ratio. In other words, each smart sensor installed to the structure analyzes the response signals from the structure into a damping ratio, which in turn is computed into an energy dissipation ratio, using the smart sensor's ability to handle data. Thus, this method detects the damages and locations of the damages in a structure using the changes in the energy dissipation ratio it has calculated. In this study proves the usefulness of the developed energy dissipation ratio by comparing it with the Eigenparameter change method and MAC.

6932-148, Poster Session

Sensing rich drive trains for modern mechatronic systems: second year progress report

M. Tomizuka, H. Cheng, C. Wang, Univ. of California/Berkeley

1. Vision guided online trajectory generation.

Vision-based online trajectory generation has already been considered by Namiki[2] and Rouleau[3] among others. However, their focus was primarily on catching or grasping objects. The task we focus on is high precision contour following, since it has a broad range of industrial applications such as welding, metal cutting, painting, and inspection. One traditional approach to perform this task is by generating the reference trajectories for robot joints offline, based on contour information, which is assumed to be known in advance. This trajectory is then utilized for real time control of the robot arm. The obvious disadvantage of this approach is this assumption. In practical applications, more often than not, the contour is known only approximately because it depends on the positioning and orientation errors of parts, among other factors.

With the help of a vision camera, the robot arm can obtain position information regarding the contour in real time. Therefore, it is not necessary to know the absolute position of the contour in advance. We propose a real time reference generation scheme for robot manipulators based on vision sensing. Since the sampling rate of the camera is slower than that of the joint loop, once the image feature information of a new image is available, it is used to generate the reference trajectory for several successive joint sampling times until the next image is captured. This formulation is for two dimensional (2-d) tracking, but can be easily extended to 3-d tracking.

In the first year of this project [1], the proposed method was tested on straight lines only. In the second year report, real time experimental results are presented for a variety of trajectories to verify the proposed trajectory generation scheme along with a newly built experimental setup with a two link direct drive robot.

2. Controller tuning of drive trains with auxiliary load-side accelerometers.

The servo controllers in drive train systems are normally actuator (motor) position feedback controllers, since the actuator (motor) positions are often the only measurements available. On the other hand, drive train system performance is generally specified by the load-side variables instead of motor-side ones. Since the load-side variables are not available, controller performance can only be predicted based on the model in the controller design. Due to the uncertainties and nonlinearities, such as friction and backlash of the gear mechanism in the system, it is often necessary to tune the motor feedback controller for particular applications to ensure satisfactory load-side response. The tuning process can be time consuming when the controller structure becomes more complicated. Therefore, it is desirable to have a field tuning procedure to shorten tuning time. Since load-side performance is of interest, it will be beneficial if some information of the load-side variables is available during the tuning process. We suggest measurement of the load-side acceleration due to the fact that accelerometers, especially MEMS ones, are small and easy to install without modification the existing mechanical parts. Furthermore, the acceleration signal also directly reflects the load-side vibration. Notice that the additional load-side acceleration measurement is for the controller tuning purposes only, and not used as a feedback quantity.

A gradient-based experimental tuning method for the above stated configuration was proposed and evaluated by simulation in the first year [1]. In the second year, the proposed method has been experimentally tested to confirm the effectiveness of the approach.

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6932-150, Poster Session

Optical fiber grating-based sensing system for use in pavement health monitoring

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In this paper, we report the development and realization of an optical sensing system by using a high-resolution temperature and strain sensor with fiber Bragg grating (FBG) technology and a simple and low-cost long-period grating (LPG) sensor for the water-level measurement in pavement structures. The FBG sensor system consists of a reference fiber grating and a grating pair scheme that could offer the potential of simultaneous measurement of strain and temperature for monitoring pavement structures. Experimental results show that measurement errors of 6 microstrains and 0.13 degree Celsius for strain and temperature could be achieved, respectively. The LPG sensor is extremely sensitive to the refractive index of the medium surrounding the cladding surface of the sensing grating, thus allowing it to be used as an ambient index sensor (such as water-level sensing) or chemical concentration indicator. We have measured chloride ion levels in a concrete sample immersed in salt water solution with different weight concentration ranging from 0 % to 20 %, and results show that the LPG sensor exhibited a linear decrease in the transmission loss and resonance wavelength shift when the concentration increased. For this study, LPG sensors were used to distinguish between air and water inside different layers or materials of pavement structures. This FBG sensor was examined by mounting sensors on the surface of asphalt and concrete specimens. Small root mean square temperature variations (better than 1C) and excellent long-term stability (within 2%) were obtained. The maximum variations in temperature for 48 hours were only 1.94% and 2.32% for asphalt and concrete specimens, respectively. The feasibility of strain measurement for pavement structures was conducted by mounting the packaged sensor on the surface of an asphalt specimen under the indirect tensile loading condition. The measured strains from the packaged FBG sensor agreed linearly with applied loads. A finite-element model (FEM) was conducted to verify the strains obtained from the sensors. In comparison with experimental data and numerical results, the numerical values were all located within FBG measurement error ranges. The strain differences between measurements from the FBG sensor and FEM predictions were 5~7%. Experimental water-level measurements using LPG sensors will be presented, including laboratory evaluation of water-level sensing responses and accuracy using different LPG sensing measurements. This simple and low-cost combined FBG and LPG sensing system is expected to benefit the health monitoring of multi-layer pavement structures.

6932-151, Poster Session

Experimental study on the method of bridge safety evaluation by fiber Bragg grating optical sensor

B. C. Joo, K. Park, W. S. Lee, Y. Hwang, Korea Institute of Construction Technology (South Korea)

Generally, the management reference by monitoring items applied to the bridge management is decided through the intuition of the based on the empirical data without any professional and systematic background.

In this study, the span deflection is selected among the bridge monitoring items and verify the appropriate management reference in the case of deflection by the laboratory test.

Test specimens are the small-sizing bridge specimens which are made by reinforced concrete. Those are classified by variation of span length and stiffness of section.

As a result of test, the relationship between the center deflection of span and the safety level of bridge is suggested.

Additionally, Fiber Bragg Grating (FBG) optical sensors are used in the test. Through the comparing FBG optical sensors and general sensors, it is concluded that the FBG optical sensor can be applied effectively in structure behavior monitoring.

6932-152, Poster Session

Communication network-based strategy to establish the smart bridge safety management system

W. S. Lee, K. Park, B. C. Joo, Y. Hwang, Korea Institute of Construction Technology (South Korea)

Currently the safety management of bridges in most cases is carried out in periodic method such as safety inspection and in-depth safety diagnosis in Korea. Therefore, there is the demerit that the bridge condition cannot be managed continuously and the danger situation that occurs in a short time cannot be monitored. Recently structure health monitoring system [SHM] is erected on the important bridges in a way to solve such problems so that the bridges can be monitored at real-time basis. Nevertheless, the current SHM is established independently by bridges, and therefore the management is not made systematically and efficiently due to the lack of professional management man power.

In this study, the emphasis was put on the research on the establishment of smart bridge safety management system using the communication network and the advanced sensor technology that are rapidly developed these days which enables the reliability and systematic management.

6932-154, Poster Session

Large-deformation polymer optical fiber sensors for civil infrastructure systems

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POFs provide a large strain to failure, are more flexible than silica optical fibers, are more durable in harsh chemical or environmental conditions and have a relatively high fracture toughness. These characteristics make them ideal for large-strain civil infrastructure applications such as seismic load conditions. Conventional strain gages for cyclic load applications can be reliable up to approximately 3% strain when surface mounted on steel structures and less than 1% when embedded in concrete. These limitations are a serious challenge for civil infrastructures subjected to seismic loads, where material strains can exceed 2% in the concrete and 5% in the reinforcing steel. Recent advances in the fabrication of singlemode POFs have made it possible to extend POFs to interferometric sensor capabilities. Therefore, interferometric POF sensor systems potentially offer a larger strain range measurement capability along with more long-term survivability for civil infrastructure systems.

This paper describes recent advances in the application of a single-mode POF interferometric sensor for the measurement of strains in civil infrastructure applications. The demonstration of phase-shift measurements within the POF up to 15.8% nominal strain is demonstrated on a laboratory bench. The phase-shift sensitivity was measured to be 1.39×10^{-7} rad/m for this strain range. This strain range is well beyond that previously measured for intrinsic optical fiber sensors. The results of these phase-shift measurements are then combined with previous mechanical testing of the single-mode POFs to develop a nonlinear, opto-mechanical response calibration of the in-fiber interferometer covering both the small and large strain ranges.

Furthermore, practical considerations for the application of this POF in-fiber interferometer as an embedded sensor are discussed. The bond strength between various civil structural materials (cement paste, hydrostone and mortar) and the POF was investigated through tensile pull-out tests of casted specimens with an embedded POF. The cement paste was the optimal material system in which to embed the POF due to the ease of mixing and casting and the strong bond between the cement and the POF. Furthermore, the force vs. displacement behavior for the cement paste specimen indicated that no pullout occurred prior to fracture of the POF. A procedure for the embedment of POFs into large scale reinforced concrete structures was also developed. Small concrete blocks with an embedded POF were pre-cast, after which light transmission through the embedded POF was verified. Negligible reduction in light propagation occurred, indicating that the transverse residual strain on the POF was sufficiently small. The pre-cast blocks were then successfully embedded into full-scale structural members for verification of the POF sensors. Finally, trials for the preparation of the POF end-faces for coupling with conventional silica optical fiber sensor interrogation systems are presented.

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6932-155, Poster Session

Reliable data transmission of rotating wireless sensors using automatic repeat request

L. Tang, J. Jacob, K. Wang, Y. Huang, Clemson Univ.; F. Gu, General Motors Corp.

Wireless sensors capable of sensing, processing, and wireless communication have been adopted for monitoring purposes in a variety of contexts, many of which feature challenging radio propagation characteristics. Fast rotating structures are commonly found in mechanical, transportation and energy systems, and the challenges of using wireless sensors on such structures have not been adequately addressed. For wireless sensors on rotating structures, it has been found there is an eminent dependency of packet error rates on rotation speeds, bursty bit errors, periodic variation in received signal strengths, and dominance of multipath effects due to harsh industrial environments. The objective of this study is to develop a reliable data transmission approach for such a rotating sensing system and assess the efficacy of the automatic repeat request (ARQ) approach in terms of transmission success rate, retransmission overheads, and reliable transmission throughput.

The spindle, with a 60–6000 revolutions per minute controllable range, of a computer numerical control lathe has been selected as the testbed in this study. The wireless sensors used were the Crossbow IEEE 802.15.4 compatible sensor nodes. Bit pattern analysis suggested that transmission errors have most probably taken place in certain high-error regions, with their retransmissions mostly in low-error regions due to the rotation. The transmission and retransmission success rates both increased as the packet size decreased, the received signal strength indication strongly correlated with the transmission success probability as the packet size decreased, and the saturated reliable throughput was an upper bound for the feasible packet generation rate.

6932-156, Poster Session

Design of a prototype laminated sheet galfenol actuator

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Alloys of iron and non-magnetic gallium of the form $Fe_{1-x}Ga_x$ with $15 < x < 30$, collectively referred to as Galfenol, have been shown to exhibit magnetostrictions in excess of 400 microstrain under quasi-static magnetic fields. When this material is used in dynamic actuator applications, e.g. for vibration control, eddy current induced losses associated with the relatively high permeability of the alloy limit actuator bandwidth. The most common way of circumventing this limitation of magnetostrictive devices is through the use of thin laminates of active material. For more brittle alloys, it is common to use electron discharge machining techniques to form laminae of the thickness required for a specific actuator bandwidth. This can be expensive and/or lead to net material losses due to curf losses associated with the cutting process. Galfenol, however, is a relatively ductile alloy that exhibits sufficient formability that it has successfully been rolled into thin sheets with thicknesses of less than 0.3mm. In this paper, we first present a review of the design criteria that relate bandwidth to permeability and active material cross sectional thickness, which motivates the interest in rolled sheet laminated devices. We then discussed the method for obtaining the rolled sheet used and discuss the design of a prototype dynamic actuator that uses laminated rolled sheets of Galfenol as the active actuator material. We provide preliminary experimental results demonstrating the enhanced bandwidth that is achievable as a result of employing rolled Galfenol sheet as the active material in our actuators.

6932-157, Poster Session

Granular segregation studies for retroreflector sensor development

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We are developing a three-dimensional sensing system that enables the tracking of localized material movement by recording displacement and

rotation of passive radar targets within materials of interest. Ultimately, the development of this system will provide a highly reliable, cost-efficient set of tools for basic and applied granular materials research. However, the size and material density of the passive radar targets will be inevitably different than the material in which they are embedded, and particles of different sizes and densities tend to segregate when jostled, sheared, or otherwise disturbed. In other words, neighboring particles of different sizes and/or densities will likely not have identical movements. Therefore, effective use of the passive radar targets to predict movement of the bulk material will require a systematic understanding of how segregation depends on relative size and density of the tracer particles.

In many situations, it is difficult to isolate granular segregation driven by a velocity gradient and associated Reynolds stresses from the additional segregation effects of gravity and a volume fraction gradient. In some situations the segregation is simple enough that this distinction seems unimportant: smaller particles tend to sink compared to their larger equal-density counterparts; denser particles tend to sink compared with their equal-sized lighter counterparts. These are often attributed to kinetic sieving and buoyancy, respectively. However, in some situations the segregation is more complex: particles poured into a pile may segregate into stratified layers, and in drums some mixtures will segregate into radial stripes and axial bands. We compare segregation in a number of different systems to isolate different segregation effects in densely sheared granular mixtures: velocity gradients, volume fraction gradients and gravity. While gravity is important, eliminating the volume fraction gradient significantly reduces the effect of gravity on size segregation. Shear-induced segregation is also important, but appears the weakest of the three mechanisms in dense granular flow. We will discuss these details and demonstrate how this could be applied to relate sensor particle movement with bulk movement in basic and applied research on densely sheared granular materials.

6932-69, Session 14

**The effect of through-the-thickness holes on a reference-free damage diagnosis technique

C. G. Lee, H. Sohn, Korea Advanced Institute of Science and Technology (South Korea)

In this study, a damage detection technique is developed based on the polarization characteristics of the piezoceramic (PZT) transducers attached on the both sides of a thin and uniform metal plate. Damage is identified using instantaneously measured Lamb wave signals without using previously obtained baseline data. If the propagating waves along a thin plate encounter a discontinuity point such as a crack, mode conversion occurs and this mode conversion is extracted using the proposed technique. So far, the proposed technique is demonstrated for specimens with uniform thickness although many structural systems have more complex structural features such as stiffeners, holes and bolts. In this study, the effect of through-the-thickness holes on the proposed technique is investigated. An array of holes creates multiple reflections and refractions of Lamb waves, and these multiple modes may cause difficulties in analyzing responses of Lamb waves. Because the through-the-thickness holes should not produce mode conversions, it is expected that these holes will not affect the performance of the proposed technique. This study investigates whether a crack damage can be still identified even at the presence of the holes. Numerical and experimental results are presented to examine the usefulness of the technique at the existence of the holes.

6932-70, Session 14

Nondestructive estimation of crack depth in concrete

J. Min, Korea Advanced Institute of Science and Technology (South Korea); S. W. Shin, Univ. of Illinois at Urbana-Champaign; C. Yun, Korea Advanced Institute of Science and Technology (South Korea); J. Zhu, The Univ. of Texas at Austin; J. S. Popovics, Univ. of Illinois at Urbana-Champaign

Cracks affect the durability of concrete and may lead to early failure of concrete structures. Therefore, early detection, accurate measurement and repair of cracks in concrete are important for maintaining structural

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health. A surface wave spectral energy transmission method is proposed for surface-breaking crack depth estimation in this study. This method is an extension of the self-calibrating surface wave transmission method, but the test results may be independent of the wave frequencies. Consequently, the proposed method simplifies the data analysis and improves the consistency of results. A relationship between the surface wave spectral energy transmission coefficient and the crack depth has been established based on the experimental data, which were collected on various concrete specimens with different crack depths and different compositions. The effectiveness of the proposed method is validated by comparing the results using the time-of-flight of diffraction method and the cut-off frequency method. The results show that spectral energy transmission method has promising potential as a practical and reliable in-situ nondestructive method for crack depth estimation in concrete structures.

6932-71, Session 14

****Detection and assessment of wood decay in structural lumber using surface waves**

H. L. Reis, A. Senalik, Univ. of Illinois at Urbana-Champaign

The two major forms of bio-deterioration of wood and wood products are decay and insect attack. While many wood structures are routinely inspected for insect attack, such as for termite inspection in real state transactions, inspection for incipient wood decay is rarely performed mainly because of the lack of an effective testing method. In this study, a surface wave (i.e., Rayleigh) based approach is presented to detect and assess wood decay in structural lumber. This one-sided proposed approach takes advantage of the dispersion effects in the surface wave caused by the presence of a layer of decayed wood. A frequency sweep approach is used and the experimental results are compared with theoretical predictions. Results reveal that the proposed method can effectively be used to detect and assess the amount of wood decay.

6932-02, Session 15

****Sensitivity analysis of a luminescent photoelastic coating**

E. Esirgemez, C. Lira, J. P. Hubner, The Univ. of Alabama at Tuscaloosa

This paper will present results from a thermal sensitivity and corresponding uncertainty analysis of the luminescent photoelastic coating technique. The investigation is part of larger research program to integrate luminescence sensing for strain measurement and health monitoring in civil, automotive and aerodynamic applications. Luminescent photoelasticity is a new approach to measure mechanically induced stress and strain on structural components. The technique incorporates a luminescent dye that partially preserves the stress-modified polarization state within a birefringent coating and provides high emission signal strength at oblique surface orientations. These characteristics can facilitate determining the principle strains and directions on complex geometries, without additional experimental or analytical techniques, by exploiting the angle dependent emission when obliquely illuminated.

The optical strain response of the coating is a nonlinear function of the maximum shear strain in the plane perpendicular to the propagation of light. Several parameters affect the strain response including luminescent polarization efficiency, optical sensitivity, coating absorptivity and effective excitation-emission wavelength. The temperature dependency of these parameters is important to characterize if the technique is extended to high-temperature or cyclic-temperature environments. A small thermal chamber has been constructed with open optical access to test coated cantilevered specimens under a linearly varying bending stress. Initial results show that the overall optical strain response initially decreases with temperature (approximately 75% between 25 to 75 °C) and then stabilizes at higher temperatures (> 75 °C). Further tests will focus the individual temperature dependency of each of the primary parameters. The temperature sensitivity will be discussed in the context of a corresponding general uncertainty analysis of the technique.

6932-72, Session 15

****Monitoring the bending and twist of morphing structures**

A. M. Baz, J. Smoker, Univ. of Maryland/College Park

This paper presents the development of the theoretical basis for the design of sensor networks for determining the 2-dimensional shape of morphing structures by monitoring simultaneously the bending and twist deflections. The proposed development is based on the non-linear theory of finite elements to extract the transverse linear and angular deflections of a plate-like structure.

The sensors outputs are wirelessly transmitted to the command unit to simultaneously compute maps of the linear and angular deflections and maps of the strain distribution of the entire structure.

The deflection and shape information are required to ascertain that the structure is properly deployed and that its surfaces are operating wrinkle-free. The strain map ensures that the structure is not loaded excessively to adversely affect its service life.

The developed theoretical model is validated experimentally using a prototype of a variable cambered span morphing structure provided with a network of distributed sensors. The structure/sensor network system is tested under various static and dynamic loading conditions to determine the time and frequency response characteristics of the proposed sensor network as compared to other conventional sensor systems.

The presented theoretical and experimental techniques can have a great impact on the safe deployment and effective operation of a wide variety of morphing and inflatable structures such as morphing aircraft, solar sails, inflatable wings, and large antennas. [Work is funded by NSF].

6932-73, Session 15

****Optimization of sensor introduction into laminated composite materials**

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This work seeks to extend the functionality of the composite material beyond that of simply load-bearing and to enable in situ sensing, without compromising the structural integrity of the host composite material. Essential to the application of smart composites is the issue of the mechanical coupling of the sensor to the host material. Here we present various methods of embedding sensors within the host composite material. In this study, quasi-static three-point bending (short beam) and fatigue three-point bending (short beam) tests are conducted in order to characterize the effects of introducing the sensors into the host composite material. The sensors that are examined include three types of polyvinylidene fluoride (PVDF) thin film sensors: silver ink with a protective coating of urethane, silver ink without a protective coating, and nickel-copper alloy without a protective coating. The methods of sensor integration include placement at the midplane between the layers of prepreg material as well as a sandwich configuration in which a PVDF thin film sensor was placed between the first and second and nineteenth and twentieth layers of prepreg. Each PVDF sensor is continuous and occupies the entire layer, lying in the plane normal to the thickness direction in laminated composites. The work described here is part of an ongoing effort to understand the structural effects of integrating microsensor networks into a host composite material.

6932-74, Session 15

Three-parameter elastic foundation model of piezoelectric smart beams

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External bonding of PZT patches to host structures as sensors and actuators has emerged as a popular method in smart structural applications such as structural health monitoring and vibration and shape control. Due to the strong material mismatches between the PZT patch and host structure, severe stress concentration can be induced along the PZT-host structure interface, which can lead to interface debonding and premature failure of the smart structure. For this reason, stresses along the PZT-host structure interface are of great research interest. Existing solutions mainly

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adopt the classical solutions of adhesive joint in which the adhesive layer is essentially modeled as a two-parameter elastic foundation. However, this model can't satisfy the shear stress boundary condition because a degree-of-freedom of the adhesive layer is lost in the two-parameter elastic foundation model. In this paper, we propose an innovative three-parameter elastic foundation model to simulate the adhesive layer. This new model regains the missing "degree-of-freedom" in the two-parameter foundation model of the adhesive layer by introducing an extra parameter. Closed-form solutions of interface stresses are obtained and all the boundary conditions are satisfied naturally. The salient features of the model are as follows: 1) it reveals The significant difference of the interface normal stresses along the PZT-adhesive interface and the adhesive-host beam interface; 2) it satisfies all boundary conditions, including the zero shear stress at the edge of the adhesive layer; 3) its solutions are in explicit closed-form, and, therefore, can be easily implemented for analysis and design of piezoelectric smart beams. The accuracy of the present model is verified by its good agreements with FEA solutions.

6932-75, Session 15

Estimation of deflections of bridge by two-step model updating approach based on ambient acceleration measurements

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Structural identification techniques have been frequently applied for the structural integrity assessment of civil infrastructures. In the case of bridges, deflection data by load tests using trucks with known axes weights have been widely used for the bridge integrity assessment, such as bridge rating. However, for measurement of deflection of a bridge, the traffic block and sensor inaccessibility which may be caused by a ditch, river, vehicle-passing road under the bridge during the load test may cause lots of inconvenience to traffic and increase of logistic cost and time. Therefore, an alternative deflection estimation method using measured acceleration data from an ambient vibration test is proposed in this study. The present method consists of ambient acceleration measurement on a bridge, experimental modal analysis using the measured ambient acceleration data, model updating of the initial finite element (FE) model of the bridge based on the identified modal properties, and estimation of the deflection using the updated FE model. For the verification of the present method, load and ambient tests were carried out on an old PSC girder bridge with two spans. For the fast and stabilized optimization process during the model updating, two step model updating approach - the first updating the initial FE model of the test bridge is performed using the bending-governing factors like EI values, support conditions, and connection stiffness of two spans as the updating parameters and the second is performed using the torsion-governing parameters like the torsional coefficients and support conditions - is additionally proposed. To find out the effect of used modal parameters and their weighting in the model updating, model updatings using only natural frequencies, using only mode shapes, and using both of them, were performed by applying several kinds of weightings on them. By simulating the load test on each of the updated model, deflection by the present two step model updating approach was estimated and compared with the real measured deflection data in the load test.

6932-76, Session 15

Analytical and experimental evaluation of vehicle-bridge interaction

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A new and simple vehicle-bridge interaction analysis is proposed. The accurate vehicle-bridge interaction analysis is required for assessing and designing of bridges for wheel loads, or for reducing the dynamic response of bridges. There are many factors affecting the dynamic behavior of bridges such as the type, natural frequencies and damping ratios of bridges, surface roughness, ballast stiffness, the number of vehicles,

vehicle characteristics, path, speed, and the position of wheels, therefore vehicle-bridge interaction analysis is very a complex dynamic problem. Various models have been developed for the analysis including moving-load moving-mass model, moving-sprung-mass model, and moving vehicle model, but the system matrices - mass and stiffness matrices - need to be constructed at every iteration requiring very complicated computation. In the proposed analysis method, the necessity of system matrices update is eliminated using the equivalent interaction force acting on the bridge. The bridge is considered as an elastic Bernoulli-Euler beam with surface irregularity and ballast stiffness which can be used to model rail for trains. The moving vehicle is modeled as a multi-axle mass-spring-damper system having many degrees of freedom according to the number of axles, and the pitching effect is also considered. The method is experimentally verified using a simple beam under moving vehicle. The vehicle is designed to have varying speeds so that the effect of moving speed to the dynamic response of the beam. The mass of vehicle can also be varied for experimental verification of the mass effect to the dynamic response. The mid-span deflection is measured using both a linear variable differential transformer (LVDT) and laser distance sensor. The measured mid-span deflection and acceleration of the simple beam are compared with the results of the proposed model and various vehicle-bridge interaction models. It is shown that experimental results agree well to the analysis results using the proposed method and previous methods

6932-77, Session 16

Input force identification by using system identification techniques: Kalman filter with a recursive estimator

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An accurate characterization of dynamic excitation forces acting on a structure during services operation is significant for designing, controlling and diagnosing the structures. For some physical and mechanical systems, direct measurements of dynamic excitation forces are difficult, if not impossible, to be realized due to various reasons, such as very large magnitudes of forces or installation obstacles of load transducers. Therefore, an alternate method to reconstruct dynamic excitation forces is needed. An identification method for estimating time varying excitation forces acting on a structural system based on the measurement responses is presented in this study. Our method is based on a combination of the Kalman filter and an input estimation technique; the later is a least-squares algorithm from which a regression model is established between the residual innovation and the input excitation forces. Based on the regression model, a recursive least-squares estimator is proposed to identify the input excitation forces incorporating measurement noise and modeling error. The accuracy of the method is discussed by numerical simulations for a multiple-degree-of-freedom lumped-mass system with multiple unknown inputs and multiple output measurements.

6932-79, Session 16

Low-power feedback-enhanced electromechanical impedance (FEMI) sensors

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Electromechanical impedance (EMI) method utilizing smart piezoelectric sensors has emerged as a promising technology for structural health monitoring in civil, mechanical and aerospace engineering. However, two major limiting factors have prevented field deployment of this method in real life. First, smart piezoelectric sensors, such as Lead Zirconate Titanate (PZT) patches, are highly sensitive to environmental changes such as temperature, humidity, and vibration. Secondly, bulky and expensive equipment is needed for performing impedance measurement. This paper proposes a feedback-enhanced electro-mechanical impedance (FEMI) technique for improving robustness against environmental variations and a design of a low-power EMI sensor with built-in measurement circuitries based on this new technique.

The proposed FEMI technique employs a feedback scheme to amplify the peaking characteristics of the natural resonance frequencies in the

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EMI frequency response. The feedback loop includes a phase locked loop (PLL) and a transimpedance amplifier (TIA). An analog EMI measurement circuit is developed to replace bulky EMI measurement instruments. To keep the power consumption low, the proposed system does not require any analog-to-digital conversion or DSP circuit blocks, but uses a simple analog mixer to multiply the input and output waveforms of the PZT sensor, and then extract the EMI amplitude by passing the mixer output through a low-pass filter (LPF).

The performance of the proposed FEMI sensor is verified by simulations using MATLAB. Simulated natural frequency peaks in the EMI spectrum are noticeably sharper with the feedback scheme than the one without feedback, so that the natural frequency change can be easily detected. To quantify the shift of these natural frequency peaks, the root mean square deviation (RMSD) of the difference between cases without damage and with damage is calculated. The simulation results show that the RMSD with feedback is greater than the RMSD without feedback by a factor of 3.2, when the damage is emulated by a 30% decrease in stiffness. This result confirms that the FEMI technique with the proposed EMI measurement circuits can detect the shift in the natural frequency caused by damage, with higher sensitivity compared to existing methods.

6932-80, Session 16

****Comparison of various structural damage tracking techniques based on experimental data**

H. Huang, Tongji Univ. (China); J. N. Yang, Univ. of California/Irvine; L. L. Zhou, Nanjing Univ. of Aeronautics and Astronautics (China)

Damage identification of structures is an important task of a health monitoring system. The ability to detect damages on-line or almost on-line will ensure the reliability and safety of structures. Analysis methodologies for structural damage identification based on measured vibration data have received considerable attention, including the least-square estimation (LSE), extended Kalman filter (EKF), etc. Recently, new analysis methods, referred to as the sequential non-linear least-square estimation (SNLSE) and adaptive quadratic sum squares error (AQSSSE), have been proposed for the damage tracking of structures. In this paper, these newly proposed analysis methods will be compared with the LSE and EKF approaches, in terms of accuracy, convergence and efficiency, for damage identification of structures based on experimental data. A series of experimental tests using a small-scale 3-story building model have been conducted. In these experimental tests, white noise and earthquake excitations were applied to the model, respectively, and different damage scenarios were simulated and tested. Here, the capability of the LSE, EKF, SNLSE and AQSSSE approaches in tracking the structural damage will be verified using experimental data. The tracking results for the stiffness of all stories, based on each approach with different measured response data, are compared with the stiffness predicted by the finite-element method. The advantages and drawbacks of each damage tracking approach will be evaluated in terms of the accuracy, efficiency, and practicality.

6932-81, Session 16

Structural damage assessment using damage locating vector with limited sensors

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The damage locating vector (DLV) method based on dynamic response is (a) modified for structural damage detection using normalized cumulative energy (instead of stress) criterion, (b) applied to the case where the number of sensors used is small compared to the structural degrees of freedom (dofs), and (c) employed to identify multiple damaged elements of an existing structure. Essential to the method is the determination of a special set of static load vector (the DLV) which has the property that when the set is applied to the structure at reference state, no energy is induced in the damaged elements. From the measured structural dynamic response, Eigensystem Realization Algorithm (ERA) is employed to extract structural realization matrices from which the flexibility matrix at sensor locations is formulated. Based on the change in flexibility matrices of the structure from the reference to the damaged states, the DLV is calculated

and then applied to the structure at its reference state to identify damaged elements. To avoid error in identifying damaged elements, the set of sensors are shifted to different locations to produce different sets of potential damaged elements. The intersection of all available sets of potential damaged elements yields an improved (smaller) number of potential damaged elements and the procedure is repeated until the number of potential damaged elements cannot be further reduced. The efficiency and robustness of the proposed method are examined for the case of multiple damaged elements in a 3D truss structure. Simulated and experimental data successfully verified the feasibility of the proposed method in assessing structural damage with limited sensors.

6932-162, Session 16

Reduction of shock noise using acoustic nonlinear energy sink technology

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Following the nonlinear sink (NES) principles developed by Bergman, this paper introduces Acoustic Nonlinear Energy Sink (ANES), a technique for reduction of shock noises. The ANES model as established can both reflect and absorb the acoustic energy of the input waves. Using this model two broadband passive noise control systems in terms of ANES appendix are studied. One system is designed with the bottom part of a classical Helmholtz resonator (HR) as a linear oscillator, which is weakly coupled with an essentially nonlinear mechanical oscillator. The second system is designed with the bottom part of a HR as a nonlinear oscillator. Numerical simulations of these noise reduction systems are carried out. By properly selecting system parameters of ANES, it is shown that the shock pressure amplitude of an acoustic duct equipped with ANES can be effectively reduced. Likewise an acoustic duct equipped with two double ANES systems could also reduce the amplitude of input noise through reflecting and absorbing a portion of input energy into the energy sink.

6932-01, Session 17

Demonstration of detectability of SHM system with FBG/PZT hybrid system in composite wing box structure

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In the field of aircraft industry, a large amount of application of carbon fiber reinforced plastics (CFRPs) has been progressing, because of their contribution of weight reduction of airframe and reduction of number of parts, and so on. Although application of CFRPs to aircraft structures will be increasing hereafter, the complexity of the fracture behavior of CFRPs structures is still one of the issues to prevent their optimum design as the damage tolerance design of metal structures.

So, we had been developing novel SHM system, which could monitor the integrity of composite structures for aircraft. The SHM system was composed of fiber bragg grating (FBG) sensor, arrayed waveguide grating (AWG) type filter and piezo transducer (PZT). In this system, FBG sensor was used as sensor and PZT was used as generator of elastic waves, which propagated in the structure that should be monitored or inspected. The SHM system could detect the structural integrity by the change of elastic waves, which were measured by FBG sensor and AWG type filter. We had confirmed that the SHM system could monitor the damage propagation as the change of the elastic waveform with coupon and structural element type specimens.

In this study, we demonstrated the detectability of the SHM system by using the large size test component, which simulated practical aircraft wing box structure of CFRPs. The size of the wing box test component is about 4000 mm in span, about 2000 mm in chord and about 800 mm in thickness, respectively. FBG sensors and PZTs were bonded on the surfaces of hat-shaped stringers by adhesive. Damages, such as debonding and delamination, were introduced to the bonded sections of skin and stringers by impact using a drop weight type impactor and some impact energy levels were determined in order to verify the accuracy of detection of the SHM system. Impact detection and damage monitoring were carried out by the SHM system at ambient condition. Demonstration

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of our SHM system was successfully finished for the verification of affordability of the damage monitoring system. In this article, the demonstration of detectability of the SHM system is presented.

6932-83, Session 17

A regularization scheme for displacement reconstruction

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In structural health monitoring (SHM) and structural control (SC), dynamic responses in time domain such as acceleration, velocity, and displacement are required for monitoring and identification of structural system of interest. Among these dynamic responses of the structural system, time history data of displacement play an important role in system identification of nonlinear dynamic systems and various SC applications. Unfortunately, direct measurement of time history displacements has been limited due to difficulties caused by installation and instrumental problems.

Generally, accelerations have been most commonly measured dynamic responses because various types of commercial accelerometers can measure acceleration data reliably for a wide range of dynamic frequencies without need for the fixed reference points. According to the kinematics of a body, the corresponding displacements can be calculated through double integration of measured acceleration data in time domain. Newmark's method and trapezoidal rules are typical time integration schemes for calculating displacements.

Although these integrations schemes are straightforward and easy to apply, there exist inherent difficulties that yield erroneous displacements in double integration of accelerations. First, initial velocity and displacement conditions required for determining unique time history displacements via double integration are usually unknown in real situation. Even though the initial conditions could be measured, a small amount of perturbation of the initial conditions should create significant constant or linear drift in the calculated displacements. Second, random measurement noise in acceleration data creates physically inadmissible nonlinear drift in calculated displacements during double integration of accelerations. In particular, low frequency noise components in measured acceleration data are strongly amplified and contribute to most of the inadmissible nonlinear drift in the calculated displacements. Note that this phenomenon is a serious problem to calculate the displacements of low-frequency dominant civil structures because it is very difficult to distinguish real displacement components from the noise-polluted calculated displacements.

To alleviate these undesirable results of double integration of acceleration data, we introduce displacement reconstruction algorithm using only measured acceleration data. For given measured acceleration data, displacement reconstruction can be defined as an elliptic boundary value problem. This elliptic boundary value problem is discretized in time domain by using central difference method in which calculated acceleration can be obtained. The proposed algorithm estimates time-history displacement through the minimization of an error function defined by the least-squared error between the measured and calculated accelerations.

Because the displacements associated with boundary conditions of the elliptic problem and low-frequency noise components in measured acceleration are significantly amplified, the minimization problem for displacement reconstruction becomes rank-deficient and ill-posed. To alleviate the rank-deficiency and ill-posedness, a regularization technique is adopted in the minimization problem.

The real-time displacement reconstruction is often required for the on-line structural health monitoring. The time window concept is proposed to reduce computational costs for real time displacement reconstruction. The validity of the proposed method is demonstrated in reconstructing displacements using real acceleration data measured from vibration tests of a cantilever beam, a stay cable and a bridge on Korea highspeed railroad.

6932-84, Session 17

Tracking time-varying properties of hysteretic structure by wavelet multiresolution analysis

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The ability of an early detection of possible damage in a structure especially when subjected to severe external loadings is a very important research topic. Damage in a structure usually comes with time-varying characteristics, such as hysteresis, that lead to time-varying structural parameters. Identification of time-varying structural parameters is necessary for assessing the safety of these damaged structures. A time-varying system identification technique using wavelet multi-resolution analysis is proposed in this paper. Wavelet is well known for its ability to approximate and represent time-varying functions. Expressing time-varying parameters in a hysteretic structure using wavelet multi-resolution models, the identification of these time-varying parameters is transformed to a time-invariant problem that depends on solving constant wavelet coefficients. An orthogonal forward regression algorithm is then adopted to prune insignificant wavelet coefficients before estimating those significant ones. Examples of single- and multi-degree-of-freedom hysteretic structures with different time-varying properties are given to demonstrate the applicability and accuracy of the proposed approach.

6932-85, Session 17

Filtering techniques in the dynamic deformation estimation using multiple strains measured by FBGs

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We investigated the dynamic structural displacement estimation based on measured strains at multiple locations. Because of excellent multiplexing property of optical fiber Bragg grating sensors, strain data at several points can be easily obtained. The present study focuses on the filtering techniques in the dynamic deformation estimation using modal approaches. This paper shows that the proper use of filters plays an important role in the improvement of deformation estimation performances.

In the last decade optical fiber Bragg grating sensors have been introduced as innovative strain sensors with several advantages in comparison to basic strain gauges. The wavelength change of the reflected Bragg wavelength of each sensor allows a high resolution strain measurement ($\sim 1\text{11}/4\mu$) with minimal noise corruption. The thin optical fibers are insensitive to electromagnetic radiation and light in weight which allows a direct integration of the fiber into modern composite materials. The fiber's ability of multiplexing enables an integration of several strain sensors in only one optical fiber. The author's research group showed that the dynamic shape of a structure can be estimated in real time using multiplexed fiber Bragg grating sensors and modal approaches.

The dynamic shape of a structure is essential for the modern approach of structural health monitoring and even more for structural control applications. The difficulty of direct measurement of the shape of a structure in operation is solved by introducing the strain-displacement relation in the modal approach and estimating the structure's shape with measured strain over the structure.

However, the measurement of strain and its transformation into structural displacement on the basis of a transfiguration matrix is corrupted by several error sources, e.g. measurement noise in the strain data (aliasing) and model errors in the structural state space model of the modal approach (residual modes). The strain-deflection transformation matrix (SDT) of the modal approach which represents the dynamic structure by separating its structural response in a combination of its modal amplitudes limits the number of useable modal amplitudes to the number of used strain signals. Hence, higher frequent strain signal contents (residual modes) above the highest considered natural frequency in the modal approach are misinterpreted as combination of lower frequent deflection. Aliasing of high frequent noise and model errors can lead to unacceptable high

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estimation errors of above 100%. In control theory different filtering techniques are used to compensate signal noise and other error sources in a state space model.

In this study three representative filtering techniques, the Low Pass Filter (LPF), the Modal Filter (MF) and the Kalman Filter (KF) in two variations, are translated and applied to the shape estimation process. Aim of the study is to investigate the possible application of the filtering techniques to the used strain-deflection transformation and the improvement of the shape estimation process by compensation the occurring signal noise contents and model errors.

The Low-Pass Filter is applied directly to the measured strain signal to attenuate higher frequent noise contents. Lower frequent noise contents can be separated from the strain signals by applying separated Low-Pass filter as Modal filter to each modal amplitude which is obtained from the strain signals. In contrary to the basic Low-Pass filter, the Kalman Filter is applied as state space estimator filtering low and high frequent noise and compensating model errors by introducing error covariances which are used together with the reference strain signal to minimize the state error. Main advantage of the Kalman filter method is the unrestricted number of useable mode shapes for the structural modelling in the modal approach.

To investigate the influence of residual modes, noise level of the measured strain signal and further filter parameters on the estimation quality the three different types of filter were applied to a simulated 1-dim simply supported beam. The beam was excited with various resonant, off-resonant and random excitations. Sensor number and noise level have been varied to show the sensitivity of the shape estimation process against each parameter. To verify the sensitivity results of each filter method in combination with the shape estimation matrix an experiment was conducted on an acrylic cantilever beam which was equipped with four equally distributed fiber optic strain sensors. The beam structure was excited with a modal shaker at low resonant and off-resonant frequencies, as well as random bandwidth excitation. The estimated, filtered deflection of the beam was compared with the real deflection of the beam, which was measured by high resolution laser displacement sensors at four points of maximum deflection along the beam structure.

Especially for off-resonant and higher frequent excitation with noise corruption the Kalman Filter showed high capability to reduce the shape estimation errors from above 200 % below 7 %.

The investigation shows the high potential and capability of the different filtering techniques to improve the shape estimation results even for a small number of strain sensor signals and for this reason the general applicability of the modal approach as shape estimation algorithm. However it also points the requirements up which limit the use of each filter method for real-time shape estimation based on a small number of strain signals.

6932-86, Session 17

Sensor-based warranty system for improving seismic performance of building structures

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Recently, it has become evident that we do not have appropriate way of warranting the real seismic performance of building structures. The buildings are only checked if the structural design follows the seismic codes or not. Thus, we do not know how much seismic performance we could expect for individual buildings.

In this paper, the economic and rigorous warranty system for knowing and improving seismic performance of building structures is proposed. The proposed system defines that liability of seismic damage using sensors for strong ground motion. The obtained information is used for triggering insurance or derivatives for covering the resulting damage. We chose seismic isolated buildings for demonstrating the effectiveness of our proposed approach as the damage scenario of such structures is rather simple.

6932-87, Session 17

Vibration-based damage detection algorithms for combined stiffness-loss and prestress-loss in PSC bridges

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The prestress-loss and the flexural stiffness-loss are typical types of damage, which can be occurred in the PSC bridges. The structural damages are quite different in nature although both of them obviously change vibration characteristic of the structure. The prestress-loss is related to reduce the stiffness for entire structure while the flexural stiffness-loss is related to reduce the stiffness for local element. To date, there have been many researches to detect stiffness-loss and prestress-loss on PSC girder bridges; however, most of the efforts mainly focused on monitoring individual damage types but not the combined stiffness-loss and prestress-loss.

In this study, vibration-based damage detection algorithms for combined stiffness-loss and prestress-loss are proposed. The following approaches are implemented to achieve the objective. Firstly, several vibration-based damage detection algorithms are described to detect stiffness-loss and prestress-loss. Secondly, a vibration-based damage detection scheme is proposed to detect combined stiffness-loss and prestress-loss. Thirdly, a large-scaled PSC girder with an internal unbonded tendon is manufactured and the vibration test is performed in the PSC girder for several damage scenarios. Finally, the feasibility and practicality of the proposed methods are verified in the PSC girder.

6932-88, Session 17

Robust water leakage detection approach using sound signals and pattern recognition

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Water supply systems are indispensable for healthy and comfortable civil life and industrial activities. When water leakage occurs by land subsidence, aged deterioration, construction works and so on, it could not just be a waste of water resource, but also it could lead to serious economical and social loss. Therefore, early detection and treatment of such incidents is essential.

At present acoustic method is most popular in detecting the leakage. In this method experts who have skills detect the leakage so the accuracy relies heavily on their experience. Training a person to become an expert costs a lot. And the accuracy may be person-dependent. Thus more convenient and accurate detection system is needed.

In our study we added new digital sound data using a new measuring device and by combining the old and new data we constructed a robust water leakage detection method. The robustness of the system was improved compared with the previous studies.

6932-89, Session 18

Development of a high-flow-rate/high-operating frequency NiTiInol MEMS valve

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This paper presents modeling, fabrication, and testing results for a high flow-rate and high frequency Nitinol MEMS valve. One application of the valve is for a compact hydraulic actuator that requires high actuation frequencies (i.e. 10 kHz) and large flow rates (i.e. 10 cc/s) [1]. Of valves available, only micromachined valves produce high frequencies and only a few researchers have fabricated them [1-4]. Furthermore, previous valves, made with either nickel or silicon, have nominal deflections due to material limitations. One unique material worth considering is Nitinol, a material that achieves high strains (i.e. > 4%) thru a detwinning mechanism, but MEMS standard processing steps are unavailable for complex Nitinol structures. In 2005, Shin et al. fabricated a microthermostat using Nitinol to overcome some limitations but they did not address the complicated fabrication issues [5].

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In this work, ANSYS® is used to initially evaluate several structural designs. Previously, rotational structures were used to achieve ortho-planar deflection [1-5]; however, failures were observed which we attribute to the additional torsional stress. Consequently, we investigated other non-rotational designs [6]. A three dimensional structure pairing a pentagonal flap with five legs was found to achieve ortho-planar deflection without rotation. The new penta-leg spring, however, poses significant fabrication issues for the Nitinol including undercutting at discontinuities and non-planar features associated with isotropic etching [7]. Therefore, a bi-layer lift-off method was developed. In this research, a PMGI polymer layer is used as an underlayer while a chromium layer is used as a top layer.

Using the bi-layer lift-off method, a non-rotational ortho-planar Nitinol MEMS valve array was fabricated. This array consists of 65 microvalves with dimensions of 1000µm in circumference, 50µm in leg width, and 8.2µm in thickness. Each microvalve covers an orifice of 220µm in diameter and 500µm in length. A vertical deflection over 150µm was measured using a Keyence laser sensor and the maximum deflection is over 3 times higher than those of other microvalves [1-4]. This array was tested for flow rates in a hydraulic system as a function of applied pressure. A maximum water flow rate of 16.44 cc/s was measured and no leakage was observed at a pressure difference of 103 kPa.

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6932-90, Session 18

Detection of abnormalities in human gait with smart shoes

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Health monitoring systems require a means for detecting and quantifying abnormalities from measured signals. In this paper, a new method for detecting abnormalities in a human gait is proposed for an improved gait monitoring system for patients with walking problems. In the previous work (K. Kong and M. Tomizuka, "Human Motion Phase Detection Based on Ground Contact Force Measurement," Submitted to IEEE Transaction on Rehabilitation Engineering, May 2007.), we introduced the smart shoes that measure ground contact forces (GCF), and a fuzzy logic algorithm for detecting phases in a human gait from the signals of the smart shoes for the right and left foot. Each smart shoe has four bladders filled with air, the pressure changes in which are detected by pressure transducers as GCFs. The fuzzy logic algorithm detects the gait phases smoothly and continuously, and retains all information obtained from sensors.

In this paper, a higher level algorithm for detecting abnormalities in the gait phases obtained from the fuzzy logic is discussed. In the proposed algorithm, two major abnormalities are detected: 1) when the sensors measure unusual foot pressure patterns, and 2) when the human does not follow a natural sequence of gait phases. For the first objective, the scaling factor, which is supposed to make the summation of all fuzzy membership values about one for normal gaits, is utilized as a performance index. Since the fuzzy logic is designed based on the foot pressure patterns during the normal gait, the scaling factor is about one when human has a normal gait. In the case of an abnormal gait, however, the distribution of GCF exhibits patterns, which do not belong to the set of standard patterns, and the scaling factor deviates from one. For the second objective, the sequence of the fuzzy membership values is observed to check whether or not human follows a natural sequence of gait phases. In the case of a normal gait, eight gait phases appear sequentially and repeatedly. However, an abnormal gait may exhibit an unusual sequence, or miss some phases during one stride. For mathematical realization of the detection algorithm, the time varying fuzzy membership functions are utilized and analyzed by a vector analysis method. The proposed detection algorithms are verified by experiments using the smart shoes on patients with walking problems (Poliomyelitis and Muscular Disorders) as well as normal persons. The integration of two detection algorithms is also discussed in the paper.

6932-91, Session 18

**A multimode sensing system for corrosion detection using piezoelectric wafer active sensors

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Pipelines are important infrastructures in petroleum and gas industries vital to the national economy. These pipes are typically subjected to corrosion on the inside of the pipe under harsh environment. These lines, which may be operated under high temperature, usually are supplemented by periodic either internal or external inspection. However, these solutions have limitations and thus lead to an urgent need for the development of a cost-effective, non-excavating, in-service, and permanent critical pipeline damage detection and prediction system.

As an emerging technology for in-situ damage detection and nondestructive evaluation, structural health monitoring with active sensors (active SHM) plays as a promising candidate for the pipeline inspection and diagnosis. Piezoelectric wafer active sensor (PWAS), as an active sensing device, can be permanently attached to the structure to interrogate it at will and can operate in propagating wave mode or electromechanical impedance mode. Also, PWAS transducers can operate at a temperature as high as 260°C which is sufficient for most critical pipeline systems used in gas/petroleum industry. Its small size and low cost (about ~\$10 each) make itself a potential and unique technology for in-situ SHM application. The objective of the research in this paper is to develop a permanently installed in-situ "multi-mode" sensing system for the corrosion monitoring and prediction of critical pipeline systems. Such a system is used during in-service period, recording and monitoring the changes of the pipelines over time, such as corrosion, wall thickness, etc. Having the real-time data available, maintenance strategies based on these data can then be developed to ensure a safe and less expensive operation of the pipeline systems. In this paper, after a detailed literature review of current pipeline corrosion detection, we will introduce the concept of PWAS-based multimode sensing approach for corrosion detection in pipelines. Then the basic principles in applying PWAS to in-situ SHM using guided waves and impedance spectrum will be developed. Particularly, we will investigate the scientific understanding for using PWAS waves for in thickness mode. Next, experiments are conducted to verify the corrosion detection and thickness measurement ability of PWAS sensor network in metallic plate in a laboratory setting. Finally, the PWAS consistency is verified with tests in water pipe with flowing fluid inside. The corrosion monitoring will be repeated on metallic pipe to further confirm the multi-sensing corrosion monitoring approach. In addition, the potential of PWAS application for high temperature pipeline thickness monitoring will also be investigated.

6932-92, Session 19

Estimation of flexural properties degradation in composite sandwich structures using fiber Bragg grating sensors

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The reflective spectra of FBG sensors under uniform axial stresses have single peak, narrow bandwidth and high reflectivity. But, under non-uniform transverse stresses, multiple peaks, broadening bandwidth, reflectivity attenuation can occur. These peak splits can give information of damage, fracture and dynamic strains, etc. Thus, if it is possible to obtain the information about damage levels from the reflective spectra changes due to impacts, the estimation of flexural properties degradation can be performed. Shift of Bragg wavelength, bandwidth change, number of peaks etc. are the information that can be used in this experiment. The surface-attached FBG sensors are affected by impact induced damages. There are wavelength shift to left, bandwidth broadening and unsymmetrical shape of spectral peak subjected to impact. So, the estimation of damage levels is possible by using these phenomena. And by performing the flexural tests, the flexural properties degradations can be measured. Finally, the flexural properties degradations can be estimated using the reflective spectrum changes.

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6932-93, Session 19

Fiber optics based ion discriminator

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Radiation dosimeters currently available for spaceflight have several limitations. Passive film and thermoluminescent radiation badges can only be read on the ground, long after a potentially dangerous exposure. Although active personal discharge tubes are compact, the position of the quartz fibers inside must be manually read and these tubes do not distinguish between particle types. The size of real-time electronic dosimeters has decreased from a ~10 cm sphere in Skylab to units the size of a wallet or a pen, but these still do not distinguish between protons, neutrons, electrons, heavy charged particles, gamma rays and x-rays. Therefore compact electronically-readable active dosimeters, to measure cumulative dose and also to identify radiation particle type and energy in real time are desired. In this way astronauts can be warned at the onset of hazardous solar particle events. Scintillation detectors provide particle energy measurements based on the amount of light produced by a single ionized track; however, bulky scintillator geometries and photomultiplier tube detectors and power supplies make this approach better suited for ground-based laboratories. Semiconductor diodes form compact charged particle detectors with superior energy resolution, but they are prone to deteriorate in the presence of radiation, so their service lifetime in space would be short. A reasonable compromise is needed to provide robust, reliable, compact, real-time dosimetry with particle identification and modest energy resolution.

We propose the optical fiber based real time ions detector and discriminator. The detector is based on the fact that energy dissipation versus ion penetration depth in the matter is strongly dependent on the type of the ion. Optical fiber experiences refractive index change in the vicinity of particle track due to the ionization. This effect has been confirmed experimentally at Luna Innovations and efficient highly precise methods for the index change detection have been developed. The opportunity given by optical fiber allows measuring the energy dissipation of incident particle versus penetration depth, as well as total energy released, simultaneously in real time. By measuring total energy dissipated and energy dissipation versus distance different types of ions can be distinguished. To discriminate between ions species we propose to use measurement of the Bragg peak position. Total energy dissipated by the particle in the detector material and determination of the Bragg peak position gives the full information on the kind of the incident ion, as confirmed via simulations.

6932-94, Session 19

**Optimal demodulation of wavelength shifts in a fiber Bragg grating sensor using an adaptive two wave mixing photorefractive interferometer

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Recent work by our group on the dynamic demodulation of strain-induced wavelength shifts in a Fiber Bragg grating (FBG) sensor show that the sensor is suitable for the detection of high frequency ultrasonic waves produced by impact loading. In this work, a FBG sensor is incorporated into an optical detection system that uses a broadband tunable laser source in the C-band, a two wave-mixing photorefractive interferometer, and a high-speed photodetector. When an ultrasonic wave interacts with the FBG sensor, the wavelength of the reflected light in the fiber is dynamically shifted due to strain-induced perturbation of the index of refraction of the grating in the fiber. The wavelength shift is converted into an intensity change by splitting the light into signal and pump beams and interfering the beams in an InP:Fe photorefractive crystal (PRC). The resulting intensity change is measured by the photodetector. The two-wave mixing photorefractive interferometer allows for several FBG sensors to be wavelength multiplexed in one crystal and it also actively compensates for low frequency signal drifts associated with unwanted room vibrations.

In this paper, we report on two new advances to the demodulation system. First, an auxiliary incoherent beam is used to optimize the density of photo-excited carriers in the PRC leading to a simpler configuration of the demodulation system. Secondly, the reflected light from several FBG sensors are angularly multiplexed into the PRC, mixed with a single pump

beam, and imaged onto separate photodetectors. The resulting system can demodulate a large number of FBG sensors simultaneously.

6932-95, Session 19

Flow direction discrimination sensor using FBG optical fiber and leverage amplification mechanism

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Fiber Bragg Grating (FBG) sensor has 1 pico-meter time resolution. However, if the strain distribution is not uniform on the sensor part, the FBG sensor cannot produce correct signals due to the irregular reflections inside the fiber. Those irregular reflections are caused by bending and torsion of the fiber and fluctuation of ambient temperature. In this study, authors tried to remove those factors.

First, in order to minimize the influence of bending and torsion and amplify the target signal, geometry of the fiber support was improved. By this improvement, flows with wider velocity range can be measured. Second, another similar FBG sensor was set in addition to the flow direction discrimination sensor to compensate temperature fluctuation in real time. Third, the FBG sensor with above improvements will be tested in the wind tunnel for 1 to 20 m/sec velocities. In the last, the sensor will be applied to the separation control of a back-step flow in order to verify the present sensor system.

6932-96, Session 19

Design and laboratory validation of a structural element instrumented with multiplexed interferometric fiber optic sensors

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This paper presents the laboratory validation of a novel construction system for the real-time condition monitoring of bridge structures. The concept is to build them using smart structural elements, i.e. precast RC (reinforced concrete) elements embedding a sensing system and capable of self-diagnosis. Sensors are not just applied to the member, but will be an integral part of the prefabricated element, influencing its design criteria, performance and detailing. The sensing system is conceived in two separate parts, embeddable and external. The embeddable part is permanently installed in the RC element, and therefore must be durable and robust. The sensor technology selected for this application is a multiplexed version of the standard SOFO (Surveillance d'Ouvrages par Fibres Optiques) interferometric sensor, originally developed, produced and commercialized by Smartec SA. While the standard SOFO employs total reflectors at the end of the measurement and reference fibers, allowing measurement of the strain only over a single field, in the solution presented in-line multiplexing is obtained by separating each measurement field through partial reflectors, consisting of broadband Fiber Bragg Gratings (FBGs) with low reflectivity. The embeddable sensing system is prepared in the form of a linear subassembly, referred to as smart bar. In this smart bar, all optical sensors and wires are mounted onto an FRP (Fiber Reinforced Polymer) support specifically designed for the purpose. Optical signals are carried along the smart bar and collected at the element edges. In order to verify the effectiveness of the damage assessment technology, a 3-field smart bar has been produced and integrated into a pre-stressed RC element prototype. The specimen is 3.8 m long and has a 0.3 by 0.5 rectangular cross-section, and has been pre-stressed using an instrumented Dywidag bar, in such a way as to control the preload level. Apart from the optical instrumentation, the prototype is equipped with additional traditional sensors, including metal-foil strain gauges and thermocouples. The scope of the experiment was to correlate the response of the embedded sensor to different damage scenarios artificially induced on the beam. Different level of cracking have been produced through the application of a vertical load action using an hydraulic actuator: the load protocol includes a sequence of load-

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unload cycles of increasing amplitude, repeated for different values of pre-stressing, up to the yielding of the regular reinforcement. Additional damage conditions, such as cover spalling and partial reinforcement corrosion have then been artificially reproduced. A numerical algorithm, based on Bayesian logic, is adopted to real-time self-diagnosis. More specifically, each possible damage scenario is described by a vector of random parameters (such as location and extent of damage), and by a theoretical response model. Based on the prior distribution of this vector and on the on the real-time recording, the method assigns posterior probability to each scenario as well as updated probability distributions to each parameter. The paper discusses the ability of the system to identify the different damage conditions.

6932-97, Session 19

Performance of the fiber Bragg grating sensors at low temperatures

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The strain and temperature sensing performance of FBG are studied in the temperature range of 123K to 273K by the experiment. The temperature sensitive, strain coefficient and cross-sensitivity coefficient of the sensors were derived analytically and are verified by experiments. It is found that they are nonlinear. Cross sensitivity increase with lower temperature. At a constant temperature, the Bragg wavelength shift is linear with the longitudinal strain within the range of 6000 micro strains.

6932-98, Session 20

**Evaluation of adhesive bond quality in laminated safety glass using guided waves: a parametric study

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Laminated safety glass consists of a plastic interlayer, such as a layer of poly vinyl butyral (PVB), surrounded by two adjacent glass plates. Samples with different levels of adhesive bond strength were manufactured and tested using mechanical guided waves. The adhesive bond strength of the test samples was then also evaluated using the pummet test method. The imperfect interfaces were modeled using a bed of longitudinal and shear springs. The spring constants were estimated using fracture mechanics and surface analysis of the plastic interlayer and of the glass plates using atomic force microscopy and profilometer measurements. The guided wave theoretical predictions of adhesion levels using energy velocities and attenuation measurements were validated using the pummet test results. A sensitivity analysis of the proposed method to system parameters (i.e., interlayer and glass thickness, and elastic and viscoelastic material properties) is also presented and discussed.

6932-99, Session 20

Shape identification of variously deformed composite laminates using Brillouin type distributed strain sensing system with embedded optical fibers

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This research proposes a shape monitoring system using the optical fiber sensor network which is embedded in composite structures. We have constructed a shape identification algorithm that derives the displacement from distributed strain data obtained by one of the optical fiber sensing systems, pulse-pre-pump Brillouin optical time domain analysis (PPP-BOTDA) system.

The accurate shape monitoring system is expected to be useful for full-scaled structural monitoring of large structures. Nowadays, especially in the manufacturing of composite structures, large-scaled products are adopted for main wings or fuselages of aircraft. Therefore, the global shape identification system for composite structures, which uses the embedded optical fiber network, will have many applications in their life time. In this paper, we report our shape identification algorithm for the composite laminates using distributed strain data. And then, the effectiveness of

the algorithm to the thermal deformation monitoring, which is one of important applications for the high-accuracy manufacturing of composite structures, is shown.

In the shape identification algorithm, we use one of the optical fiber strain sensing system, PPP-BOTDA system. This system uses Brillouin scattering, which is excited by incident pulse lasers, and the strain distribution can be available with the spatial resolution of 10 cm along whole length of the optical fiber. Therefore, when an optical fiber network is embedded, high-resolution strain distributions of whole body of the structure can be obtained. The flow of algorithm is that, firstly the strain distribution function is estimated from raw data using the weighted least-square method. And then, the displacement is calculated using the strain-displacement relation of the thin plate theory. The most characteristic point of distributed data is that the reliability of distributed data becomes low at the structural discontinuous point, such as loading points or ends of structures. This characteristic comes from the influence of the special resolution of the sensing system. In response to this, the weighted least-square method was adopted with adjusting of the weight of each data point depending on the degree of reliability of distributed strain data. This method makes it possible to estimate deformations of variously-deformed structures. In addition, the measurement error distribution of the sensing system was also considered statistically, and the M-estimation method was adopted for the robust estimation against outliers of data.

Then, we applied the constructed algorithm to the thermal deformation identification of composite laminates. For the verification, the antisymmetric laminate was adopted. This laminate shows complex and global deformations, which is caused by the thermal residual stress after the curing. The optical fiber network was embedded two-dimensionally, and the estimation was carried out. Using our shape identification algorithm, the displacements of laminates could be derived appropriately from estimated thermal residual strain distributions.

From these results, it is shown that the structural deformation of composite laminates can be identified using the constructed shape identification algorithm and embedded optical fiber networks. In addition, it can be said that the global shape identification system using the optical fiber sensing system is of significance for the global monitoring of composite structures.

6932-100, Session 20

Smart composite structure based on integrated passive wireless strain sensors

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Embedding wireless and battery-free strain sensors in fiber reinforced polymer (FRP) composite structure remains a great challenge in aerospace or automobile structural engineering field. This is for the stringent demand for good sensing performance, thin sensor thickness, autoclave curing survivability and cost-effectiveness as large number of them will be deployed for full-scale structural health monitoring (SHM). In this research, we develop a low-cost film type passive wireless strain sensor which can be easily embedded within composite prepreg layers besides maintaining its performance upon curing. A planar inductor-capacitor resonant circuit constitutes the sensor and its operational principle relies on inductive coupling, passive RF telemetry and resonant frequency shift in response to strain. First, we verify its feasibility via a simple tensile test experiment. Then, a series of characterization works are carried out to quantify the sensor performance, using conventional electrical strain gage as the reference sensor. The sensor response shows great linearity, low hysteresis and drift, and sufficient sensing range for wireless interrogation. The sensor sensitivity is found to be relatively low, hence some modifications on the sensor pattern design are introduced and we manage to obtain approximately three-fold increase in sensitivity. The investigation on both sensor array and sensor directivity verifies its potential to be developed as a wireless rosette strain gage. In addition, mechanical tests are performed on both pristine composite specimens and sensor embedded composite specimens. Among the tested mechanical properties, the interlaminar shear strength degrades the most upon sensor embedment. Some possible solutions are thus proposed. Finally, an analytical model has also been developed, and though it does not predict the initial resonant frequency accurately, but its normalized resonant frequency shift due to strain change agrees well with the experimental result.

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6932-101, Session 20

Concept and model of a piezoelectric structural fiber for multifunctional composites

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The use of piezoceramic materials for structural sensing and actuation is a fairly well developed practice that has found use in a wide variety of applications. However, just as advanced composites offer numerous benefits over traditional engineering materials for structural design, actuators that utilize the active properties of piezoelectric fibers can improve upon many of the limitations encountered when using monolithic piezoceramic devices. Several new piezoelectric fiber composites have been developed, however almost all studies have implemented these devices such that they are surface-bonded patches used for sensing or actuation. This paper will introduce a novel active piezoelectric structural fiber that can be laid up in a composite material to perform sensing and actuation, in addition to providing load bearing functionality. The sensing and actuation aspects of this multifunctional material will allow composites to be designed with numerous embedded functions including, structural health monitoring, power generation, vibration sensing and control, damping, and shape control through anisotropic actuation. A one dimensional micromechanics model of the piezoelectric fiber will be developed to characterize the feasibility of constructing composite lamina with high piezoelectric coupling. The theoretical model will be validated through finite element (FE) modeling in ABAQUS. The results will show that the electromechanical coupling of a fiber reinforced polymer composite incorporating the active structural fiber (ASF) could be more than 70% of the bulk piezoelectric material.

6932-102, Session 20

Robustness of vibration-based health assessment of bonded composite patch repairs

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Structural health monitoring (SHM) may be applied to bonded composite repairs to enable the continuous through-life assessment of structural integrity. Further, adhesively bonded joints are an ideal starting point for real-time, in-situ monitoring due to knowledge of mechanisms and locations of failure. The robustness of a SHM technique for the detection of debonding in external patch repairs based on the vibration response of the repaired structure is discussed in this paper.

An earlier, proof-of-concept experimental investigation studied the vibration response of carbon/epoxy doubler repairs bonded to carbon/epoxy substrates. Piezoelectric devices were used to measure changes in the vibration response of the repaired structure due to debonding of the external doubler. The study measured reduced natural frequencies of vibration and increased damping for external patch specimens with partial debonding damage compared to those for undamaged specimens. A vibration response based SHM system may be based on the detection of these changes. Such a system would compare a contemporary signature with a known signature of a healthy structure and report on any differences. For the system to be effective, signatures must be consistent or vary within a known bound. The measured signature must be repeatable and only alter due to damage, otherwise, false positive damage indications will result. Clearly, the usefulness of the system will be somewhat limited if the variation between interrogations is greater than that due to debonding.

This paper will present the results of robustness tests over a significant time period for the vibration signatures of specimens with an external patch repair. Repeatability of the signature for both baseline and damaged repairs was found to be good. This is highly encouraging for the development of a SHM system based on frequency response techniques.

6932-103, Session 21

Numerical and experimental research on active vibration control of flexible structures using PZT patches

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Vibration of flexible structures may influence serviceability of a structure and cause fatigues of structural materials, even generate fatal damages during operations. The vibration can be suppressed passively by adjusting the natural frequency and damping of the structure. However, complexity of the vibration and uncertainty of environmental loads usually decreased efficiencies of the suppression by the passive methods. An active vibration control method using smart piezoelectric material such as lead zirconate titanate (PZT) can increase the control efficiencies. The PZT material can be made as controllers or sensors and used in flexible structures due to its unique characteristics. The PZT material has the advantages of high reliability, wide bandwidth and solid state actuation et al. These properties are suitable to applications in vibration control of the flexible structures.

In the paper, PZT patches bonded on the surface of the structure were adopted as actuators and sensors, respectively. The PZT actuators were used as controllers to suppress the vibration of the flexible structure. The PZT sensors located on the given places of the structure can get feedback signals for directing the actuators to work effectively. A positive position feedback (PPF) control which was first proposed by Goh and Gaughey for the collocated sensors and actuators was used as control algorithm. The PPF control works by feeding the structural position coordinate directly to the compensator, and product of the compensator and scalar gain positively back to the structure system.

The active control system is validated numerically and experimentally by two examples. One example was a flexible cantilever steel beam, which was excited with a PZT actuator, to validate a finite element method (FEM). The FEM considered the piezoelectric element and steel element, respectively. The other example was a flexible square steel tube with the two ends fixed, which was excited by a motor with an eccentricity mass. Both examples aimed at the validation of the active vibration control with PZT patches. For both examples, identifications of the two systems using sweep sine signals were firstly carried out and then active controls using the PPF method were finished.

The results of the numerical analysis and experimental research in both examples were shown that the responses of the structures were obviously decreased and the PZT patches can be used successfully as both sensors and actuators for the vibration control of the flexible structures using the PPF control strategy.

6932-104, Session 21

Vibration control of hysteretic and frictional systems via neural network adaptive backstepping

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In recent years, significant advances in vibration control of structures have been achieved due greatly to the emergent technologies based on smart materials. Some materials such as magnetorheological (MR) fluids, have interesting properties. The possibility of changing their rheological properties by means of a magnetic field, plus their high yield strength, has been exploited to design and manufacture dampers for vibration control of mechanical systems and civil engineering structures. These dampers, compared to other devices of their class, are small, require less power resources, are easy to maintain and their production costs is low. But despite these advantages, MR dampers feature a complex behavior, mainly characterized by the magnetic field dependent hysteretic response to velocity inputs. Finding a good mathematical model that can describe MR dampers is a challenging task and developing control algorithms for systems containing MR dampers is rather complicated.

In this paper, an intelligent hybrid control methodology is proposed to mitigate earthquake vibrations in a building. The structure object of study is a 10-story building whose base is isolated by means of a passive frictional actuator and an MR damper. The system has uncertain

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parameters and nonmeasurable variables that must be accounted for in order to gain good control performance. Besides, the system is subject to unknown perturbations (incoming earthquakes). An adaptive backstepping controller is designed to generate the actuator control signal based on the base velocity and displacement measurements as well as on the dynamics of the base isolation system. Uncertainty in structure stiffness, damping coefficients and mass are compensated by parameter adaptation. The MR damper can be modeled by the well known Bouc-Wen model. However, this model contains an unmeasurable variable, z , that describes the hysteretic behavior, so it must be estimated. A neural network approximator is proposed to estimate the unmeasurable variable. This way, the hysteresis effect is modeled by the neural network. The control performance is verified by simulations performed in MATLAB/Simulink using common earthquakes such as those of El Centro and Taft.

6932-105, Session 21

Embeddable sensor mote for structural monitoring

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An embeddable sensor mote for structural monitoring is described. The University of Missouri-Rolla (UMR) F1 mote is designed to provide a general platform for sensing, networking, and data processing. The platform consists of an 8051 variant processor, two 802.15.4 variant radio platform options, micro Smart Digital (SD™) flash storage, USB connectivity, RS-232 connectivity, and various sensor capabilities. Sensor capabilities include strain gauges, a three-axis multi-range accelerometer, thermocouples, and interface options for other digital and analog sensors via a screw terminal block. In its default configuration the strain conditioning channel is appropriate for structural monitoring, but through reconfiguration it can be used with other resistive bridge transducers for pressure, force, displacement, etc. The F1 mote provides capabilities for strain, temperature, and vibration sensing that is useful to civil infrastructure sensing in a small package. The mote is used at UMR for networked monitoring of structures and networked robotic vehicles. In this paper an overview of the F1 mote will be given that emphasizes its operating architecture and potential applications. Applications include infrastructure monitoring for structures such as bridges, levees, and buildings as well as robotics, machine monitoring, and sensor networks. The described platform provides novelty in that it has the ability to be a dedicated structural monitoring system, however can be also used in development of other systems. The F1 platform was designed to combine features of between available dedicated platforms and available development kits. The F1 provides a novel combination of sensing, processing, and application possibilities for the targeted application areas.

6932-106, Session 21

Design of piezoelectric sensors, actuators, and energy harvesting devices using topology optimization

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Sensors and actuators based on piezoelectric plates have shown increasing demand in the field of smart structures, including the development of actuators for cooling and fluid pumping applications and transducers for novel energy harvesting devices. This project involves the development of a finite element and topology optimization software to design piezoelectric sensors, actuators and energy harvesting devices by distributing piezoelectric material over a metallic plate in order to achieve a desired dynamic behavior with specified vibration frequencies and modes.

The finite element employs a general formulation capable of representing both direct and converse piezoelectric effects. It is also based on the MITC formulation, which is reliable, efficient and avoids the shear locking problem.

The topology optimization formulation is based on the PEMP-P model (Piezoelectric Material with Penalization and Polarization) and RAMP (Rational Approximation of Material Properties), where the design variables are the pseudo-densities that describe the amount of piezoelectric material in each finite element.

The optimization problem has a multi-objective function, which can be subdivided into three distinct problems: maximization of mean transduction, minimization of mean compliance and optimization of Eigenvectors. The first one is responsible for maximizing the amount of electric energy converted into elastic energy, the second one guarantees that the structure does not become excessively flexible and the third one tunes the structure for a given frequency and vibration mode.

This paper presents the implementation of the finite element and optimization software and shows preliminary results achieved.

6932-107, Session 21

Microhorn array (SMIHA) for acoustic matching

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Transduction of electrical signals to mechanical signals and vice-versa in piezoelectric materials is controlled by the material coupling coefficient. In general in a loss-less material the ratio of energy conversion per cycle is proportional to the square of the coupling coefficient. In practical transduction however the impedance mismatch between the piezoelectric material and the electrical drive circuitry or the mechanical structure can have a significant impact on the power transfer. This paper looks at novel methods of matching the acoustic impedance of structures to the piezoelectric material in an effort to increase power transmission and efficiency. In typical methods the density and acoustic velocity of the matching layer is adjusted to give good matching between the transducer and the load. The approach discussed in this paper utilizes solid micro horn arrays in the matching layer which channel the stress and increase the strain in the layer. This approach is found to have potential applications in energy harvesting, medical ultrasound and in liquid and gas coupled transducers.

6932-108, Session 21

**Biology-inspired acoustic sensors for sound source localization

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In humans and animals, directional hearing relies on acoustic cues such as the interaural intensity difference (IID) and interaural time difference (ITD). To accurately detect these differences, the two ears need to be located far away enough such that the difference of the sound signal arriving at the two ears can be detected. This poses a fundamental challenge to the miniaturization of directional acoustic sensors. However, in some small insects, the auditory receptors are forcibly set close to each other. In this case, the interaural differences are often too small to be useful as directional cues. Such ears can be found in the parasitoid fly *Ormia ochracea*, which shows a remarkable ability to locate sound source. Study found that the interaural difference in fly ear response is greatly amplified due to the mechanical coupling of the ears' motion through a bridge that joins the two membranes and pivots about its center. The small auditory systems of the fly *Ormia* can inspire one to solve the technological challenge of miniaturizing directional acoustic sensors. In this paper, a novel design of a directional acoustic sensor inspired by the fly's ear is presented. This sensor consists of two clamped circular diaphragms, which are mechanically coupled by a connecting bridge that is pivoted at its center. A mechanics model is developed to determine the response of the sensor to sound source incident from an arbitrary direction. Different parameters such as coupling strength, damp factor, and dimensions are studied to evaluate the performance of the biology-inspired directional acoustic sensor. Our simulation results indicate that for a miniature directional acoustic sensor like the fly's ear, the information of both amplitude differences and time delay of the responses has to be used to locate a sound source. However, for a large scale sensor, the time delay of the responses itself can provide enough directional cues for sound source localization. Preliminary experiment results obtained from a large-scale biology-inspired directional microphone subject to sound excitation are presented and compared with the model predictions. These analyses and results are expected to be helpful for designing a biology-inspired directional microphone of various scales, from microscales to macroscales.

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6932-109, Session 21

A novel thermally driven actuator based upon the physics of metal hydrides

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The purpose of this study is to develop a novel thermally driven actuator technology based upon the physics of metal hydride (MH). A metal hydride absorbs and desorbs hydrogen given a reasonable range of temperature swing. It can also work as an effective thermally driven hydrogen compressor (up to 5,000 psia). The MH actuation system can be built in a simple structure, exhibits high power, produces soft actuating, and is essentially noiseless. Moreover, it is much more powerful and compact than conventional pneumatic systems that require bulky auxiliary systems. It is our belief that the MH actuators are useful for many emerging industrial, biorobotic, and civil structural applications. In this paper, we report the recent experimental results for a laboratory prototyped MH actuation system. In particular, dynamic response characteristics, enhanced controllability, thermodynamic performances, and reliability of the metal hydride actuator was laid out to adequately estimate the actuation ability of the MH actuator. Additionally, a unique design of MH actuator encasing so-called "porous metal hydride (PMH)" in the reactor, to achieve desirable performance matrixes is discussed based upon the experimental results.

6932-110, Session 22

****Anodized aluminum oxide (AAO) based nanowells for hydrogen detection**

F. A. Rumiche, E. Indacochea, A. Polar, M. L. Wang, Univ. of Illinois at Chicago; H. Wang, Argonne National Lab.

Recent research thrusts for alternate methods of power generation has turn to production and storage of H₂ as alternative fuel, as it is the most environmental friendly fuel. It is foreseen that H₂ will become a basic energy infrastructure to power future generations; however it is also recognized that if it is not handled properly (e.g. transportation, storage), it is as dangerous as any other fuel available. Safety, therefore, is a natural concern in all aspects of H₂ energy. It can be said that H₂ sensors are essential to achieve a H₂ economy. Ultra sensitive hydrogen sensors are urgently needed for fast detection of hydrogen leakage at any level, such as the H₂ leaks in solid oxide fuel cells (SOFC). Having developed a number of different sensing mechanisms, researchers are now focusing on lowering the sensing temperature and optimizing the sensitivity of hydrogen sensors. The desirable porous structure of the anodized aluminum oxide (AAO) has attracted many researchers' attention. AAO membrane is a material that exhibits an ordered array of nanopores with high aspect ratio used as a template for nanofabrication. Anodization conditions, substrate surface indents, and pretreatment, have a remarkable influence on the resulting membrane. This study focuses on the AAO shallow nanowell region with a pore diameter to depth ratio less than 10. A two-step anodization process was used to fabricate the nanowells. A thick AAO membrane resulted after a first anodization for 4 hours. The membrane was chemically removed and the patterned surface was anodized for very short times (0-12 min). The resulting nanowells have an average diameter of 50 nm and a depth proportional to the anodization time. The nanowells were then evaporated with Pd and tested for hydrogen detection using the electrical resistance of the nanostructure as the sensing parameter. The nanostructure was characterized using AFM, FE-SEM, EDAX, UV reflectance and contact angle test. Responses down to 0.05 vol% H₂ in Ar were measured at room temperature. Response times as fast as 4 seconds were obtained. The AAO nanowell/Pd nanostructure has been found to be very fast compared to current devices and nanostructures in development, without compromising sensitivity and selectivity.

6932-111, Session 22

Multi-objective optimal control of vibratory energy harvesting systems

J. T. Scruggs, Duke Univ.

There is a growing interest in the development of sensing and intelligence systems which are capable of operating in energy-autonomy over the duration of a decades-long service life. This has given rise to various

energy-harvesting technologies, which scavenge available power from their immediate surroundings. Among these systems, one of the more promising involves transduction of power from ambient vibration. Although many different modes of transduction could be used for such systems, applications employing piezoelectric bimorph cantilever beams have received the most attention. This paper presents a new approach, based on multi-objective H₂ optimal control theory, for maximal power transduction from energy harvesting systems. It allows for harvested power to be explicitly optimized, through feedback control of the piezoelectric transducer current. Although the theory is applicable across a broad range of applications, it is presented in the context of a piezoelectric bimorph example.

Most of the existing theory on energy harvesting assumes harmonic vibratory response. By contrast, the theory proposed here applies to stochastically-excited vibratory systems in broadband response, and can be used to harvest power simultaneously from multiple significant vibratory modes. It is also applicable to coupled networks of many transducers. For the bimorph example, it is shown that by subdividing a single PZT patch into multiple patches situated consecutively along the beam, and controlling each of these patches, the optimal conversion efficiency can be improved significantly beyond the optimal attainable efficiency with a single continuous patch.

Additionally, the theory accounts for the impact of energy harvesting on the dynamics of the structure to which the transducers are attached. It also accounts for resistive and semiconductor dissipation in the power-electronic network interfacing the transducers with energy storage. Thus, losses in the electronics are addressed in the formulation of the optimal control law.

Finally, the H₂-optimal control formulation of the problem naturally allows for harvested power to be systematically balanced against other response objectives, such as beam stress limits, drive voltage limits, current limits, and power-electronic bandwidth and pole-placement restrictions. This gives rise to a multi-objective approach to energy harvesting control design, which is illustrated through example.

6932-112, Session 22

****Enhanced power harvesting using poly(vinylidene fluoride) thin films tuned by carbon nanotube fillers**

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Recently, the development of wireless technologies and portable electronics has warranted the need for power harvesting solutions. While piezoelectric materials such as poly(vinylidene fluoride) (PVDF) thin films have been considered as potential candidates for energy harvesting, the electrical energy transduced from ambient vibrations is insufficient for powering contemporary wireless sensors or electronics. However, the addition of carbon nanotubes (CNT) as fillers within PVDF thin films modifies the composite's dielectric properties to enhance its direct piezoelectricity (i.e. the generation of electricity when stress is applied). In this study, homogeneous CNT-PVDF composites are fabricated by slow evaporation within a mould structure and then hot-pressed to anneal and stretch films while simultaneously controlling film thickness. A variety of measuring experiments for piezoelectricity (e.g. polarization vs. electric field (PE) curves, piezoelectric d-constants, and dielectric constants) are conducted and different CNT-PVDF composites (e.g. different carbon nanotube concentrations) are fabricated for optimization of power harvesting efficiency. The aforementioned thin films are then mounted upon a cantilever structure to validate and compare its performance against pristine PVDF thin films.

6932-113, Session 23

****Hybrid structural health monitoring through global sensing and local infrared imaging**

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This paper presents the study of using a method for global damage detection based on displacement, velocity, and acceleration

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measurements in combination with a method for local damage detection based on sonic infrared imaging technique to develop a hybrid structural health monitoring system. Measurements of displacement, velocity, and acceleration are used as feedback for the global damage detection algorithm which was presented in the previous study. Once the proposed global damage detection algorithm determines the health condition of a structure (such as interior cracks of a local column, a beam, or a joint) based on the changes in dynamic responses and characteristics, infrared imaging is introduced to detect local defects so as to provide more detailed and accurate assessment about the severity and extent of the damage which are otherwise not able to be detected either visually or more accurately. The concept of combining the proposed global damage detection algorithm based on all three kinds of measurements and local damage detection based on infrared imaging technique is studied, and the method developed is evaluated through two illustrative examples. Examples include a single story steel frame model with changes in joint flexibility and a three story steel frame model with local defect of a beam with channel cross section. Once the existence of damage is identified through the global damage detection algorithm, sonic infrared imaging can be used to detect and evaluate local damages more accurately. Thus the changes in structural properties of the local members can be modeled as feedback to enable a more accurate global structural model and other local damages can be detected.

6932-114, Session 23

****Structural health monitoring sensor development for the Imote2 platform**

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The declining state of civil infrastructure requires effective methods for real-time structural health monitoring (SHM). The ability to implement continuous monitoring reduces maintenance and inspection costs, while providing increased public safety. Decentralized computing and data aggregation enable adaptable smart sensors which allow new potential scenarios to be explored, such as the deployment of a dense array of sensors throughout a structure. Intel has developed an open-interface platform, the Intel Mote2 (Imote2), built around a low power XScale processor. The Imote2 provides enhanced computation and communication resources that allow demanding sensor network applications, such as SHM of civil infrastructure, to be supported, while low-power operation and small physical size are still considered. This study explores the development of a sensor board for the Imote2 specifically designed for the demands of SHM applications. The components of the accelerometer board have been carefully selected to allow for the low-noise and high resolution data acquisition that is necessary to successfully implement SHM algorithms. In addition, environmental hardening of the Imote2 and sensor board is discussed.

6932-115, Session 23

Development of autonomous triggering instrumentation

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Triggering instrumentation for autonomous monitoring of load-induced strain is described. Bridge monitoring and inspection represent a large investment in the management of transportation infrastructure systems. The development of smart embedded systems offer improvements in both available information and economics. The objectives are to provide quantitative performance information from a load test, to minimize the setup time at the bridge, and to minimize the closure time to traffic. An approach is developed for a bridge monitoring applications to provide economical, fast measurements using embedded sensors and associated instrumentation. Also, the instrumentation is scaleable in that a single measurement can be made from one embedded module, multiple simultaneous measurements can be made from a network of modules, or multiple measurements can be made for a prescribed loading sequence. The proposed smart system consists of in-situ strain sensors, an embedded data acquisition module, and a measurement triggering system. The embedded module addresses strain instrumentation (electrical resistance gages for this study) and provides a wireless data acquisition channel to the control unit. A passive infrared reflector is mounted on the bridge to

mark the correct load position. A companion control unit with an infrared transmitter is mounted on the truck serving as the load. As the truck moves to the proper position, the triggering system communicates with the embedded module through a wireless link. The directionality of the infrared trigger is capable of positioning the truck within centimeters of the desired position. The desired strain measurement is taken and relayed back to the control unit. In this work, the testing protocol is discussed and the timing parameters for the triggering and data acquisition are measured in a laboratory system. The test system uses a dedicated wireless, sensor mote and an infrared positioning system. The results show the suitability of the electronic procedure for automated testing. Improvements in the speed and cost of inspection promote safety and management of infrastructure.

6932-117, Session 23

Acoustic emission monitoring of stay cables in noisy environments

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Recent disease surveys on some cable-supported bridges show that cable corrosion is one of the main dangers for bridge safety, serviceability and durability. Since cables are the main supporting elements for these bridges, this type of damage must be detected at the earliest possible stage for further maintenance. Acoustic monitoring technique shows an efficient way for this purpose. Through monitoring and processing the acoustic response in the cable, this technique can detect the sudden energy release due to cable wire breaking and thus can be used for cable damage alarming. Recent studies show that by analyzing the amplitude and frequency contents of the acoustic emission (AE) wave signal, the type of fracture mechanism and damage progression of the monitored cables can be determined. Following this idea, this study focuses on setting up baseline acoustic wave patterns for various types of cable damages through both numerical simulations and AE tests during large scale cable failure tests. The wave patterns due to the environmental noise, such as friction and impaction, are also investigated during the tests. During the pattern extraction, the wavelet analysis technique is used. It is shown to be successful for cable damage detection and localization.

6932-118, Session 24

A novel fiber optic acoustic emission sensor

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Abstract

This paper presents details on the design, theory, characterisation and application of a novel fibre optic acoustic emission (AE) sensor. The sensor essentially consists of a pair of optical fibres that are heated, fused and drawn to create a sensing region that is sensitive to ultrasound frequencies in the range 25kHz to 600kHz. The so-called "fused-tapered region" or sensing region is housed and secured within a precision bore capillary tube.

The theory behind the mode of operation of this fibre optic AE sensor is presented along with a finite element analysis of the effect of the geometry on the strain fields within the sensing region. The characterisation of the fibre optic AE sensor was carried out using a glass block with 160mm thickness. In this experiment, an acoustic transducer was used to initiate acoustic waves in the glass block and an optical interferometer was used to quantify the resultant displacement on the surface of the glass block. The experiment with the glass block was then repeated with the surface-mounted fibre optic AE sensor. The outputs from the interferometer and the fibre optic AE sensor were compared and correlated.

The application of this fibre optic AE sensor was demonstrated using three sets of experiments. In the first case, the sensors were surface-mounted in carbon fibre reinforced composite samples and tested to failure under tensile loading. A conventional piezo-electric AE sensor was used as reference and the output signals from the two sensor systems were

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compared. In the second series of experiments, the fibre optic AE sensor was surface-mounted on double-cantilever Mode-I test specimens. Once again, a conventional piezo-electric AE sensor was used as a reference sensor system. The output characteristics from the two sensor systems were correlated to the inferred modes of failure during the Mode-I test. In the final series of experiments, the fibre optic AE sensor was surface-mounted onto the composite "blow-off" test samples. This is a standard test method that is used to assess the integrity of pipe repair. Here, impregnated glass and carbon fibres are laminated over a steel plate with a hole (13mm diameter) in the centre. After the pre-form is cured and after subjecting the test specimen to a specified environmental regime, hydraulic oil is forced into the hole and the force required to delaminate the composite from the steel plate is measured. The feasibility of using the fibre optic AE sensor to detect damage development in real-time was demonstrated.

6932-119, Session 24

****Acoustic emission beamforming for enhanced damage detection**

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As civil infrastructure ages, the early detection of damage in a structure becomes increasingly important for both human safety and economic reasons. The method of acoustic emission offers is a tool for detecting damage, such as cracking, as it occurs on or in a structure. In order to gain meaningful information from acoustic emission analyses, the damage must be localized. Current acoustic emission systems with localization capabilities are very costly and difficult to install. Sensors must be placed all over the structure to ensure that the damage is encompassed by the array. Beamforming offers a promising solution to these problems. Using the beamforming technique, the azimuthal direction of the location of the damage may be estimated by the stress waves impinging upon a small array (e.g. 30mm) of acoustic emission sensors. Conventional acoustic emission source location methods, using triangulation to determine the source coordinates, rely on very accurate arrival time information, use complicated analysis routines, and require exact time synchronization of the data acquisition systems for arrays of sensors physically located many meters apart. The beamforming approach requires no arrival time information, is based on very simple delay and sum beamforming algorithms, and can be implemented with a compact array of sensors. This paper includes the theoretical background for the beamforming techniques as well as the promising results of preliminary experimental tests comparing results for high quality broadband sensors and low cost resonance sensors on a concrete bridge deck.

6932-120, Session 24

Smart acoustic emission system for wireless monitoring of concrete structures

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Acoustic emission (AE) has emerged as a powerful nondestructive tool to detect preexisting defects or to characterize failure mechanisms. Recently, this technique or this kind of principle, that is an in-situ monitoring of inside damages of materials or structures, becomes increasingly popular for monitoring the integrity of large structures. Concrete is one of the most widely used materials for constructing civil structures. In the nondestructive evaluation point of view, a lot of acoustic emission (AE) signals are generated in concrete structures under loading whether the crack development is active or not. Also, it was required to find a symptom of damage propagation before catastrophic failure through a continuous monitoring. Therefore we have done a practical study in this work to fabricate compact wireless AE sensor and to develop diagnosis system. First, this study aims to identify the differences of AE event patterns caused by both real damage sources and the other normal sources. Secondly, it was focused to develop acoustic emission diagnosis system for assessing the deterioration of concrete structures such as a bridge, dam, building slab, tunnel etc.. Thirdly, the wireless acoustic emission system was developed for the application of monitoring

concrete structures. From the previous laboratory study such as AE event patterns analysis under various loading conditions, we confirmed that AE analysis provided a promising approach for estimating the condition of damage and distress in concrete structures. In this work, the algorithm for determining the damage status of concrete structures was developed and typical criteria for decision making was also suggested. For the future application of wireless monitoring, a low energy consumable, compact, and robust wireless acoustic emission sensor module was developed and applied to the concrete beam for performance test. Finally, based on the self-developed diagnosis algorithm and compact wireless AE sensor, new AE system for practical AE diagnosis was demonstrated for assessing the conditions of damage and distress in concrete structures.

6932-137, Session 24

A hybrid wireless sensor network for acoustic emission testing in SHM

C. U. Grosse, M. Krueger, Univ. Stuttgart (Germany)

Acoustic emission techniques (AET) have a lot of potential in structural health monitoring for example to detect cracks or wire breaks. However, the number of actual applications of conventional wired AET on structures is limited due to the expensive and time consuming installation process. Wires are also vulnerable to damage and vandalisms. Wireless systems instead are easy to be attached to structures, scalable and cost efficient.

A hybrid sensor network system is presented being able to use any kind of commercial available AE sensor controlled by a sensor node. In addition micro-electro-mechanical sensors (MEMS) can be used measuring for example temperature, humidity or strain. A pre-processing of the data of different sensors is done in the node. Moreover, clusters of sensor nodes are formed within a network to compare the pre-processed data. All these efforts are made to limit the data transfer through the network and to the sink. In particular, this paper deals with the optimization of the AE data recording and the extraction of relevant information out of the data.

6932-158, Session 24

Surface wave propagation in concrete structures by using piezoelectric actuators/sensors

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No abstract available

6932-122, Session 25

Identification of structural damage using wavelet-based data classification

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This paper presents newly developed damage identification technique using wavelet-based signal classification and data mining methodologies. The predicted time-history response from a finite-element (FE) model provide a baseline map where damage locations are clustered and classified by extracted damage-sensitive wavelet coefficients such as vertical energy threshold (VET) positions having large silhouette statistics. Likewise, the measured data from damaged structure are also decomposed and rearranged according to the most dominant positions of wavelet coefficients. Having projected the coefficients to the baseline map, the success of damage localization is assessed by the level of closeness between the measurement and predictions. The statistical confidence of baseline map improves as the number of prediction cases increases. Also, the metrics such as misclassification error rate of classification and regression tree (CART) evaluates the quality of the baseline map. Finally, the technique is applied to accelerometer instrumented 4-bay truss structure with random noise excitation. The laboratory experiments demonstrate that the proposed method successfully classifies the unknown location of damage in the structure.

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6932-123, Session 25

Delay of boundary layer separation by means of streamwise line acoustic sources

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By using a series of acoustic speakers aligned along the streamwise direction with a certain phase distribution, it is possible to focus acoustic waves in spanwise direction to the speakers. The purpose of the study is to delay onset of the laminar boundary layer separation on a 2-D airfoil based on the wave focusing technology. MEL001 airfoil is used.

First, we propose single acoustic speaker sound vibration method, in which we can vary both phase and amplitude of the acoustic wave by adjusting length and bore of the wave guide tubes. The separation control principle is tested by using a flat plate. Second, we apply the above control method to the MEL001 airfoil and observe whether or not the present method works. Finally, we make experiment at a chord Reynolds number $Re=1.0_{105}$ to examine the delay effect of the actuator on the delay of boundary layer separation of the airfoil.

6932-124, Session 26

**Enhanced statistical damage identification using frequency change information with tunable piezoelectric circuitry

J. Zhao, J. Tang, Univ. of Connecticut

Structural damage detection and identification has been under intensive research recently, with wide applications in aerospace, civil, and mechanical systems. Among the various methods being studied, the vibration based method that utilizes the information of frequency change (caused by damage) entertains certain advantages which include the global detection capability and the easy implementation with a small number of sensors. When combined with a credible finite element model of the baseline healthy structure, the information of frequency change may lead to the identification of elemental property change, yielding both the location and severity of the damage. On the other hand, there are also well-known drawbacks in such method, i.e., the lack of detection sensitivity and the difficulty in inverse identification due to the usually low number of measurable frequencies. A variety of methods have then been proposed to improve such method. One idea explored recently is to integrate tunable piezoelectric circuitry to the structure, which allows the generation of a family of frequency responses under different circuitry tunings. This can greatly enrich the measurable frequency information, and can alter the system dynamic behavior favorably for the damage detection purpose.

Real structures are inevitably subject to modeling error/uncertainty and measurement noise. Essentially, the statistical property of such uncertainty and noise should be taken into account in the damage identification process, so the identification result can be robust. Some recent studies have incorporated perturbation-based statistical techniques into the inverse identification of structural damage, and allowed not only the mean, but also the variance of the identification results. With such results, one may declare the damage information with confidence level.

In this research, we investigate systematically an enhanced statistical damage identification method using the frequency change information with tunable piezoelectric circuitry. With tunable circuitry elements, the implementation of the piezoelectric circuitry can lead to a family of frequency responses before and after the damage occurrence, where the much enriched frequency change information is used for damage identification. The circuitry elements, meanwhile, are discrete elements which can be directly and accurately measured and thus can be considered uncertainty free. Therefore, the integrated system consists of the structural part with uncertainty characterized by statistical means and the electrical part without uncertainty. Moreover, the tuning of the circuitry elements to different values leads to a family of systems that have the same mechanical structure with uncertainty and different but deterministic electrical circuitries. The objectives of this research include the development of statistical damage identification algorithm for this new detection approach, and then evaluate the enhancement of

detection robustness under the tunable piezoelectric circuitry. Based on the high order sensitivity analysis, a new damage identification algorithm is established which can provide both the mean and variance of the elemental property change. This algorithm is verified by comprehensive numerical studies using Monte Carlo simulation. A number of case studies with a variety of damage patterns are carried out. Our analysis indicates that the integration of the tunable piezoelectric circuitry can significantly enhance the confidence level in damage identification under uncertainty and noise, thus leading to much improved detection robustness.

6932-125, Session 26

**Damage detection using piezoelectric impedance and spectral element method

X. Wang, J. Tang, Univ. of Connecticut

Today, the detection of damage in various structures is under intensive investigation. One method that has attracted recent attention is the impedance-based approach using piezoelectric transducer attached to the structure to be monitored. The basic idea is that the electrical impedance of the piezoelectric transducer is directly related to the mechanical impedance of the host structure. Therefore, damage effect is reflected in the change of the piezoelectric impedance curves before and after damage occurrence. This method allows one to fully exploit the two-way electromechanical coupling of the piezoelectric transducer which serves as both the actuator and the sensor. Since reliable impedance curves can be generated at relatively high frequency range, this method has the promise to have high detection sensitivity for small-size damages.

With measured impedance curves of the healthy and damaged structures, previous studies have suggested a few damage indices to indicate the occurrence of the damages in the structure. These studies, however, mainly focus on declaring occurrence of the damage; the location and severity of the damages are still difficult to be identified. Normally, the identification of both the damage location and severity requires a model that can reflect the damage effect. In this research, we develop a model-based damage identification algorithm using the impedance curves. For a benchmark beam-type structure, the relation between the structure and the impedance curve is established with the dynamic stiffness matrix using the spectral element method. The spectral element method has high accuracy as well as numerical efficiency for impedance-based damage detection. This is especially true for high frequency range investigation. It is well known that, in order to detect small-sized damages, the wave length of the excitation needs to be smaller than the characteristics length of the damage. The high accuracy of model is needed in credible damage identification, while the high numerical efficiency is critical to real-time damage identification. Both are now achieved with the spectral element method. In the analysis, the beam is divided into a number of elements. Using the difference between the measured and healthy impedance curves as input, an inverse identification procedure based on the spectral element method is developed that allows us to extract directly the property change of the elements before and after damage occurrence, yielding both the damage location and severity information. A series of numerical studies are first carried out to verify the spectral element method developed. Extensive experimental studies are then performed to examine the numerical analysis and to demonstrate the simplified impedance measurement circuit. Finally, damage identification case studies are illustrated via correlated experimental measurements and numerical simulations, which show the effectiveness of the proposed approach.

6932-126, Session 26

An optical fiber sensor for acoustic wave mode decomposition

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This paper reports on a study into the development of an advanced optical fibre based sensor for the modal decomposition of acoustical wave fields. When used as part of an integrated structural health monitoring system where elastic waves generated by piezoelectric elements provide the interrogating field, the sensor furnishes robust predictions of the wave mode composition. It accordingly affords greater diagnostic value than

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a conventional piezoelectric sensing element. Aspects of the design and manufacture of the fibre optic sensor are discussed and experimental work is presented to demonstrate the efficacy of the sensor and the high diagnostic value of its output. The paper emphasises the role of optimal design of the bragg grating reflection spectrum to afford high sensitivity. Consideration is also given to parasitic influences on the sensor response, factors affecting load transfer to the optical fibre and issues relating to signal stability.

Included in the paper is a review of the experimental and numerical approaches used to validate the sensor output, including laser scanning vibrometry and numerical modelling using an advanced piezoelectrically-coupled analysis of wave propagation in an isotropic plate.

An experimental case study is presented involving an aluminium plate with a surface mounted optical fibre sensor. Synthetic damage is introduced to the panel which is then interrogated by an acoustic wave field produced by a surface mounted piezoelectric transducer. The optical fibre sensor is successfully applied to the characterisation of the modal composition of the wave field scattered by the defect. The example highlights the potential of the sensor to provide a robust basis for in situ structural health monitoring.

6932-127, Session 26

Improved IPMC sensing by use of cations and through induced nano-to-micro scale surface cracks

R. Tiwari, K. J. Kim, Univ. of Nevada/Reno

Ionic Polymer Metal Composite (IPMC) is a nano-scale metal deposited ionic polymer and may be used as soft actuator and sensor. Numerous researches have been conducted to study IPMC as actuator. Many applications like energy harvesting, impact sensing and velocity sensing use IPMC as a sensor, thus making it necessary to understand sensing nature of IPMC. It has been demonstrated that production of charge under the influence of mechanical deformation in IPMC, is a combined effect of chemical, mechanical and electrical response which may be affected by nature of existing cation and, conductivity and morphology of electrodes. This paper presents a comparison between the sensing behavior of IPMC under the influence of different cations like Li^+ , Na^+ and H^+ . In addition, experiments were also performed to study the effect of nano-to-micro scale surface cracks in IPMC. Test results are in accordance with the actuation results of IPMC showing that smaller cation leads to improved characteristics. It was also discovered that inducing nano-to-micro scale surface cracks in IPMC improves the sensing characteristics of IPMC. Experiments were also performed to compare the effect of electrode surface morphology and conductivity on sensing performance of IPMC. These effects were also compared for energy harvesting applications of IPMC.

6932-128, Session 26

Embedded algorithms within an FPGA and microprocessor-based system to process nonlinear time series data for structural health monitoring

J. D. Jones, J. Pei, K. Piyawat, M. P. Tull, J. K. Antonio, Univ. of Oklahoma

This paper presents some preliminary results of an ongoing project. A pattern classification algorithm is being developed and embedded into a Field-Programmable Gate Array (FPGA) and microprocessor-based data processing core. The goal is to enable and optimize the functionality of onboard data processing of nonlinear, nonstationary data in smart wireless health monitoring.

Compared with traditional microprocessor-based systems, fast growing FPGA technology offers a more powerful, efficient, and flexible hardware platform including on-site (field-programmable) reconfiguration capability of hardware. This paper first overviews the landscape of the FPGA technology and reviews a proof-of-concept work that this project is built upon. Challenges in taking advantage of the available off-the-shelf hardware and software design tools to facilitate the research and practice

in civil infrastructural health monitoring are also discussed.

An existing nonlinear identification algorithm is used as the baseline in this study. The implementation within a hardware and software-based system is presented in this paper, detailing the design requirements, validation, tradeoffs, optimization, and challenges in embedding this algorithm. An off-the-shelf high-level abstraction tool along with the Matlab/Simulink environment is used to program the FPGA and embedded processor, rather than coding the hardware description language (HDL) manually. The implementation is validated by comparing the simulation results with those from Matlab.

In particular, the Hilbert Transform is embedded into the FPGA hardware and applied to the baseline algorithm as the centerpiece in processing nonlinear time histories and extracting instantaneous features of nonstationary dynamic data. Two design options are developed to implement the Hilbert Transform; tradeoffs such as computation time, resource consumption, and numerical accuracy, resulting from adopting different design operations are detailed. The selection of proper numerical methods for the hardware execution of the selected identification algorithm and consideration of the fixed-point representation are elaborated. Other challenges include the issues of the timing in the hardware execution cycle of the design, floating and fixed-point data preservation within a hybrid hardware/software system, approximation accuracy, and user flexibility of input data types limited by the simplicity of this preliminary design.

Future work is identified including the development of a more comprehensive version of the identification algorithm that can eventually be embedded for damage detection and striving for an optimal balance of hardware and software collaboration in a nonlinear, nonstationary data processing system.

6932-130, Session 27

A study on smart-materials-based structural health monitoring

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A smart, intelligent or adaptive material is one which possesses extraordinary and useful properties that can be designed and developed into a smart structure. Ideally, smart structure should have the capability to sense, measure, process, and diagnose any change in selected variables at critical locations, and to command appropriate action in a predetermined manner within a certain time frame and continue to perform the intended function. An engineered smart structure must meet the following six criteria: functionality, reliability, durability, affordability, safety and cost effectiveness. Some of the notable developed smart materials are piezoelectric materials, shape memory alloys (SMA), electrostrictive and magnetostrictive materials, electrorheological (ER) and magnetorheological (MR) fluids and fiber optics. Even though the basic principle of application of these materials differs, they have some similar characteristic properties. These materials can be used individual or collectively for monitoring structure. The results can be complementary to each other when used collectively. This paper presents some of the most widely used smart materials and their merits and demerits for use in structural health monitoring (SHM)

6932-131, Session 27

**Structural configuration study for an acoustic wave sensor

W. S. Shepard, Jr., B. Zhang, The Univ. of Alabama; C. Chen, Tuskegee Univ.

A continuous structure has several response characteristics that make it a candidate for a sensor used to locate an acoustic source. One of the primary goals in developing such a sensor is to ensure that the response is rich enough to provide information about the impinging acoustic wave and its direction of travel without being too sensitive to background noise. As such, there are several factors that must be examined with regard to sensor configuration and measurement requirements. The research described here includes the initial configuration study that examines various configuration requirements for such as sensor. Some of the parameters of interest include the size and aperture of the structure, boundary conditions,

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orientation, materials, as well as response sensing requirements. Since it is expected that an inverse formulation will be used to reconstruct the transient acoustic pressure wave propagating across the structure's surface, the requirements for the inverse approach may also impact the structure's configuration. To evaluate a structure's potential to serve as this sensor, parallel configuration assessment studies are being conducted. One study is based on an analytical formulation. This formulation enables an efficient assessment of various configuration parameters in impacting the structure's dynamic response. Another formulation, based on finite and boundary element models, is also being used. In addition to providing a means to validate the analytical study, the discretized formulation provides additional flexibility in considering other potentially important factors. The initial results presented here include the impact and relative importance of various factors that influence the structure's ability to respond in an appropriate manner. Other important considerations are also discussed. This work is supported by NSF Sensor Innovation and Systems.

6932-132, Session 27

Static analysis of an artificial muscle system based on PZT strain amplification

T. W. Secord, Massachusetts Institute of Technology; J. Ueda, Massachusetts Institute of Technology and Nara Institute of Science and Technology (Japan); H. H. Asada, Massachusetts Institute of Technology

Artificial muscle actuators based on smart materials are becoming more widespread. However, most smart material actuators suffer from a combination of small strain, low stress capacity, low bandwidth, and stringent input requirements. Relative to other smart materials, thin film PZT has a large stress capacity, a high bandwidth, and a low power input requirement. The performance of PZT as a robotic and mechatronic actuator is restricted only by its small strain output, which makes PZT ideally suited to strain amplification. In this paper, the design and analysis of a novel artificial muscle system based on power law strain amplification of PZT stack output are presented.

Power law strain amplification is achieved by means of a nested cellular architecture. The first of the nested layers consists of a commercially available thin-film PZT stack actuator coupled to a moonie flexural amplification mechanism. The PZT stack and moonie unit form a 5mm x 13mm x 8.5 mm basis cell. A serial combination of six first layer basis cells are then placed inside a brass rhombus-shaped flexural amplification mechanism to form a new basis cell for the second layer. Using this layering scheme, artificial muscles can be constructed to meet the mechanical impedance specifications required by a specific task.

The primary limitation of the nested strain amplification mechanisms is the loss of performance due to structural compliance. To quantify the design performance, analytical expressions are obtained for the blocking force, free displacement, and input stiffness of both the moonie and rhombus strain amplification flexures. Theoretical model development is based on Castigliano's strain energy-displacement theorem. A lumped parameter model of the actuator force and displacement characteristics is then presented for later use in controller design. Design implications and guidelines are enumerated based on the theoretical modeling.

Finite element analysis and experiments validate the static behavior predicted by theoretical solid mechanics. The finite element analysis is carried out using the COSMOS Express package available in SolidWorks. Experiments are performed using two custom designed test stands capable of measuring blocked force to within 0.1 N and free displacement to within 1 micron. The theoretical and measured values for blocked force and free displacement are in close agreement for both the moonie and rhombus strain amplification flexures.

6932-133, Session 27

Finite element modeling of fiber Bragg grating strain sensors and experimental validation

S. A. Malik, G. F. Fernando, D. Collins, L. Wang, V. Machavaram, The Univ. of Birmingham (United Kingdom)

Fiber Bragg grating (FBG) sensors continue to be used extensively for

monitoring strain and temperature in and on engineering materials and structures. Previous researchers have also developed analytical models to predict the load-transfer characteristics of FBG sensors as a function of applied strain. The general properties of the coating or adhesive that is used to surface-bond the FBG sensor to the substrate has also been modeled using finite element analysis.

In this current paper, a technique was developed to surface-mount FBG sensors with a known volume and thickness of adhesive. The substrates used were neat-resins (with different failure strains) and steel dog-bone tensile test specimens. Neat-resin samples with embedded FBG sensors were also studied as a function of silane surface treatment. The FBG sensors were tensile tested in a series of ramp-hold sequences until failure. The reflected FBG spectra were recorded using a commercial instrument. The FBGs were also subjected to monotonic tensile loading until failure.

Finite element analysis was performed to model the response of the surface-mounted and embedded FBG sensors. In the first instance, the effect of the mechanical properties of the adhesive and substrate were modeled. This was followed by modeling the volume of adhesive used to bond the FBG sensor to the substrate. Finally, the predicted values obtained via finite element modeling was correlated to the experimental results. In addition to the FBG sensors, the tensile test specimens were instrumented with surface-mounted electrical resistance strain gauges and a pair of conventional piezo-electric acoustic emission transducers.

6932-134, Session 27

Machine maintenance with wireless sensor networks

M. Zhang, V. Sundararajan, Univ. of California/Riverside

Wireless sensor networks (WSNs) are mainly adopted in the field of environmental monitoring and structural engineering. Meanwhile, sensor nodes abilities, including local computation, storage capacity, reduced size and multiple sensor information providers show their application potential on machine maintenance. Previously machine maintenance is done with manual work. Human frailty cannot be avoided, such as fatigue, operator error, oversight, and so on. The emergence of WSNs provides a new method of maintenance. It can perform instant and reliable condition monitoring. Also, they can bring extra benefits. They reduce maintenance cost and increase efficiency. Especially, the nodes can be mounted on various positions of machinery, even deploying sensors in risky locations, e.g. close to tool tips. This paper discusses the special requirements for wireless sensor networks application on maintenance and shows an application case on lathe machine maintenance.

6932-135, Session 28

Development of wireless carbon nanotube/nanofiber-based sensor for health monitoring of composite structures

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Damage detection at the microscopic and nanoscale level is very important in maintaining the structural health of civil and aerospace structures. Several non-destructive evaluations (NDE) such as eddy current, ultrasonic, acoustic, vibration and thermography have been used to assess the damage that the structure accumulates. However, these NDE techniques are expensive, time consuming and non-reliable. This paper investigates the feasibility of developing wireless nanotube and nanofiber-based mechanical sensors for health monitoring and structural damage detection in composite structures. When integrated into the structure the proposed sensors can greatly reduce the inspection burden through fast in-situ data collection and processing. The response of the proposed sensors under different load conditions will be presented and their wireless damage detection capability will be discussed in this paper.

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6932-136, Session 28

Experimental investigations of wireless active-sensor nodes using impedance-based structural health monitoring

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This paper describes the development of the next generation of an extremely compact, wireless impedance sensor node for use in structural health monitoring (SHM). The sensor node uses a recently developed, low-cost integrated circuit (IC) that can measure and record the electric impedance of a piezoelectric transducer. The sensor node also integrates several components, including a microcontroller for local computing, telemetry for wirelessly transmitting data, multiplexers for managing up to seven piezoelectric transducers per node, energy storage mediums, and several triggering options including a wireless triggering circuit into one package to truly realize a comprehensive, self-contained wireless active-sensor node for SHM applications. It is estimated that this developed sensor node requires less than 50 mW of total power to operate measurement, computation and data transmission. In addition, the sensor node can also be used for the active-sensor self-diagnostic process that can monitor the operational condition of piezoelectric transducers used in SHM applications. The performance of this miniaturized and portable device is compared to our previous results and its broader capabilities are demonstrated in the laboratory and field testing, which was performed at the Alamos Canyon bridge, NM, 2007.

6932-138, Session 28

Design and implementation of a wireless sensor network for smart living spaces

W. Wu, C. S. Yeh, C. K. Lee, J. D. Huang, National Taiwan Univ. (Taiwan)

After an evolution over the last ten years, a newly designed wireless sensor network is now ready for adoption to applications such as remote medical care, health monitoring, smart houses and vehicle electron fields. Many existing technologies such as IC design, sensor technology, circuits/firmware development, communication protocol design, and network programming, already incorporate wireless sensor networks. In order to further expand the application arena of wireless sensor networks, a team of researchers from different fields, funded by Taiwan's Nation Science Council worked together on a project titled the "Development of a Wireless Sensor Network Common Platform and Demonstration on Smart Living Spaces and Environmental Safety Program.". The objective of the group was to establish a new wireless sensor network development platform for nationwide use geared towards education and scientific purposes. This paper details the Super Node, Simple Node, and Nodes implemented within this program for terminal data collection. In addition, package routing, data collection, and connections to a computer of the Super Nodes will be further elaborated. The modulus design concept of both a Simple Node and Super Node for further integration with other application circuits in order to facilitate the prototype design directed towards education will also be examined. The advantages of having an IEEE802.15.4 communication ability within both nodal circuits are discussed. To provide compatibility to tinyOS, Super Node's circuit was developed using Tmote as a reference even though humidity, temperature and light sensors typically implemented in Tmote are not adopted so that systems cost and package size can be minimized.

The system functional test results obtained by implementation within National Taiwan University's demonstration facility, which served as the evaluation platform for the wireless sensor network, will also be presented.

6932-139, Session 28

Two degree of freedom energy harvesting device with a variable stiffness for resonance frequency tuning

V. R. Challa, M. Prasad, F. T. Fisher, Stevens Institute of Technology

Wireless sensors are becoming extremely popular for their ability to be employed in hostile and inaccessible locations to monitor various parameters of importance. The key challenge for these sensors is having a long-life power source that can match the life expectancy of the sensor. Vibration energy harvesting shows a great potential in powering these wireless sensors with its self sustainable capability. While the technique can be employed to harvest energy from ambient vibrations and vibrating structures, a general requirement is that the vibration energy harvesting device should operate in resonance at the excitation frequency. However, many of the energy harvesting devices developed to date are designed based on single resonant frequency, making them applicable only for a specific application thereby hindering their commercial viability.

To efficiently harvest energy over a range of frequencies, the energy harvesting device should have the ability to tune its natural frequency to match the source frequency. While the natural frequency of the energy harvesting structures can be altered by changing the mass or the stiffness, it is still a challenge to have a robust method without sacrificing the overall power output. Recently efforts have been attempted to broaden the frequency range of energy harvesting devices, by altering one or more of these parameters, but in terms of power density they still lag an efficient methodology.

In this work, a tunable two degree freedom energy harvesting device with resonance frequency tunability is presented. The device consists of three cantilever beams with identical resonance frequencies, which are coupled in a novel fashion by means of magnetic force, resulting in a two degree of freedom system to enable resonance frequency tuning when required. Here the magnetic force acts as the variable spring stiffness, allowing one to alter the resonance response of the device. Through this mechanism one can both increase and decrease the stiffness of the beam, which allows one to tune the device to lower or higher frequencies as necessary to match the excitation frequency. A proof-of-concept prototype device has been developed which demonstrates this mechanisms is successful in tuning to +/- 20% of the natural frequency of the untuned cantilever. As the tuning mechanism is itself comprised of an energy harvesting cantilever beam, the design results in an overall increase in the power density achievable from the device.

6932-141, Session 28

A wireless bonded patch repair monitoring approach

N. Mrad, Defence Research and Development Canada (Canada)

Military and civilian aircraft are designed to operate within established operational envelopes for a determined lifetime. Within several countries, the military is undergoing significant economic pressure to extend the use of its air fleets beyond their established design lives. The availability of efficient, reliable and cost-effective technologies to repair or extend the life of aging air fleets is becoming a critical requirement to sustain the operational effectiveness of current fleets. Bonded composite patch repair is considered to be among the most promising technologies for damage repair and component life extension. Assessment of in-service repair integrity continues to be the challenging key factor for effective implementation on primary structure. This paper presents a strain-based wireless approach to assess the bondline integrity of a composite bonded patch repair. Experimental results, on the disbond growth and the state of the patch's load carrying capacity and efficiency, using wireless sensors are also presented

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6933-01, Session 1

Fiber optic sensor-based SHM technologies for aerospace applications in Japan

N. Takeda, The Univ. of Tokyo (Japan)

Optical fiber sensors are promising as tools for damage and structural health monitoring (SHM) of aerospace composite structures. Hence many researchers have conceived various kinds of optical fiber sensors. First, a brief summary of optical fiber sensors used for composites is presented. Then, the authors' studies on the small-diameter FBG sensors for damage monitoring and SHM of composite structures are described. The authors and Hitachi Cable, Ltd. have developed small-diameter optical fiber and its fiber Bragg grating (FBG) sensor for embedment inside a lamina of composite laminates without strength reduction. Then, some recent results in the current ACS-SIDE (Structural Integrity Diagnosis and Evaluation of Advanced Composite Structures) project are presented on optical fiber based SHM for some feasible applications in aerospace composite structures in Japan.

6933-02, Session 1

High-accuracy fiber optic localization for bend sensing and end-point detection

R. G. Duncan, M. E. Froggatt, M. T. Raum, Luna Innovations Inc.

Abstract: We describe the results of a study of the performance characteristics of a monolithic fiber-optic bend and shape sensor. Strain measurements from distributed fiber Bragg gratings in a multi-core optical fiber multiplexed via the frequency domain reflectometry technique are used to deduce the shape of the optical fiber. We have performed bend measurements and end-point detection under a variety of circumstances using a multi-core fiber with extremely dense fiber Bragg grating arrays within the multiple cores and have reported the accuracy and precision of these measurements. A discussion of error sources is also included.

6933-03, Session 1

Effects of coating and diametric load on fiber Bragg gratings as cryogenic temperature sensors

M. Wu, R. H. Pater, S. L. DeHaven, NASA Langley Research Ctr.

Cryogenic temperature sensing was demonstrated using pressurized fiber Bragg gratings (PFBGs) with polymer coating of various thickness. The PFBG was obtained by applying a small diametric load to a regular fiber Bragg grating (FBG). The Bragg wavelengths of FBGs and PFBG were measured at temperatures from 295 K to 4.2 K. The temperature sensitivities of the FBGs were increased by the polymer coating. A physical model was developed to relate the Bragg wavelength shifts to the thermal expansion coefficients, the Young's moduli and the geometries (thicknesses) of the coating polymers. When a diametric load of no more than 15 N was applied to a FBG, a pressure-induced transition occurred at 200 K during the cooling cycle. As a result, the temperature sensitivity of the PFBG was greater than expected from thermal expansion of the fiber and the coating for a regular FBG. From room temperature to liquid helium temperature the PFBGs gave an increased wavelength shift of at least 2.2 nm. This effect was attributed to the change of the thermo-optic coefficient of the fiber.

6933-04, Session 1

Micron-sized optical fiber sensor interrogation system

N. Mrad, Ministry of National Defence (Canada)

Within several countries, the military is undergoing significant economic pressure to extend the use of its air fleets beyond their established

design lives. The availability of low weight, small size, efficient, reliable and cost-effective technologies to detect and monitor incipient damage and to alert prior to catastrophic failures is critical to sustain operational effectiveness. To enable the implementation of distributed and highly multiplexed optical fiber sensors networks to aerospace platforms, the data acquisition (demodulation) system has to meet small size and low weight requirements. This paper reports on our current development of a micron-sized Echelle Diffractive gratings (EDG) demultiplexer for the interrogation of several serially multiplexed fiber sensors gratings. The operation principle of the interrogator and its suitability for both strain and temperature measurements is demonstrated. The developed interrogator met established criteria of weighing less than 60 grams and providing measurement accuracy of 10 pm and measurement resolution of less than 1 pm.

6933-05, Session 2

Fiber Bragg grating sensors and SHM applications: a market overview

A. Mendez, MCH Engineering LLC

Over the last few years, optical fiber sensors have seen increased acceptance and widespread use for a variety of applications ranging from structural sensing and health monitoring of composites and structures in civil and aeronautic areas; to downhole pressure and temperature sensors for oil and gas reservoir monitoring; to high voltage and high current sensing systems for the power industry-to name just a few.

Optical fiber sensor operation and instrumentation have become well understood and developed. And a variety of commercial discrete sensors based on Fabry-Perot (FP) cavities and fiber Bragg gratings (FBGs), as well as distributed sensors based on Raman and Brillouin scattering methods, are readily available along with pertinent interrogation instruments. Among all of these, FBG based sensors, more than any other particular sensor type, have become widely known and popular within and out the photonics community and seen a rise in their utilization and commercial growth.

Given the intrinsic capability of FBGS to measure a multitude of parameters such as strain, temperature, pressure, chemical and biological agents-and many others-coupled with their flexibility of design to be used as single point or multi-point sensing arrays and their relative low cost, make them ideal devices to be used for on-line monitoring devices in Structural Health Monitoring (SHM) applications. However, some technical hurdles and market barriers need to be overcome in order for this technology-and fiber sensors in general-to gain more commercial momentum and achieve faster market growth.

An overview of the commercial status of FBG-based sensors and their related SHM applications and market trends will be given along with an analysis of the estimated market size, segments, players, driving factors and most relevant commercial applications.

6933-06, Session 2

Dielectrically packaged fiber Bragg grating strain and temperature sensors

D. Snyder, S. Ferguson, T. W. Graver, Micron Optics, Inc.; A. Mendez, MCH Engineering LLC

Over the last few years, optical fiber sensors have seen an increased acceptance as well as a widespread use for structural sensing and monitoring in civil engineering, aerospace, marine, oil & gas, composites and smart structure applications. Optical fiber sensor operation and instrumentation have become well understood and developed. However, one of the areas in need of further development and commercial maturity is that of sensor packaging and installation technique. Furthermore, given the intrinsic dielectric nature of optical fibers and their immunity to electromagnetic interference (EMI), it is also indispensable to provide the devices with dielectric and EM passive packaging designs so that they can be safely used in applications and environments where high voltages, electric

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currents and EM fields are present such as in electric power systems applications.

In this paper, we report the design and development of a novel temperature and strain sensors based on the use of an optical fiber Bragg grating (FBG) mounted into a custom-made miniature dielectric flexure. The FBG element is attached-a special bonding technique- to a carrier flexure made of special dielectric materials to avoid any possible magnetization or electric conduction of the substrate. These devices display a linear, drift-free and repeatable response-even under harsh environments-and are intended for use in diverse structural health monitoring (SHM) and equipment condition monitoring (CM) applications and can be easily mounted using epoxy bonding. Pertinent test data will be presented describing the sensor's strain and temperature sensitivities, environmental stability and endurance under continuous mechanical cyclic loading.

6933-07, Session 2

Local strain measure of Kevlar strand with fiber optic Bragg grating

C. E. Banks, NASA Marshall Space Flight Ctr.; S. Arnett, Texas Research International, Inc.

1987 4560 denier Kevlar/Epoxy Strands were instrumented with nine and three fiber bragg grating sensors each. Stress tests were performed at 30,45,60,70 and 80% of ultimate strength with dwell times of 10,000 seconds. FBG showed uneven stress levels which is contrary to conventional observation.

6933-08, Session 2

Packaging of surface relief fiber Bragg gratings for harsh high-temperature environments

J. D. Young, T. L. Lowder, S. M. Schultz, R. H. Selfridge, Brigham Young Univ.

In submitting this extended abstract I am requesting consideration for the 2008 SPIE/ASME Best Student Paper Presentation Contest.

There is a growing need for durable, light weight high temperature sensors in the oil industry and for use in gas turbine engines. An in-fiber optical temperature sensor is ideal for these requirements. Fiber Bragg gratings (FBGs) rely on a periodic photoinduced refractive index modulation to reflect light in a narrow wavelength band centered on the Bragg wavelength. As the temperature of the fiber increases, the effective index of the guided mode changes and the glass expands, shifting the Bragg wavelength and allowing for temperature sensing.

Unfortunately, FBGs are not fit for sensing at high temperatures because the photoinduced index modulation grating washes out above ~350 °C. As an alternative method to creating a Bragg grating, we etch the grating into the flat surface of an elliptical-core D-fiber. The flat surface of the D-fiber is etched close to the core so that the grating can influence the guided light. The gratings are about 1.5 cm long, 0.4 microns above the core and have a peak-to-trough distance of about 80 nm. These Surface Relief Fiber Bragg gratings (SR-FBGs) can operate at high temperatures above that of a standard FBG because the grating is a physical feature of the surface of the fiber.

We test the SR-FBGs at high temperatures using a Lindberg/Blue tube furnace and a Micon Optics Optical Interrogator to monitor reflection and transmission spectra. As the fiber is heated we observe a linear relationship between temperature and Bragg wavelength with a sensitivity of ~16 pm/°C. At high temperature (1000 °C) transmission and reflection power are resilient even after several hours. As the fiber is cooled no hysteresis is observed.

After repeated heating we observe brittleness in the fiber and an increased susceptibility to grating contamination. Contaminants on the grating reduce the grating contrast and ultimately reduce the reflection efficiency. Also because the grating is close to the fiber core, these contaminants lead to transmission losses due to absorption and scattering. To protect against contamination we overcoat the grating with ~90 nm of Sapphire using a Denton E-beam Evaporator and ~500 nm of silicon-dioxide using a Denton Suptterer. The 90 nm Sapphire overcoat is used to maintain the

index contrast of the grating and act as a buffer between the cladding layer of the fiber and the low index sputtered silicon-dioxide. The fiber jacket is also removed using sulfuric acid to avoid any contamination that might occur as the jacket burns off. To overcome brittleness the stripped fiber is threaded through a stainless steel tube with an inner diameter of 250 um. To minimize power loss and facilitate ease of use, the end of the D-fiber is fusion spliced to elliptical core round fiber and then to a standard SMF-28 patch cord. With the protective overcoat and packaging the sensor becomes robust at high temperature.

Using this packaging scheme, two temperature sensors are successfully multiplexed and integrated into an aircraft engine. The aircraft is flown from Florida to Wisconsin while using the optical sensors to monitor engine temperature. In Wisconsin additional test flights are conducted using the optical sensors, again with success.

These results demonstrate the SR-FBG suitability for use in high temperature applications and with proper packaging the SR-FBG is a viable alternative to current thermocouple technology. The SR-FBG is lighter and can be multiplexed into vast sensor arrays. It is also more sensitive to temperature changes. In short, the SR-FBG has the potential to improve the way high temperature is monitored.

6933-09, Session 3

Fiber optic sensor networks for monitoring displacement and temperature fields in adaptive structures

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An approach to meet the increasing performance requirements of aerospace and other challenging types of structures is the design of smart or adaptive structures, which also provide different integrated functions. In applications like large high precision space reflectors or high aspect ratio airplane wings, with aeroelastic requirements, the structures shape under operational conditions is of interest. Knowledge of static and dynamic deformations of these structures provides the possibility to increase their performance by appropriate control measures. During operation, however, such monitoring is often quite difficult to implement. A technique is presented for the estimation of deformation fields using strain data measured via a network of fibre optic (strain) sensors (FOS). This allows many measurement points within only a few channels. Besides deformations, temperatures and temperature fields often are of interest as well, which could be handled using similar methods and sensor networks.

For proper implementation of such approaches, some basic elements have to be clarified such as

- proper behaviour of the FOS system (!) esp. with respect to accuracy, bandwidth and long term stability
- techniques to properly integrate FOS into mostly fibre composite materials and structures such that spurious effects are minimized
- methods to establish proper transfer matrices from measured strain values to displacement fields to be determined

Though most FBG sensor systems provide high precision, their delay time and maximum acquisition frequency makes them difficult to use for vibration control purposes. Therefore, a multi-channel FBG sensor system was developed using a position sensitive detector for the wavelength interrogation which has much less delay time than a CCD-based system and a theoretical maximum bandwidth of >300 kHz. This system was tested for high-precision strain measurements for deformation control applications at low frequencies as well as for high frequency strain measurements of more than 10 kHz. Its application potential for static and dynamic shape and vibration control will be demonstrated.

Mechanical integration techniques depend on the kind of structure under consideration. Possibilities for these will be discussed in the context of carbon composite laminate structures and sandwiches. Within this context, special techniques have to be provided and will be shown for the case of temperature sensing in order to decouple mechanically induced from thermally induced strains.

Methods for establishing transfer matrices from strain data to (discretised) displacement fields based on modal vectors, Krylov vectors and also

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of base vectors established via Finite Element analysis are discussed. Techniques for reducing measurement errors via several types of Kalman filters will be presented. These approaches are experimentally verified by a dynamically excited plate. To reduce systematic estimation errors due to aliasing, a related sensor locations optimization has been carried out.

As an outlook, some possible technical applications for static and dynamic shape control of opto-mechanical systems and for aerospace adaptive structures will be outlined. It will be also highlighted that once FOS are integrated, virtually the whole lifetime of the structural system ranging from manufacturing monitoring over experimental verification to operational monitoring can be covered.

6933-10, Session 3

Improvement of FBG/PZT hybrid sensing system for composite materials

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We have been developing a system for monitoring the health of aircraft structures made of composite materials. In this system, Lamb waves generated by PZT actuators travel through composite material structures and are received by embedded FBG sensors. Arrayed waveguide grating (AWG) is used to detect Bragg wavelength change due to the reception of the Lamb wave. AWG is used for converting the Bragg wavelength change into output power change. The conversion ratio has large initial Bragg wavelength dependency and it has required temperature control to obtain optimum condition. We have achieved the system without temperature control of the AWG by adopting denser AWG. This can reduce number of the parts and improve the reliability of the system. It also reduce power consumption of the system. For these reason, this improved system is suitable for on board usage. On the other hand, for the frequency of the Lamb waves, we have used several hundred kHz. This high frequency is suitable for detecting small damage, but it require complex analyzing process due to many propagation modes of the Lamb wave. By lowering the frequency, the propagation modes can be reduced and it allow simple analyzing process, so there is demand for damage detection using lower frequency Lamb wave. To meet this demand we have expand the frequency band of the Lamb waves and allowed the system to operate with 10 kHz to 1MHz in frequency. Damage detection with various frequencies will increase the reliability of the results.

6933-11, Session 3

Damage detection system with nanosecond resolution

E. Udd, Columbia Gorge Research

Fiber optic grating sensors have the capability of operating at very high speed. This paper explores the usage of these sensor to perform damage assessment at very high speed including a system operating at a GHz. Examples of applications and demonstrations of this system are given.

6933-12, Session 3

The use of fiber Bragg gratings for ultrasound detection in anisotropic materials

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The use of fibre Bragg gratings (FBG) to detect ultrasound in isotropic materials has been previously described. In particular the FBG directional properties may be used to determine the direction of propagation of an incident acoustic wave. Directional information was obtained by configuring the gratings into rosettes and measuring the relative amplitudes of the signals obtained from each grating. This is similar in principle to the way in which electrical strain gauges are used to determine principal static strains. Two or more rosettes may be used to determine the location of a hole, which can be considered as a passive source if excited by an active one such as a PZT. Since the gratings can also be used to detect static strain, they can be considered to be multifunctional sensors. If

conventional electrical sensors were to be employed to perform both functions, two arrays would be required, one of which would be electrical strain gauges and the other PZTs, both accompanied by a considerable mesh of wiring.

It would clearly be useful to be able to use the FBG in a similar way in materials such as carbon fibre composites, which are, however, anisotropic. This presents a considerable challenge, however since both the group and phase velocities, together with the acoustic attenuation all show considerable directional variation. In addition, the group and phase velocity vectors may not be parallel. In order to assess the possibility of using Bragg gratings for directional measurements of ultrasound, we have completed experiments to measure both the propagation velocities and attenuation of ultrasound with varying wave propagation direction and sensor orientation. This was carried out on a carbon fibre plate of lay-up 0°-90° using a matrix of PZT disc actuators and Bragg grating sensors bonded on to the plate. The gratings were bonded on using a temporary bond so that they could be readily debonded and relocated at different orientations. By this method the grating response at different angles relative to an acoustic Lamb wave could be determined and, further, these measurements could be repeated for acoustic waves propagating at different directions relative to the composite weave. These results will be described in detail in the paper and their characteristics analysed. We shall show that with the correct detailed analytical and experimental approach, these results may be used to make directional ultrasound measurements in anisotropic materials, but that applying these results requires significant additional care and computation when compared to the previously demonstrated source location algorithms utilised for isotropic systems.

6933-13, Session 3

Rapid spectral interrogation enables advanced FBG sensing

W. M. Kunzler, J. Newman, D. Wilding, Z. Zhu, R. H. Selfridge, S. M. Schultz, M. J. Wirthlin, Brigham Young Univ.

A fiber optic sensor system capable of monitoring a sensor's entire spectrum can gather another dimension of information for characterization of complex structures. Recently, BYU developed a system to monitor full spectra at high speeds and is employing it to research complex temperature and strain gradients induced from a CO2 laser.

Fiber Bragg gratings (FBGs) can translate environmental parameters into wavelength encoded optical signals. These optical signals combine to form a monochrome reflection in an optical fiber. If the spacing of the grating indices varies as it would under non-uniform temperature or strain, the grating spectral response becomes non-uniform, fooling many FBG interrogators that are designed to expect a Gaussian optical distribution which typically stems from quasi-regular index spacing.

Rather than limiting FBG usefulness to one-dimensional stimulus, the researchers desired to capitalize on the grating retention of information by designing an FBG interrogator that could capture all the spectral responses to fast environmental stimuli. The data can then be analyzed for greater understanding of the stimulated effects upon the material under test and digital signal processing techniques can automate the interrogation process. Extrapolation of this information is not foolproof, and variations are discussed. However, this new tool enables three valuable advancements:

- multiple independent sensing points become available from a single sensor for understanding fast phenomena
- movement of strain gradients and temperature gradients can be monitored in complex materials such as composites
- new types of sensors become possible at high speed, including embedded references within a sensor

Using an FPGA with high speed DAC/ADC components and a kilohertz rate MEMS optical filter, the optical spectrum can be scanned at rates in excess of 10 million nanometers per second allowing sensor sampling rates of many kilohertz while maintaining the necessary resolution to understand sensor changes. The autonomous system design performs all necessary detection and processing of multiple sensors and allows spectral measurements to be exported as fast as Ethernet, USB, or RS232 devices can receive it over a simple memory mapped interface.

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6933-14, Session 4

Structural health monitoring of wind turbine blades

M. A. Rumsey, J. Paquette, Sandia National Labs.

Introduction: As electric utility wind turbines increase in size, and correspondingly, the increase in initial capital investment cost, there is an increasing need to monitor the health of the structure. Acquiring an early indication of structural or mechanical problems allows operators to better plan for maintenance, possibly operate the machine in a derated condition rather than taking the unit off-line, or in the case of an emergency, shut the machine down to avoid further damage. Numerous possible health monitoring devices and damage computation algorithms exist for a whole host of wind turbine components, especially gearboxes and blades. This paper will focus on structural health monitoring (SHM) of wind turbine blades. Specifically, the results obtained by different SHM technologies applied to fatigue tests of 9-meter subscale blades will be presented.

SHM Technologies: Several SHM technologies exist that present possible solutions for wind turbine blades. This presentation will focus on piezoelectric, accelerometer, and acoustic emissions sensor based monitoring.

Test Configuration: The sensor technologies to be presented were applied to fatigue tests of two 9-meter subscale wind turbine research blades. The first test was of a TX-100 blade which included off-axis carbon fiber in the skin to produce twist-bend coupling, and thus, passive aerodynamic load alleviation. The second test was of a BSDS blade which incorporates several advanced structural and aerodynamic features in its design, most notably, flatback airfoils. These fatigue tests were conducted at the National Wind Technology Center (NWTC), in Boulder, CO. The NWTC is a laboratory within the National Renewable Energy Laboratories complex. The blades were bolted to a test stand and subjected to an oscillating load produced by either an oscillating mass or a hydraulic ram. The oscillating load was calculated and prescribed to simulate the cyclical loading that the blades would see in a 20-year field operation. The tests were planned such that the blades would fail sometime between 1 to 3 million cycles, or over 1 to 2 months of testing. During the tests, some of the sensor technologies monitored the blade continuously, while others required the test to be paused periodically to perform their data acquisition.

Results: The TX-100 fatigue test has been completed to blade failure, but the data is currently being analyzed. The BSDS fatigue test is scheduled to start mid-October 2007. Therefore, the results from the various different sensor technologies are not presently available, but will be presented at conference time.

Conclusion: SHM has a bright future in the wind turbine industry. Utilizing SHM could provide for lower maintenance costs and possibly provide additional revenue generation. However, much work remains to be done in the determination of what technologies are the best suited for turbine applications, and how to most effectively use the information that such devices produce to make decisions that impact turbine operation.

6933-15, Session 4

Integrated monitoring of wind plant systems

M. J. Whelan, K. D. Janoyan, T. Qiu, Clarkson Univ.

Wind power is a renewable source of energy that is quickly gaining acceptance by many. Advanced sensor technologies have currently focused solely on improving wind turbine rotor aerodynamics and increasing of the efficiency of the blade design and concentration. Alternatively, potential improvements in wind plant efficiency may be realized through reduction of reactionary losses of kinetic energy to the structural and substructural systems supporting the turbine mechanics. Investigation of the complete dynamic structural response of the wind plant is proposed using a large-scale, high-rate wireless sensor network. The wireless network enables sensors to be placed across the sizable structure, including the rotating blades, without consideration of cabling issues and the economic burden associated with large spools of measurement cables. A large array of multi-axis accelerometers is utilized to evaluate the modal properties of the system as well as individual members and would enable long-term

structural condition monitoring of the wind turbine as well. Additionally, environmental parameters, including wind speed, temperature, and humidity, are wirelessly collected for correlation. Such a wireless system could be integrated with electrical monitoring sensors and actuators and incorporated into a remote multi-turbine centralized plant monitoring and control system.

6933-16, Session 5

The rising demand for energy: a potential for optical fiber sensors in the monitoring sector

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In the past electric power was taken as a natural unlimited resource. With globalisation the demand for energy has risen. As a consequence, prices for fossil fuels as well as raw materials are rising. And a diversification of power generating sources can be observed. Besides the conventional fossil power plants nuclear plants are coming up again. Renewable energy sources are gaining in importance, resulting in a recent boom of wind energy plants in the US. In the past utility operators had a focus on reliability and availability and an extremely long lifetime of power components. Today cost and efficiency are coming into focus, due to the global competition and the high fuel costs. New designs of power components need increased efficiency by using lesser material. Higher efficiency causes inevitably higher stress on the materials, from which the machines are built. As operators do not accept a reduction of lifetime and maintenance costs are expected to be kept at a minimum, sensor systems are more and more used to monitor the condition of power components. This offers potentials for fibre optic sensor application.

6933-17, Session 5

On-line structural health and fire monitoring of a composite personal aircraft using an FBG sensing system

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Over the last few years, optical fiber sensors have seen an increased acceptance as well as a widespread use for structural sensing and monitoring in civil engineering, aerospace, marine, oil & gas, composites and smart structure applications. Optical Fiber Sensor Operation and Instrumentation have become well understood and Developed and a variety of commercial sensors and sensing systems are now readily available. However, their historical implementation and actual adoption in real life and commercial platforms has tended to be limited and slow moving.

In sharp contrast to this reality, we report in this paper on the design and development of a novel on-line structural health monitoring and fire detection system based on an array of optical fiber Bragg grating (FBG) sensors and interrogation system installed on a new, pre-commercial compact aircraft. A combined total of 28 FBG sensors-strain, temperature and high-temperature-were installed at critical locations in an around the wings, fuselage and engine compartment of a prototype, Comp Air CA 12 all-composite, 10 (ten) passenger personal airplane powered by a 1,650 hp turbine engine. The sensors are interrogated on-line and in real time by a swept laser FBG interrogator (Micron Optics sm125-700) mounted on board the plane. Sensors readings are then combined with the plane's avionics system and displayed on the pilot's aviation control panel.

This system represents the first of its kind in commercial, small frame, airplanes and a first for optical fiber sensors. Pertinent details on the sensor design, packaging, installation, data analysis and processing will be presented along with the experiences and lessons learned from this exciting application.

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6933-18, Session 5

Fiber Bragg grating sensor system for operational load monitoring of wind turbine blades

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A fibre Bragg grating sensor system has been installed in a horizontal axis wind turbine and was successfully tested for several years. We report the requirements, system design and realisation of the sensor system for continuous on-line load monitoring of the rotor blades, and provide examples of strain measurement results.

6933-19, Session 6

Wireless vibration monitoring for damage detection of highway bridges

M. J. Whelan, M. V. Gangone, K. D. Janoyan, R. Jha, Clarkson Univ.

The development of low-cost wireless sensor networks has resulted in resurgence in the development of ambient vibration monitoring methods to assess the in-service condition of highway bridges. However, a reliable approach towards assessing the health of an in-service bridge and identifying and localizing damage without a priori knowledge of the vibration response history has yet to be formulated. A two-part study is in progress to evaluate and develop existing and proposed damage detection schemes. The first phase utilizes a laboratory bridge model to investigate the vibration response characteristics induced through introduction of changes to structural members, connections, and support conditions. A second phase of the study will validate the damage detection methods developed from the laboratory testing with progressive damage testing of an in-service highway bridge scheduled for replacement. The laboratory bridge features a four meter span, one meter wide, steel frame with a steel deck composed of sheet layers to regulate mass loading and simulate deck wear. Bolted connections and elastomeric bearings provide a means for prescribing variable local stiffness and damping effects to the laboratory model. A wireless sensor network consisting of sixty accelerometers accommodated by thirty local nodes facilitates simultaneous, real-time and high-rate acquisition of the vibrations throughout the bridge structure. Measurement redundancy is provided by an array of wired linear displacement sensors as well as a scanning laser vibrometer. This paper presents the laboratory model and damage scenarios, a brief description of the developed wireless instrumentation, and an assessment of existing and proposed damage detection algorithms as applied to measurement histories acquired from the structure.

6933-19, Session 6

Field deployment of a dense wireless sensor network for condition assessment of a multispan bridge

M. V. Gangone, M. J. Whelan, K. D. Janoyan, R. Jha, Clarkson Univ.

With the increased demand placed on aging infrastructure, there is great interest in new condition assessment tools for bridges. The routine deterioration that bridges undergo causes a loss in the intended performance that, if undetected or unattended, can eventually lead to structural failure. Currently the primary method of bridge condition assessment involves a qualitative bridge inspection routine based on visual observations. Discussed in this paper are methods of in-situ quantitative bridge condition assessment using a dense wireless sensor array. At the core of the wireless system is an integrated network which collects data from a variety of sensors in real-time and provides analysis, assessment and decision-making tools. The advanced wireless sensor system, developed at Clarkson University for diagnostic bridge monitoring, provides independent conditioning for both accelerometers and strain transducers with high-rate wireless data transmission in a large-scale sensor network. Results from a field deployment of a dense wireless sensor network on a multi-span bridge located in New York State are presented. The field deployment and testing aid to quantify the current bridge response as well as demonstrate the ability of the system to perform both long and short term bridge monitoring and condition assessment.

6933-20, Session 6

Demonstration of a roving-host wireless sensor network for rapid assessment monitoring of structural health

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A major challenge impeding the deployment of wireless sensor networks for structural health monitoring (SHM) is developing means to supply power to the sensor nodes in a cost-effective manner. In this work an initial test of a roving-host wireless sensor network was performed on a bridge near Truth or Consequences, NM in August of 2007. The roving-host wireless sensor network features a radio controlled helicopter responsible for wirelessly delivering energy to sensor nodes on an "as-needed" basis. In addition, the helicopter also serves as a central data repository and processing center for the information collected by the sensor network. The sensor nodes used on the bridge were developed for measuring the peak displacement of the bridge, as well as measuring the preload of some of the bolted joints in the bridge. These sensors and sensor nodes were specifically designed to be able to operate from energy supplied wirelessly from the helicopter. The ultimate goal of this research is to ease the requirement for battery power supplies in wireless sensor networks.

6933-22, Session 6

Technique issues for wireless structural health monitoring of bridges

J. Su, Research Institute of Highway (China)

Recent advances in sensing, data acquisition, computing, communication, data and information management have made increasing application of structural health monitoring systems in bridges. Successful implementation and operation of structural health monitoring (SHM) on bridges have been reported worldwide. Structural health monitoring (SHM) is an active area of research devoted to systems that can autonomously and proactively assess the structural integrity of civil buildings. Structural monitoring systems using wireless sensors have the potential to serve as low-cost alternatives to commercially available cable-based monitoring systems. In this paper we discuss our deployment experiences and evaluate the performance of a multi-hop wireless data acquisition system for structural health monitoring (SHM) on bridges. At the same time, we analyze the designed issues such as clock synchronization, real time data transmission. Our experiments indicate that, with the latest sensor network hardware, our networks can reliably deliver time-synchronized vibration data across multiple hops within millisecond for sampling rates up to 350Hz. Findings from a field validation test, strong agreement is observed between the data collected by the wireless system and cable-based monitoring system.

6933-23, Session 7

Structural health monitoring of composite and concrete structures by using fiber optic sensors

J. Leng, Harbin Institute of Technology (China)

The structural health monitoring (SHM) in-service is very important and definitely demanded for safely working of high performance composite and concrete structures. More non-destructive evaluation (NDE) techniques have been developed in the past including ultrasonic scanning, acoustic emission (AE), shearography, stimulated infrared thermography (SIT), vibration testing, etc. However, The challenge is to develop new techniques which can perform the on-line structural health assessment started from manufacture of composite and concrete structures to the real service of these structures in field. It is very difficult to carry out by these methods. A unique method was provided to real-time monitor the structural health status by using fibre optic sensors.

Fibre optic sensors (FOSs) are very important sensors used in smart materials and structures because of their many advantages. In this paper,

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we have developed few fibre optic sensors including Fibre Bragg gratings, Extrinsic Fabry-Perot interferometer (EFPI), Fibre Optic AE sensors based on tapered fused coupler, Distributed temperature sensor based on chirped fibre Bragg grating, Multimode Fibre Optic Sensors, etc..

The application of those fibre optic sensors in composite and concrete structures from cure monitoring to non-destructive evaluation (NDE) are also been investigated. The results emerged that the fibre optic sensors have huge potential applications and will be widely used in the near future soon.

6933-24, Session 7

Strain measurement during stress rupture of composite over-wrapped pressure vessel with fiber Bragg gratings sensors

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Fiber optic bragg gratings were used to measure strain fields during Stress Rupture test of Kevlar Composite Over-Wrapped Pressure Vessels. The sensors were embedded under the over-wrapped attached to the liner released from the Kevlar and attached to the Kevlar released from the liner. Additional sensors (foil gages and fiber bragg gratings) were surface mounted on the Kevlar.

6933-25, Session 7

Research and development of impact damage detection system for airframe structures using optical fiber sensors

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The basic technologies of the damage detection system of composite structures were developed and demonstrated using a composite structure with embedded small-diameter optical fiber sensors by Authors in FY2002. In current R&D, the damage detection system consisting of composites installed optical fiber sensors and damage detection system is developed for practical airframe application. The system evaluation by using composite substructures is planned to proceed towards product. As the foremost tasks for the application, the durability of the damage detection system should be verified. In this study, to investigate the durability of embedded optical fibers and composites, cyclic loading tests are conducted by using CFRP coupon specimens and a CFRP skin-stringer panel with embedded small-diameter optical fibers.

6933-26, Session 7

Embedded distributed sensing network: integration considerations and findings

P. M. Rye, Univ. of California/San Diego

Integration of a structural health monitoring distributed network and sensing elements within fiber reinforced polymer composites poses many challenges not the least of which are mechanical and computational considerations.

Mechanical integrity of the composite is of utmost importance in the embedding of sensing and electronic elements within a fiber reinforced polymer composite. However, it still must be considered in the context of a competing concern - the ability to effectively determine the health of the composite. This conflict is exacerbated by fiber reinforced polymer composites' highly attenuating, dispersive, and anisotropic nature. Mechanical integrity demands fewer/smaller inclusions while the second constraint requires a high density of sensing elements. Mechanical investigations including modeling, bending and tensile fatigue have been performed on fiber reinforced polymer composites with inclusions of varying dimensions, mechanical properties, and lay-up strategies.

Assuming a satisfactory compromise is reached, the bandwidth requirement and processing demand of a dense sensor network lends

itself well to the idea of incorporating computation at the same scale.

Distributed processing with the sensors results in a decreased demand for bandwidth and less computational power needed at each node in what could be considered a parallel processing network. This has been implemented in the form of 8051 microcontrollers - chosen for their form factor - utilizing piezoelectric materials and some analog signal conditioning as sensors and actuators. Implemented algorithms, designed to take advantage of the physical layer, allow for analysis to occur in situ, reducing bandwidth demands to status queries and probing.

The distributed network, like traditional distributed systems, allows for the inclusion of heterogeneous components. This flexibility to use multiple sensors and sensing strategies minimally allows an adaptable need-based SHM network but potentially a more full bodied analysis of the health of the material.

Our sensing strategies and signal conditioning as well as our work on an embedded distributed sensing network design and computation will be discussed.

6933-28, Session 7

Chemical process monitoring and the detection of moisture ingress in composites

R. S. Mahendran, R. Chen, L. Wang, S. N. Kukureka, G. F. Fernando, The Univ. of Birmingham (United Kingdom)

It is generally appreciated that the ingress of moisture in composites can have adverse effects on the matrix dominated properties such as the glass transition temperature and compressive mechanical properties. Moisture ingress in composites can also lead to swelling and blistering. A number of excellent studies have been reported on the detection, modelling and effects of moisture ingress on the properties of thermosetting resins (matrix) and composites. However, it is generally taken for granted that the quality of the resin and the processing conditions used to cross-link the test specimens are identical. Given the recent advances in the design and deployment of optical fibre sensors in composites, it is now possible to use the same sensor to facilitate in-situ cure monitoring and structural health monitoring (after processing).

This paper will present recent developments in the design of low-cost fibre optic sensor systems for in-situ chemical process monitoring and the detection of moisture ingress after curing. The cure kinetics derived from three fibre optic sensor system is presented along with that obtained from evanescent wave spectroscopy using E-glass fibres.

After conducting the in-situ cure monitoring experiments, one of the fibre optic sensor designs was selected and the samples (with the embedded sensors) were dried to constant mass at 50°C and then transferred to water baths that were maintained at 70, 50, and 30 °C. The diffusion kinetics for the samples was determined using samples without and with embedded optical fibre sensors. The effect of moisture ingress in the resin was also assessed using dynamic mechanical thermal analysis (DMTA), transmission infrared spectroscopy (FTIR) and differential scanning calorimetry (DSC). Preliminary results are also presented to demonstrate that the reinforcing fibres in E-glass composites can be used to detect moisture ingress.

6933-44, Poster Session

Landslide monitoring using a road-embedded optical fiber sensor

M. R. Iten, A. Schmid, A. M. Puzrin, ETH Zürich (Switzerland)

Creeping landslides can cause immense problems when they occur in inhabited areas. They damage the infrastructure and buildings in the sliding area and lead to high maintenance costs. Additionally, local construction laws often enforce special construction and reinforcement requirements, or limit construction within a landslide area. Therefore, in some cases it is of a crucial importance to determine the exact position of the boundary between the landslide and the stable part of the slope. Geodetic measurements can mark this border, but not necessarily with high precision.

This paper is an attempt to outline a new landslide monitoring technique by means of continuous strain measurements in an optical fiber embedded

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into a road. This technique is based on a simple idea, that if a landslide boundary is intersected by a road, this road can be seen as a large scale strain gage, provided it is properly instrumented.

The creeping landslide, which has been monitored, is located in the heart of the renowned mountain resort town of St. Moritz, Switzerland. The displacements have been monitored by geodetic measurements techniques for over 100 years and, yet, its boundary has not been clearly defined. The road, Via Tinus, crosses the boundary between the stable and the instable part of the slope. Existing geodetic measurements indicated that the sliding takes place perpendicular to the road. No cracks have been observed in asphalt, indicating that the boundary shear zone is sufficiently wide for the asphalt to absorb deformations without cracking.

In 2006, a 90 meter long stretch of the road was instrumented by embedding a hand-coated optical fiber cable into a 7 cm deep and 1 cm wide trench cut in asphalt along one of the road boundaries. Strain measurements in the fiber are conducted by BOTDR technology using the commercially available DiTeSt unit from Omnisens. The strain in the fiber was first measured following the integration and again half a year later. A first estimate of the boundary was then performed. The estimated position of the boundary correlated well with the damage pattern in the surrounding buildings. Furthermore, the strain measurements suggested that the sliding occurs not perpendicular, as believed before, but at 45 degrees angle to the road, which was later also confirmed by the field observations. The measured strains values correlated well with the observed landslide displacements.

In mid-2007, the fiber in the road was found broken. In the meanwhile, two improved better protected custom strain fibers were developed in a joint project with a cable manufacturer. In August 2007 these two strain sensing fibers have been embedded into the road applying an enhanced but simple to handle integration technique. These novel strain sensors should produce first results by the spring 2008. At that point, it will be also possible to compare the two sensors with each other and discuss the possible variations and improvements in the integration techniques. The proof of serviceability for distributed fiber optic sensors in this kind of practical approach is the main motivation behind the current project.

6933-45, Poster Session

Health monitoring for subway station structure by fiber Bragg grating sensors

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Many structures, such as subway station structures, long span bridges, offshore structures, large dams and high building,

often have a long service period. These structures are inevitable to suffer from environmental corrosion, long term loading,

fatigue effects, material aging and their coupling effects. In the wake of the damage accumulation, performance of the structures will degenerate, and even leading to structure failures under extreme loadings. Therefore, the structural health monitoring (SHM) has become an important technology to study the characteristics and rules of structure damage and structure failure. Subways can effectively alleviate traffic congestion and have a great impact on urban livability. Beijing's subway has been

developing for 40 years with a total of 114 kilometers of track. At present, Nos. 4, 5 and 10 subway lines, which are being constructed, cover a total distance of 88 kilometers, the subway's construction speed is unprecedented in Beijing. The safety of the subway station structure and tunnel has been concerned very much by citizens and researchers. Guomao Station on No.10 subway line is at Guomao bridge, located in CBD, Beijing, China, which is an interchange station between No.1 and No.10 lines. Because it is under the Guomao bridge, and the structure is very close to the stakes of the Guomao bridge, for ensuring the safety of structures, it is necessary to monitor the structure in real time and obtain complete and precise structural information.

6933-46, Poster Session

A novel multifunctional optical fiber sensor based on FBG and fiber optic couple

T. Fu, Sr., Harbin Institute of Technology (China); C. Wang, T. Liu, Shandong Academy of Sciences (China); J. Leng, Harbin Institute of Technology (China)

With composite materials being used widely in aerospace engineering, national defense, civil industry and etc, monitoring the damage of them is more important regarded. The temperature and strain affect the damage of composite materials mostly. This paper introduces a novel multifunctional fiber sensor with two FBGs (measuring temperature and strain simultaneously) embed in composite materials and an over fiber optic coupler mounted on composite materials for structural health monitoring. Two FBGs with different wavelengths are abreast connected to an ordinary fiber optic coupler: One is encapsulated in glass capillary to measure temperature and not affected by strain, the other one is to measure temperature and strain. The other port of the later FBG is connected to the over fiber optic coupler, which is according to the shift of coupler ratio for structural health monitoring of composite materials.

Because the wavelength of FBG varies with temperature and strain simultaneously, it is pivotal to discriminate the variable of it caused by temperature and strain. The technique is designed for distinguishing strain and temperature to solve the cross sensitivity problem. The design of the novel sensor actualizes that every sensor section is integrated into one optical fiber system. According to the AE events, the temperature and strain in composite materials, location and failure mode of composite materials is identified.

6933-47, Poster Session

Photonic crystal fiber long-period gratings for structural monitoring and chemical sensing

J. Tang, National Chung Cheng Univ. (Taiwan); J. Wang, National Yunlin Univ. of Science and Technology (Taiwan)

Long-period gratings (LPGs) consist of a large-scale periodic axial perturbation in the refractive index of the core in a single mode fiber. The effect of this modulation is to couple the fundamental core mode and forward-propagating cladding modes at the resonance wavelength in an optical fiber. LPGs have widely been used in various telecommunications and sensing applications, offering several advantages such as low back reflection, low insertion loss, polarization independence, and ease of fabrication. Previous research mainly concentrated on LPGs inscribed in conventional single mode fibers. Recently, there have been considerable research efforts on formation of LPGs in photonic crystal fibers (PCFs) that consist of a pure silica core surrounded with a regular pattern of air-holes running along the length of the fiber axis. PCFs and PCF-based optoelectronic components have attracted great attention due to their unusual optical properties and potential applications in networks and sensors. It has been shown that photonic crystal fibers can be used for sensitive sensing of biomolecules, such as DNA or proteins. In addition, PCF has been demonstrated as compact, practical, and efficient sensors of gas-phase media and multifunctional sensor and sample collector.

In this paper, we present a simple, low-cost, temperature-insensitive PCF that can be used as sensitive chemical solution sensors or bend sensors for a variety of industrial applications, including civil engineering, aircraft and spacecraft, chemistry, and biosensing. Three different types of PCFs have been used for this study, including a polarization maintaining PCF, a large mode area PCF and an endlessly single mode PCF. The LPGs have been characterised for their sensitivity to temperature, strain, bending, and surrounding refractive index (including sucrose solution and chloride ion). Attenuation bands of the LPGs were found to possess negligible temperature and strain sensitivities, whilst exhibiting usable sensitivity to refractive index and bending. These experimental results suggest that LPGs fabricated in PCF could in principle be designed for optimum sensitivity to desired measurand(s), whilst minimising or removing undesirable cross-sensitivities. The temperature-insensitive LPGs sensors are of particular important for industrial health monitoring and chemical sensing in harsh environment, since one of the persistent problems of using LPGs as sensors is their cross-sensitivity to temperature and discriminatory schemes are

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required to be employed to separate the effect of temperature from the desired measurands. The unique sensing features of these spectral filters are particularly suited for a wide variety of applications in smart structures, embedded materials, telecommunications and sensor systems. The advantage of this type of the sensor is relatively simple of construction and ease of use. Moreover, the sensor has the potential capability for on-site, in vivo, and remote sensing, can be easily multiplexed to enable high-throughout screening of chemical reactions, and has the potential use for disposable sensors. Potential applications of this class of LPG sensors in environmental sensing (mainly for chemical solution concentrations and bending) will be presented.

6933-48, Poster Session

Development and application of 3D foot-shape measurement system under different loads

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3-D foot-shape measurement under different loads makes it possible to realize custom-made shoe-making and shows great prosperity in shoe design, foot orthopaedic treatment, shoe size standardization, and establishment of a feet database for consumers and athletes. The key techniques related to the measurement system, including structure design of a laser-line-scanning measurement system, globe calibration for CCD cameras and image processing, are of significant values and applications. The paper is focused on the study of the key techniques related to the system, both in theory and with experiments, based on the development of a 3-D foot -shape measurement system under different loads.

The 3-D foot-shape measurement system under different loads based on laser-line-scanning principle is designed and the model of the measurement system is developed. 3-D foot-shape measurements without blind areas under different loads and the automatic extraction of foot-parameter are achieved with the system including a motion unit, a load support and measurement unit, an image acquisition unit and the software for globe calibration, image processing and automatic extraction of 3-D foot parameters.

A global calibration method for CCD cameras using a one-axis motion unit in the measurement system and the specialized calibration kits, based on a nonlinear coordinate mapping function and the Powell optimized method is presented. Using one-axis motion unit of the system and the specialized calibration kits, calibration points in the laser-line-scanning system are generated. Errors caused by the installation of the one axis motion unit, the laser plane and the toughened glass can be eliminated by using the Powell optimized method, and the influences due to the nonlinearity of CCD cameras and other devices can also be eliminated by using the nonlinear coordinate mapping function.

A method for automatic extraction of foot parameters is proposed, which can realize an automatic foot longitudinal alignment. A local foot coordinate system is defined with a foot longitudinal axis plane, the pternion and the acropodion extracted from the boundary of foot projection below different levels and related sections. The characteristic points can thus be located and the foot parameters be extracted automatically through the local foot coordinate system and the related sections. The measurement system can be used in measurements for mass production.

Foot measurements under different loads for 170 participants were conducted and the statistic foot parameter measurement results for male and female participants under non-weight condition and changes of foot parameters under half-body-weight condition, full-body-weight condition and over-body-weight condition compared with non-weight condition were presented.

6933-49, Poster Session

Mobile Bluetooth sensor node based on embedded arm-linux

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This paper introduces a design of mobile Bluetooth sensor node by using robot. The robot is composed of a micro processor module based on

AT91RM9200, Bluetooth module, wireless network card, GPS module and a mobile base. We adopt TCP protocol to ensure a secure transmission between robot and the control center. Robot can apperceive environment around across collecting information of the motionless Bluetooth sensor nodes, which are around it. It can receive command from the control center, and then execute the command moving to the sit that the command specified, and gather the information of the motionless Bluetooth sensor nodes. It fuses the data and sends to the control center. If robot can not find any Bluetooth sensor node when it arrives at the sit, it will move around the sit within a cycle with 10 meter radius to search Bluetooth sensor nodes. If it still can not find any Bluetooth sensor node, the conclusion can be obtained that there is no Bluetooth sensor node. It will feed back the conclusion to the control center. Otherwise it will connect the all Bluetooth sensor nodes that are found, and gather information of them transmitting to control center.

Because robot does not know the location of itself, we use GPS to locating the robot. As we know, the range that robot moves around is very small comparing with the whole earth. So we take the range as a plane in a rectangular coordinates system. In our experiment we take the longitude as y axis and woof as x axis. This means once the origin is fixed, we can easily calculate the relative coordinates when we get the GPS data of the origin and another location. When robot moves, we also use GPS data to confirm the direction that it goes forward. Experiments prove that robot can reach the sit with an error less than 3 meters by the way.

In this paper, the robot must have the ability to control movement, communicate with control center and other robots, locate itself, search Bluetooth sensor nodes and collect information of the motionless Bluetooth sensor nodes at the same time. So we transplant the open source operate system arm-linux, to the robot. Multithreading program based on arm-linux operate system can make robot to do several things at the same time. Since robots are mobile nodes, static route protocol does not suit this situation. They need a dynamic route to provide an available route. We transplant the ad hoc wireless route protocol aodv-uu to the robot and control center, and make them to compose an ad hoc WLAN. So that robots and control center are always in a local network, and communicate through it.

Experiments show that the communication between Bluetooth sensor networks and ad hoc WLAN which is composed of robots and control center is reliable, and the robot can work stably. But the bandwidth and the scheduling of robot should be improved.

6933-50, Poster Session

Comparison of the piezoelectric MEMS generators with interdigital electrodes and laminated electrodes

W. Wu, B. Lee, National Taiwan Univ. (Taiwan)

To power the tiny sensor devices by MEMS generator which scavenging energy from ambient vibrations is becoming practical due to the power consumption of low power electronics is going down to tens to hundreds μ W for integrated wireless sensor devices. In this paper, we are going to present the development on two different types of piezoelectric MEMS generators that have the ability to scavenge mechanical energy of ambient vibrations and transform it into electrical energy. These two piezoelectric MEMS generators are both cantilever type made of silicon process and transform energy with thin PZT layer. However, the first one is with the interdigital electrodes on the top and The other one is with laminated electrodes sandwiched the PZT layer. The theoretical conduction, numerical simulation and also the process development for the two types of generators will all be conducted, the evaluation and comparison of the two generators will also be detailed.

6933-29, Session 8

Aircraft structural health monitoring using on-board BOCDA system

T. Yari, M. Ishioka, K. Nagai, Mitsubishi Heavy Industries, Ltd. (Japan); S. Adachi, Yokogawa Electric Corp. (Japan); Y. Koshioka, RIMCOF (Japan)

In recent years, the demanding for reducing operational costs of commercial airplane is growing. Since aircraft structural health monitoring

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(SHM) technologies has the potential of reducing maintenance costs and maintenance downtime, the practical application of SHM technologies is starting to garner attention. At the commercial aircraft, since inspection portions spread across a wide area, the distributed optical fiber sensor fits the health monitoring for these application. Measuring systems using the Brillouin scattering light is able to measure wide area distributed strain, and many studies were conducted. A Brillouin optical time domain reflectometer (BOTDR) is popular method, but the BOTDR has low spatial resolution and long measurement interval. These performances were limited to application for airplane SHM system. Then, the authors have proposed the Brillouin optical correlation modulation analysis (BOCDA) method for improvement of the spatial resolution and measuring interval. In the former activities, the measuring accuracy is not enough to our target because of the Brillouin scattering light comes under the influence of the polarization state at optical fiber sensor (OFS).

In this study, we manufactured the prototype on-board BOCDA system and verified the robustness of disturbance at OFS. The prototype BOCDA system adopted the polarization diversity technique and temporal gating technique to improve robustness of the BOCDA system. We successfully measured distribution of fiber Brillouin gain spectrum over 500m measurement range with 50mm spatial resolution, 10Hz sampling rate and $\pm 131/4$ strain accuracy. Furthermore, we considered substructure test and flight demonstration test to verify the validity of BOCDA sensing system. From these results, it was confirmed that BOCDA system has potential to be applied to an aircraft structure health monitoring system.

6933-30, Session 8

Distributed fiber optic sensor system for dike monitoring using Brillouin optical frequency domain analysis

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We report on the development of an optical fiber sensor for distributed detection of critical soil displacement in river embankments. Our research covers the measurement unit, the sensing fiber and its coating as well as the embedding of the sensors into the soil body of river dikes.

In the measurement unit, the distribution of mechanical strain along a silica optical fiber is recorded by means of Stimulated Brillouin Scattering (SBS). To obtain a spatially resolved strain profile of the sensing fiber, Brillouin optical frequency domain analysis (BOFDA) is used. This approach performs measurements of the SBS requiring a much smaller bandwidth than systems working in the time domain (BOTDR). This holds advantages in cost efficiency over the commercially available BOTDR devices. We have successfully dealt with known issues such as dead zones due to birefringence and numerical enhancement of the recorded Brillouin gain spectra, as can be seen in the measurement results.

We will show that a defined strain profile, applied to a single-mode optical fiber, can be recorded by our measurement setup with a spatial resolution smaller than 5 m. This resolution corresponds to the minimum requirement for early detection and localization of threatening failure in river dikes and dams.

A special fiber coating is being developed to protect the sensing fiber while maintaining its sensitivity and fixation. The coated fiber is integrated into geosynthetics as they are commonly used for dike construction. These geosynthetics are embedded into the soil to serve as carrier structures for the sensing fibers while they still perform their original tasks as drainage or reinforcement. In-situ OTDR measurements during dike construction have been performed to evaluate different approaches on protective coating of the sensing fibers.

The BOFDA system has been tested in various model experiments as well as field tests. To our knowledge, these are the first in-situ measurements performed with a BOFDA system.

The results of these tests also serve to quantify the transfer of an occurring soil displacement into lateral strain of the optical fiber. In these tests, the mechanical interaction between the soil, the geosynthetics, the coating material and the sensing fiber itself has been investigated. The results show that a local slope break in the dimension of 2 m, simulated by inflating a lifting bag inside the soil body of a dike, can be detected by our system.

6933-31, Session 8

Experimental investigation of RC beams using BOTDA®-FRP-OF sensors

Z. Zhou, Harbin Institute of Technology (China)

Brillouin based fiber optic sensing turns to be a promising technology for Structural Health Monitoring (SHM). However, the bare optical fiber is too fragile to act as a practical sensor, so high durability and large gauge Brillouin distributed sensors are urgently in great needs in field applications. For this reason, high durability and large gauge fiber optic Brillouin Optical Time Domain Analysis (Reflectometer) sensors packaged by Fiber Reinforcement Polymer (FRP), named BOTDA®-FRP-OF, have been developed and tested by the dead load test. Besides, in order to study the large strain, crack and slip between the rebars and concrete in RC beam using BOTDR(A) technique, five RC Beams installed with BOTDA®-FRP-OF sensors have been set up. And the damage characteristics of the RC beams were investigated by comparing the strain measured by the BOTDA®-FRP-OF sensors and the strain measured by traditional strain gauges and FBG(Fiber Bragg Grating) sensors. The test results show that the BOTDA®-FRP-OF sensor can effectively detect the damage characteristic of RC beam, and suitable for the long-term structural health monitoring on concrete structures such as bridge, big dam and so on. Furthermore, this novel high durability, large-gauge sensors have been successfully applied to the civil defense projects in Guangzhou Province in China for long-term strain monitoring.

6933-32, Session 9

Smart technical textiles with integrated POF sensors

K. Krebber, Bundesanstalt für Materialforschung und -prüfung (Germany)

Invited paper: We will discuss the application of technical textiles such as geo-textiles and medical textiles with integrated POF for monitoring of geo-technical structures and for medical purposes, as well as our first trials to integrate POF in composites for the structural health monitoring.

6933-33, Session 9

Polymer in-fiber interferometer for large strain measurements

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Previous researchers have applied multimode POFs for the detection of cracks or the change in dynamic response of a structure by interrogating the intensity of lightwaves propagated through the POF. These measurements, while successful, are limited in application due to the presence of multiple modes and the lack of detailed, quantitative knowledge on the opto-mechanical response of the POF. Recent advances in the fabrication of singlemode POFs have made it possible to extend POFs to interferometric sensor capabilities. However, several challenges make the application of the POF interferometer more difficult than its silica counterpart at high strain magnitudes: the finite deformation of the POF, nonlinear strain optic effects, attenuation with strain.

This paper describes the recent demonstration of phase-shift measurements within a single-mode POF up to 15.8% nominal strain. The phase-shift sensitivity of the POF was interrogated through a Mach-Zehnder interferometer configuration with unbalanced sensor and reference arms to account for the high attenuation of the POF. The phase-shift sensitivity was measured to be 1.39×10^7 rad/m for this strain range. This strain range is well beyond the yield strain of the POF and that previously measured for intrinsic optical fiber sensors. The results of these phase-shift measurements were then combined with previous mechanical testing of the single-mode POFs to develop a nonlinear, opto-mechanical response calibration of the in-fiber interferometer covering both the small and large strain ranges. The effects of nonlinear photo-elastic parameters and finite deformation are included to second-order in strain. Finally, trials for the preparation of the POF end-faces for coupling with conventional silica optical fiber sensor interrogation systems are presented.

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6933-34, Session 9

Finite element formulation for self-writing of polymer optical fiber sensors

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Several alternative fabrication methods for optical fiber sensors have recently been demonstrated including micro-machining, surface relief etching and self-writing of photopolymerizable resins. In this paper, a multi-physics finite element model of sensor self-generation through optical confinement in a photopolymerizable gel is presented that accounts for the dynamics of photopolymerization, and the opto-mechanical interactions of densification, residual strains, and strain-optic effects. The model is then applied to predict the geometry and index distribution of a micro-optical fiber sensor.

In the self-writing process pulsed UV or near IR light is focused into a liquid or gel solution of photopolymerizable resin. The resin area at the light entrance is above the optical intensity threshold for photopolymerization and begins to polymerize, increasing the local index of refraction. This new polymerized resin then acts as an optical fiber waveguide since its index of refraction is higher than that of the surrounding resin, guiding the focused light until the end of the polymerized segment. The resin at the end of this segment is then polymerized by the same process. In this manner, an optical fiber waveguide self-constructs across the resin bath with a diameter of a few micrometers. The index of refraction change between the unpolymerized and polymerized resin is permanent and typically much larger than that in a standard optical fiber, resulting in much higher confinement of the propagating light in the waveguide. The important parameters in fabricating a self-writing sensor are the optical intensity of the laser source, the pulse duration and the numerical aperture of the phase mask used to focus the light in a diffraction pattern on the resin. An optimal combination of the three produces a single, well-resolved waveguide, whereas a suboptimal combination produces multiple or even chaotic waveguide self-formation. It is also important to include the shrinkage resulting from localized density changes during the photopolymerization process.

Two critical parameters are experimentally determined to characterize the dynamics of the particular photopolymerizable resin used as inputs for the finite element model. These are the index of refraction and the material density of the photopolymerizable gel as a function of optical intensity and time. For this work, these are measured through a modified version of the double interferometer technique. As the optical path length is affected both by the change in index of refraction and thickness of an optical medium and these changes are of the same order of magnitude during photopolymerization, neither can be neglected.

6933-35, Session 10

POF strain sensor using phase measurement techniques

H. Poisel, Georg-Simon-Ohm-Fachhochschule Nürnberg (Germany)

As a low-cost alternative to FBG sensors targeting the lower sensitivity range, POF elongation sensors have been proposed. A recently recovered detection system known from laser distance meters turned out to be very sensitive while staying simple. The approach is based on measuring the phase shift of a sinusoidally modulated light signal guided in a POF under different tensions resulting in different transit times. Temperature effects will be cancelled by using 2 fibers. These sensors are thought to be implemented in structures like rotor blades of a wind power generator, aircraft wings, or structures in general, which have to be monitored for their integrity (structural health monitoring).

Transmitters and receivers have been directly adopted from POF data transmission systems developed for Gbps applications. Thus activities in one area generate opportunities in another one.

6933-36, Session 10

Ultrasonic structural health monitoring: strategies, issues, and progress

J. E. Michaels, Georgia Institute of Technology

Several quite different strategies are being considered for ultrasonic structural health monitoring systems. The acousto-ultrasonic nondestructive

evaluation method has led to the use of long-time, reverberating waves which "fill" a structure and hence cover large areas. Guided wave techniques for monitoring plate-like structures have probably generated the most interest; these methods also have the potential of covering large areas with a low sensor density. Local methods based upon either bulk or guided waves have been considered for monitoring known "hot spots" such as fastener holes and critical bonds. Each of these strategies has associated issues involving implementation, sensitivity and interpretation, with one common theme being the usually adverse effects of benign environmental changes. Three examples are presented here which illustrate key issues and show progress which has been made, mainly in the context of aerospace applications. First, reverberating diffuse-like waves are used for detection of damage in components for which guided waves are not viable. A combination of temperature compensation, feature analysis and data fusion methods are applied to discriminate damage from benign environmental changes. Second, guided waves are used for damage detection and localization in plate-like structures via a spatially distributed array of sensors. Temperature compensation is applied as a preprocessing step to enable damage detection via feature analysis and localization of discrete damage via several algorithms. Third, a high frequency (10 MHz) angle beam shear wave method is used to monitor cracks originating from fastener holes. Dynamic applied loads provide nonlinear modulation of the ultrasonic energy which enables cracks to be both detected and sized. Progress and problems thus far with utilizing these different methods show both the promise of ultrasonic structural health monitoring and the challenges of taking it from the laboratory to deployed systems.

6933-37, Session 10

Video-based monitoring of structural damage: a case study on concrete surface cracks

Z. Chen, T. C. Hutchinson, Univ. of California/San Diego

Nondestructive image-based methods have been widely used and have become one of the most effective and direct approaches to structural damage detection in the engineering community. However, monitoring time-varying structural damage, which demands the use of a time series of images and spatial-temporal image analysis, is still considered a challenging problem. In this paper, the development of cracks on the surface of concrete structural components is monitored using video data. In civil engineering, the detection of concrete cracks is an essential component in state evaluation of in-service structures. Past research has shown that if it is known a priori that a surface crack has occurred, then either low-level image analysis methods, such as edge detectors, or advanced contour-based approaches may be used to characterize the crack within a single image. However, without human intervention, the practical question arises: has a crack formed? If these critical moments of crack damage occurrence are determined, the aforementioned static image analysis-based crack detection methods may be used. Answering this question is now crucial to acquiring chronological characteristics of the time-varying structural damage and performing the analysis on the video images.

In the first step of our treatment, we solve this monitoring problem by a manifold learning approach. Between a bi-temporal pair of images in video data, it is assumed that only rigid body motions take place, i.e. vertical and horizontal translation, and rotation in 2D domain. By applying these rigid-motion quantities as physical constraints, a learning procedure is used to seek an optimal path across a three-dimensional manifold subspace. A first-order approach based on the use of tangent vectors is considered in our study by taking advantage of the fact that the motion quantities to be recovered between adjacent image frames are small. With the availability of these recovered rigid body motion quantities, which are used to align adjacent image frames, monitoring the occurrence of concrete cracks becomes a traditional change detection problem, which comprises the second step. These narrow elongated cracks with topographically arbitrary curvatures in images have high-frequency content; thus, orthogonal wavelet transform is conducted on the differencing image obtained by subtraction between registered adjacent image frames. A crack occurrence signature (COS) is defined by the summed squared wavelet coefficients in the high-frequency wavelet frames and is used as an indicator of incipient or growing crack occurrences.

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Numerical analyses are conducted in this paper with the use of two image video clips, which were respectively captured from two laboratory experiments. For example, one video clip is obtained from the region of a cyclically loaded beam component within a beam-column joint experiment. With the proposed methodology, the time varying COS's are computed and successfully reveal the extent of chronological crack propagation. This evaluation using physical data demonstrates that the manifold-based approach in conjunction with wavelet analysis is successful for on-line monitoring of concrete (crack) damage.

6933-38, Session 11

Applications of optical fiber sensors of SHM in infrastructures

J. Ou, Z. Zhou, Harbin Institute of Technology (China)

Fiber optical (FO) sensors, especially fiber Bragg grating (FBG) sensors, have been considered as prominent high-durable local monitoring sensors and largely applied in structural health monitoring (SHM). However, it is still a big problem how to develop the feasible optical fiber sensors to fully meet the practical SHM for infrastructures. In this paper, some recent advances of fiber optical sensors developed and applied in bridge monitoring in mainland China, especially in Harbin Institute of Technology, are introduced. The main content include direct FBG-based sensors, indirect FBG-based sensors, FBG based smart structures, and their implementations in over 10 practical case studies of bridge monitoring, which include Yonghe River Bridge in Tianjin, Binzhou and Dongying Yellow River Bridges and Province, Songhua River Bridge, Hulan River bridge and NiutouShan bridge in Heilongjiang Province, Nanjing third Yangtze river Bridge, Maocaojie Bridge in Hunan Province, Erbian bridge in Sichuan and Guangyangdao Bridge in Chongqing, etc. Finally, some directions of researches and applications have been recommended. Researches and practical applications show that FBG sensors are becoming one of the key sensors in long-term SHM instead of some conventional electrical sensors.

6933-39, Session 11

FBG-based intelligent monitoring system of the Tianjin Yonghe Bridge

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FBG has been regarded as one of the most effective sensors for long term structural health monitoring of infrastructures under harsh environments. In this paper, techniques of FBG sensors installation have been explored, and 40 FBG strain sensors, 10 FBG temperature sensors and 96 FRP-OFBG based smart cable sensors have been successfully installed on Yonghe Bridge. Concrete strain change and cables force increments have been monitored during bridge static test with FBG sensors. After the bridge finished, the strain course under traffic load and temperature changes of the bridge were monitored with these sensors. The monitoring results show that traffic fluxes and possible fatigue damages can be monitored conveniently by FBG sensors, and information can be provided for structural health diagnosis. The monitoring system has withstood the ordeal for more than 6 months. It shows that the FBG sensing technology can meet the demand of long-term sound monitoring of the bridge in the respects of stability and durability. Furthermore, its performance is obviously superior to that of the traditional electronic sensing technology.

6933-40, Session 11

Permanent and remote monitoring of large ships with optical fiber sensors

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A real-time measurement system was developed for the monitoring of stress on ships hulls. This system represents a big improvement over the currently used theoretical structural health calculation programs, such as the loading instrument, which do not provide reliable data on the real ship's hull condition. Thanks to instrumentation, it is possible to regularly obtain measurements and reports on the stresses to which the ship is subjected, due to heat expansion and contraction, torsion, uneven loading, wind and

wave impact, storm damage, collisions, and groundings.

The system is based on a network of Fiber Bragg Grating (FBG) sensors, derived from applications in civil fields and packaged to make them extremely rugged and adapted for installation in the harshest of environments, including explosion safety areas and below water or oil.

A pilot project featuring a complete hull monitoring system with 70 sensors has been installed on an oil tanker belonging to a major Italian shipping company. The tanker is double-hull, 234 meters long and displaces 96'000 tons. The monitoring system is able to acquire data at 0.5 Hz frequency, analyze it in real time and store significant statistical parameters in the on-board database. A user interface is provided for the crew and data is made available remotely to the owner and other authorized users.

6933-42, Session 11

Research and development of smart GFRP-OFBG-based steel strand and its application in monitoring of prestress loss for RC structures

Z. Zhou, H. Zhou, Harbin Institute of Technology (China)

The technologies of long term monitoring for the press condition of steel strand, and load of steel wire bundle and especially the prestress losses of prestressed structures is in a great need. In order to cope with these problems, based on the techniques of smart GFRP-OFBG composite bars, a new kind of quasi-distributed smart steel strand has been developed in this paper. And its tensile test and destructive experiment have been conducted. The results show that the linearity and the repeatability of the new smart steel strand are good. And it can stand the maximum elongation of the steel wire of the strand. Furthermore, the monitoring results can reflect the discipline for the stress loss of anchorage and duct friction. Compared with vibrating wire sensors, the error of smart steel strand monitoring is less than 5%. All in all, the new kind of smart GFRP-OFBG steel strand has a broad and bright foreground in steel strand and prestressing construction.

6933-43, Session 11

Torque sensing using rolled galfenol patches

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Magnetostrictive iron-gallium alloys called Galfenol exhibit behaviors desirable for sensor applications [1]. Galfenol exhibits moderate magnetostriction under low magnetic fields, very low hysteresis, high tensile strength, and is easily machinable [2]. Additionally, it has nominal raw material costs and preliminary results indicate it is corrosion resistant and properties that do not degrade over time [3]. Typically, magnetostrictive sensors either have large magnetostriction but are brittle or have large ductility but have low sensitivity. Metglas remedies this problem, however, over time its loss in anisotropy and magnetostriction adversely affects its sensing. Galfenol is potentially the best solution for magnetostrictive sensors. Datta and Flatau [4] show the promise of using single crystal Galfenol as a sensor used in static and dynamic bending. Na and Flatau [5] rolled less expensive polycrystalline Galfenol into thin sheets. In this study, polycrystalline-rolled and field annealed Galfenol are used to measure torque. Rolled Galfenol patches are bonded to rods of differing materials. The patches are placed with their oriented along lines of tension and compression on the rod (+45 or -45 degrees with respect to the rod axis). The patches are made from rolled sheets of Galfenol. The sheets are first hot rolled at 1000C and then texture annealed. Small patches are then cut from the rolled sheet and field annealed to orient the magnetic domains and eliminate the need of a bias magnetic field. A torque is applied to the rod which produces a stress in the patch. The stress results in a magnetic flux change that is sensed using a Hall sensor (and GMR for comparison). The torque is then calculated based on the voltage output of the Hall sensor. The torque measuring capabilities of the galfenol patches are compared by varying several parameters. The parameters are the Galfenol composition, magnetic field sensor (Hall, GMR, etc), patch geometry including rolling thickness, field annealing condition, and variation of bias field. The rolled galfenol patches show great promise in torque sensing applications.1. A. Clark, J. Restori-É, M. Wun-Fogle, T. Lograsso, D. Schlager, C.

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6934-01, Session 1

Damage detection of laminated composite beams with progressive wavelet transform

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Structural health monitoring (SHM) and damage detection of composite materials has steadily gained interest during the last few years, due to increasing use of composites in various engineering fields, ranging from aerospace to civil infrastructure. An immediate need exists to develop effective damage detection algorithms to extract damage information from the measured data. For dynamics-based SHM techniques, one of the most crucial issues is to identify damage information from structural dynamic responses (e.g., mode shapes) which are contaminated by background and random noises. Wavelet transform has been employed to extract damage information from the dynamic mode shapes of composite structures. However, almost all the existing studies demonstrated that the wavelet transform is only capable of identifying relatively large-size of damage under a higher signal-to-noise ratio. How to identify incipient or minor damage under a relatively lower signal-to-noise ratio is still a challenge and of significance, since incipient or minor damage may lead to catastrophic consequence.

In this study, an innovative damage detection algorithm of applying the wavelet transform to identify incipient damage is proposed, and the complementary advantages of stationary discrete wavelet transform (SWT) and continuous wavelet transform (CWT) are fully explored in developing damage detection strategy. The damage detection algorithm essentially consists of two progressive steps: (1) the excellent localized property of SWT derived from the multiresolution analysis of discrete wavelet transform is used to perform subspace separation for the retrieved mode shape, and an informative subspace (i.e., scale sub-mode) is then extracted by a minimum entropy criterion from collective subspaces. This particular subspace (scale sub-mode) carries useful damage information due to the effective elimination of interferences of background and random noises; and (2) the excellent properties of smoothness and derivatives of CWT are used to identify the abnormality in the extracted subspace (scale sub-mode), and the identified abnormality relates to the damage in a more intuitive and quantitative way.

As an application, the proposed algorithm is implemented to detect various types of damage (e.g., crack, delamination, and impact damage) in laminated composite beams. The damage detection algorithm is first thoroughly evaluated using the data from the analytical solution of a cracked composite laminated beam. It is then confirmed by numerical finite element analysis of laminated composite beams with various types of damage. An experimental program using smart piezoelectric sensors/actuators is conducted to extract the curvature mode shapes of damaged composite laminated beams, for which the proposed algorithm is applied to extract the damage information. The proposed damage detection algorithm using progressive wavelet transform technique manifests the damage, and it provides an effective and viable strategy to detect incipient or minor damage in composite structures under a relatively lower signal-to-noise ratio environment.

6934-02, Session 1

Inspection of impact-induced shock waves in carbon fiber composites using shearographic interferometry

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During the past years the use of carbon fiber reinforced plastics (CFRP) in the aircraft manufacturing has increased continually. These materials are interesting for reason of their excellent mechanical properties with high strength and stiffness at low weight. But due to high motion speeds they

are exposed to damage by impacts caused e.g. by stones, birds or hail. The knowledge of the material load during and shortly after an impact and the mechanisms of wave propagation inside the component is important for the development of an 'impact load monitoring system'. Due to the anisotropic properties of CFRP composites the damage tolerances and failure limits especially in the dynamical case are not well known.

In earlier works we demonstrated the possibility of displaying impact generated lamb waves with digital double pulse holography. The lamb waves have been generated by an air driven steel ball. The experimental outcomes were in good agreement with theoretical FEM results. Never less, covering the entire wave field failed, only the first outgoing wave fronts were detectable.

In this paper we present a digital shearing interferometer that covers the entire of the impact generated wavefield. Shearography is a laser based technique for full field measurements. It displays the first order derivatives of the displacement. The method is based on the digital correlation of two speckled wavefronts representing two states of the object, in our case before and shortly after the impact. By shearing the wavefront scattered from the illuminated object surface, one of both wavefronts serves as the reference for the other. The interferometer with a shearing element is placed in front of the camera. Consequently the camera sees the usual and a sheared speckle image of the object. These two images interfere on the sensor area and result in another speckle field, which carries the interferometrically sensitive object information. After the impact, the new speckle distribution which appears now on the detector will be compared with the first one. By using a phase-shifting method, the shearogram will be transformed into a phase value distribution.

In a dynamic process like this, the temporal phase shifting method is not practicable. Therefore, to evaluate the impact induced wavefield the spatial carrier phase shifting technique is used.

With the Mach-Zehnder Interferometer both, the spatial carrier method and the shearing can be realized. The optical setup consists of two beam splitter and two mirrors. It splits the reflected wave front into two and recombines both behind the second beamsplitter. By tilting either one of the mirrors a spatial carrier frequency is generated. By translating the other mirror a shear between both wavefronts is introduced.

We describe the optical setup of the Mach-Zehnder Shear interferometer and present the experimental results and the possibility to gain the out of plane displacement. Therefore the underlying wavefield is reconstructed from the first order derivatives measured. The experimental results will be compared with FEM simulation.

6934-03, Session 1

Electrical resistance change method for delamination monitoring of CFRP plates: effect of plate scale

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Carbon-Fiber-Reinforced-Polymer (CFRP) laminates are applied to many aerospace structures. Since the delamination is invisible or difficult to detect visually, the delamination causes low reliability for primary structures. To improve the low reliability, smart systems of delamination identifications in-service are desired. A structural health monitoring system to monitor the delamination is one of the desired approaches. Recently, an Electrical Resistance Change Method (ERCM) is employed to detect the internal damages of CFRP laminates by many researchers. The ERCM does not require expensive instruments. Since the method adopts reinforcement carbon fibers themselves as sensors, this method does not cause reduction of strength, and it is applicable to existing CFRP structures. For delamination monitoring by means of ERCM, multiple electrodes are mounted on the single surface of the specimen to measure electrical resistance changes caused by delamination. The method of arranging electrodes on surface of plates is very important to detect the location or dimension of delamination.

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Author's group suggests a newly developed matrix array of electrodes to measure electrical voltage change with two-way electrical application (matrix-arrayed electrodes method) while Anderson's group proposes circularly placed multiple electrodes on the outer circumferential surface of the CFRP plate (circular array method). Both of the methods use electrical voltage changes caused by delamination at each electrode. From a large number of experiments, a relationship between measured electrical voltage changes and delamination locations or dimensions are obtained by means of response surface with the least squared errors method. Once the relationship is obtained, locations or dimensions of delaminations are estimated from measured electrical voltage changes by response surface. In the previous studies, these methods were conducted using only small CFRP plates. In the present research, the effect of the CFRP plate scale on electrical voltage changes using both matrix array method and circular array method is investigated by means of 3-D FEM analysis.

In this paper, to investigate the effect of the plate scale on electrical voltage changes, 3-D FEM analyses are performed. Electrical voltage changes at each electrode caused by delamination are calculated for small plate model (150mm_150mm_1.6mm) and large plate model (1000mm_1000mm_1.6mm). Both matrix array method and circular array model are adopted for comparison. In matrix array model, arrangement of electrodes on large plate is identical to small one. On the other hand, all electrodes are placed on the plate surface along with the edges in spite of plate scale in circular array model.

FEM analysis results show that the scale of plate does not have effect on electrical voltage changes when matrix array model is adopted, while electrical voltage changes aren't observed when circular array model is adopted. Relationship between electrical voltage changes and information of delamination could be obtained from experiments or FEM analyses using only small plates by means of matrix array method, and it is applicable to large CFRP structures. Applicability of electrical voltage change method using matrix array method for delamination monitoring for large CFRP structures is confirmed.

6934-04, Session 1

Detecting damage in full-scale honeycomb sandwich composite fuselage panels through frequency response

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Tests were conducted to evaluate the frequency response characteristics of damaged honeycomb sandwich panels using a wide band piezo-electric transmitter and receiver. The objective of this evaluation was to correlate this method with other methods of detecting damage in sandwich panels. This evaluation is part of a study investigating the damage-tolerant characteristics of several honeycomb sandwich composite curved aircraft fuselage panels subjected to quasi-static pressurization and axial loading. The evaluation was conducted using the Full-Scale Aircraft Structural Test Evaluation and Research (FASTER) facility located at the Federal Aviation Administration William J. Hughes Technical Center in Atlantic City, NJ. The overall program objective is to investigate the effects of holes and notches on the residual strength of full-scale composite curved aircraft fuselage panels and the evolution of damage under quasi-static loading up to failure.

Background:

The sandwich structural configuration in a typical airframe experiences a combination of in-plane loads, and damaged regions may experience localized out-of-plane bending and bulging due to pressurization loading. The FASTER fixture is capable of testing full-scale fuselage panel specimens under conditions representative of those seen by an aircraft in actual operation. Two curved panels were tested, each containing a 10-inch-long notch located at its center. The sandwich test articles are made of a Toray T700SC-12K-50C/#2510 plain weave carbon fabric prepreg for the facesheets and a Plascore PN2-3/16-3.0 Nomex honeycomb of 0.75_ thick for the core, reflecting a typical general aviation aircraft fuselage structure.

The frequency response technique applied in this study is based on the introduction of constant-amplitude sinusoidal waves of continuously varying frequencies (100-400 kHz of 0.1 msec duration) through a wide-

band piezo-electric transmitter and measuring the frequency response of the panel through a similar receiver located a distance away. The initiation, progression, and accumulation of the internal damage in the sandwich panel (e.g., matrix cracks, delamination, fiber breakage, and disbonding between the core and facesheet) results in changes in the frequency response of the panel in terms of shift in the dominant frequencies, amplitude attenuation, and decrease in the area under the response curve.

The results indicate that damage initiation markedly affects the frequency response of the panel. Specifically, the transmitted amplitude is highly sensitive to the presence of internal damage, decreasing rapidly on the occurrence of damage at the notch tip. Further, scanning the panel with the transmitter/receiver pair enabled the detection of material inhomogeneities such as internal disbonding. Baseline calibration study indicates that the frequency response records are highly sensitive to the transmitter/receiver distance and to the orientation of the composite lay-up relative to their position.

The frequency response results were correlated with the acoustic emission generated during loading, showing that the changes in the panel's frequency response are as sensitive. The frequency response results were also correlated with the measured deformation and strain fields through digital image correlation. Particular emphasis was given to the intensity of the strain field and the frequency response of the panel in the vicinity of the notch tips.

6934-05, Session 1

Self-monitoring fiber-reinforced polymer strengthening system for civil engineering infrastructure

G. Jiang, M. Dawood, K. J. Peters, S. H. Rizkalla, North Carolina State Univ.

Fiber reinforced polymer (FRP) materials are currently used for strengthening civil engineering infrastructures due to their high strength to weight ratio, corrosion resistance and easier installation for field applications. They are typically used to increase the flexural and shear capacity of structures by externally bonding sheets or plates to the tension zones of structural elements. The effectiveness of the strengthening system is highly dependant on the bond characteristics of the FRP sheets or plates to the concrete or steel surfaces which is required to achieve the composite action needed to resist the applied loads. Test results indicate that plate end and intermediate crack debonding are the two common types of debonding which could take place for any FRP strengthening system.

This paper presents a new FRP retrofit system with self-monitoring capabilities for strengthening civil infrastructures. This FRP system is based on easy-to-apply FRP pre-preg tapes with multiple stacked layers of global and local fiber optic sensors embedded between FRP layers or at the surface of the strengthened structures. For global strain measurements, a newly developed oscillator interrogated interferometer is adapted, in combination with a prefabricated fiber-optic ribbon, to large-scale FRP strengthened structures. For local strain measurements, existing fiber Bragg grating (FBG) sensors are incorporated. Since the proposed self-monitoring FRP system is based on a multi-layer configuration of various materials, the stress/strain transfer between the FRP and sensor layers is expected to be complex. A simplified analytical model based on three dimensional shear lag analysis is developed for the design and real-time processing of this FRP system.

This paper presents an illustration of self-monitoring FRP system, containing embedded fiber Bragg grating sensors to monitor the behavior of three double-lap shear steel spliced joint specimens tested under tensile loading up to failure. The strains were measured by embedded fiber optic sensors and surface-mounted electrical resistance strain gages for comparison purposes. The readings were used to identify abnormal structural behavior such as epoxy cracking and/or FRP debonding. The double-lap shear steel spliced joint was selected due to the linear elastic behavior of the steel which simplifies the testing procedure to study the effectiveness of the self monitoring system. The self monitoring system was able to detect the location of the epoxy crack by monitoring the sudden change in the load-strain profile as well as the change of the slope of the load-strain relationship. The position and size of the induced FRP debonding zone was also detected from the constant zone of the

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recorded strain profile. Test results were compared to the numerical values obtained for the analytical model to evaluate the effectiveness of a three dimensional shear-lag model developed.

6934-06, Session 1

Structural-health monitoring of composites using integrated ultrasonic transducers

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Composite materials such as graphite/epoxy (Gr/Ep) laminates are becoming the materials of choice for aerospace structures. Diagnostic health monitoring technologies are increasingly being investigated by the aerospace industry to enable condition-based maintenance for cost-effective increased safety and eco-efficient designs. In this investigation two types of ultrasonic sensors are presented for in-situ thickness and defect measurements of Gr/Ep composites of thickness ranging from 1 mm to 12.7 mm. These piezoelectric film based sensors were designed to operate in a wide range of temperatures (-80°C to 100°C.) and were fabricated using a sol-gel spray technique. The center operation frequency of these sensors ranged from 1 to 15 MHz. For the first sensor type, piezoelectric films of thickness greater than 40µm were deposited directly onto planar and curved Gr/Ep composites surfaces as integrated sensors. Ultrasonic signals propagating in a distance of more than 100 mm with a center frequency at near 2MHz and good signal to noise ratio (SNR) have been obtained. These composite substrates may have high or low electrical conductivity. For high electrical conductivity material, the Gr/Ep is used as the bottom electrode of the integrated sensors. For low electrical conductivity material, the bottom electrode was made by an electroless nickel plating technique. For the second sensor type, piezoelectric films were coated onto a 50µm thick polyimide membrane as flexible sensors that could be bonded or embedded into a host composite structure.

The paper further presents our current development of an induction type non-contact method for the interrogation of the Gr/Ep composites using surface integrated and embedded sensors. Such non-contact technique is highly desired for health monitoring of rotating composite components. Results of ultrasonic thickness monitoring of a composite plate rotating at 1000 rpm with good SNR were obtained.

6934-07, Session 1

Dispersion of triboluminescent fillers for structural-health monitoring

T. J. Dickens, O. O. Okoli, R. Liang, Florida State Univ.

Advanced composites which offer robust mechanical properties are being increasingly used for structural applications in the aerospace, marine, defense and transportation industries. However, the anisotropic nature of composite materials leaves it susceptible to problematic failure; the development of means for detecting failure is imperative. As design and functionality requirements of engineering structures such as spacecraft, aircraft, naval vessels, buildings, dams, bridges and ground-based vehicles become more complex; structural health monitoring (SHM) and damage assessment is becoming more rigorous. Though structures involved have regular costly inspections, the fatigue damage associated with composites in SHM systems can lead to catastrophic and expensive failures. Industry and research have no single technique used on its own to provide reliable results. Integrating several nondestructive evaluation (NDE) techniques could provide a solution for real-time health monitoring. Such studies, utilizing acoustic emission (AE), A-scans, C-scans, and laser shearography have reported considerable success. Nevertheless, damage detection has to be reliable and cost effective.

The answer may lie with the development of SHM systems by the use of triboluminescent crystals, as well as optical fibers embedded in the composite matrix. These crystals react to straining or fracture by emitting light of varied luminous intensity. Thus, a fiber-reinforced plastic (FRP) laminate doped with Triboluminescent (TL) or Mechanoluminescent (ML) crystals, acting as health sensors to its host material, will give an indication of crack initiation well ahead of catastrophic failure(s). The development of an in-situ health monitoring system for safety critical structures is a viable

route through 'Triboluminescence'. Assessing the viability of a proposed structural sensor system requires cross-linking between key areas in science and engineering.

Initial testing has shown that light can propagate through doped resins alone, as well as doped FRP laminates. The luminous intensities relation to impact velocity adds credence to a potential monitoring system that can characterize impact activity. However, Triboluminescent crystals have high material density. In response, a two-dimensional rotational mold was built to counteract massive settling under normal vacuum molding processes. Micro-structural evaluations using scanning electron microscopy (SEM) and EDAX imaging have aided in demystifying particulate dispersion of TL fillers through use of image processing.

6934-08, Session 1

Theoretical and experimental characteristics on residual stresses of advanced polymer composites

Z. Guo, Shanghai Univ. (China)

The residual stresses and mechanisms causing residual stresses in thermoset polymer composites were considered. The relative importance of the different mechanisms was analyzed. The residual stresses were determined analytically by viscoelastic model in addition to an experiment. The linear viscoelastic model was used to calculate of residual stresses in each layer of laminated composites. The fiber Bragg grating (FBG) strain sensor was used to measure the residual stresses throughout cure. The results are agreed well. The viscoelasticity of composites should be considered during calculating the residual stresses, and FBG strain sensor is shown to be a reliable for an accurate measurement of the residual stresses.

6934-09, Session 1

Robust fractal dimension-based damage identification of beam-type structures

P. Qiao, M. Cao, Washington State Univ.

Although the vibration mode shape-based damage detection for structural systems has been investigated for a long time, most of the existing methods often require a numerical or experimentally-measured baseline mode shape acting as a reference to identify damage. This requirement extremely limits the practical application of these methods. Fractal as a novel mathematical tool has potential to deal with topological types of measurement outcomes (e.g., vibration mode shapes) in a complex waveform.

In this study, fractal is introduced to detect abnormality or irregularity of vibration mode shapes without a baseline requirement. Differing from the popular Katz's waveform fractal dimension, a novel and approximate waveform capacity dimension (AWCD) capable of detecting abnormality or irregularity in vibration mode shape is first formulated mathematically, from which an AWVD-based modal abnormality algorithm (AWCD-MAA) is developed. The fundamental characteristics of AWCD-MAA, such as localization and quantification of crack-type damage, are thoroughly investigated using an analytical crack model of cantilever beams. The validity and effectiveness of the proposed AWCD-AMM under a noise environment is further evaluated using numerical finite element simulation of a cracked composite cantilever beam. An experimental study of laminated composite cantilever beams using smart piezoelectric materials (i.e., lead-zirconate-titanate (PZT) as actuators and polyvinylidene fluoride (PVDF) as sensors) is also conducted to confirm the feasibility of the proposed algorithm in practical application.

The contribution of this study lies in that from the perspective of topology, a mathematical algorithm is originated to rigorously solve the crucial problem of applying fractal dimension to vibration mode shapes for the sake of damage detection. As demonstrated in this study, the proposed AWCD-MAA provides a robust tool to effectively detect the crack damage in beam-type structures based on the vibration mode shapes.

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6934-10, Session 1

Damage detection and leakage alert of fiber composite wrapped tank for high-pressure hydrogen storage

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High pressure hydrogen (HP H₂) storage is the most popular and most highly developed storage method among the current hydrogen storage technologies due to its technical simplicity and its low cost. Fiber-composite-wrapped HP H₂ tanks are becoming widely used in onboard vehicle storage applications because of light weight and high strength. Safety issues associated with HP H₂ fiber composite wrapped tank are an important consideration. This is especially the case for target operating pressures in excess of 700 bar (10,000 psi). At operating pressure, the tank shell should be able to inhibit crack formation and development. In extreme cases, even with crack development, the equipment should be able to prevent explosion, with only leakage as the worst case. This paper investigate the effectiveness and accuracy of the nondestructive damage detection methods on the identification of fatigue micro-cracks. First, a finite-element model of the influence of fluctuation of working pressure and temperature is developed. A dynamic experiment of a fiber composite wrapped tank is undertaken to confirm the numerical simulations. The FE model is updated by the structure information of damaged and undamaged state collected during the experiment. Then damage is simulated based on the updated FE model with the position, length, and direction of the crack as the investigation parameters. Three nondestructive damage detection methods are applied to identify the damage occurred in the fiber composite wrapped tank. The damage detection accuracy of each method is investigated with a consideration of the vehicle vibration caused by road surface roughness and environment noise. The advantages and disadvantages of each method are discussed. Finally, feasible strategy to alert the leakage of the hydrogen of fiber composite wrapped tanks is proposed.

6934-11, Session 1

Vibration-based damage detection for filament wound pressure vessel filled with fluid

W. Zhou, Z. Wu, H. Li, Harbin Institute of Technology (China)

Filament wound pressure vessels have been extensively used in industry and engineering, e.g. aerospace, marine and petrochemical engineering due to their high strength-to-weight ratio, better corrosion resistance as well as the advantage of composite materials. The existing damage detection and health monitoring methods for these vessels, such as X-ray and ultrasonic scan, can not meet the requirement of online damage detection; moreover optical grating fiber can only sense the local damage, but not the damage far away from the location of sensors. Vibration-based damage detection methods have the potential to meet such requirements. There methods are based on the fact that damages in a structure results in a change in structural dynamic characteristics.

A damage detection method based on a residual associated with output-only subspace-based modal identification and global or focused χ^2 -tests built on that residual has been proposed and successfully experimented on a variety of test cases. In the proposed damage detection algorithm, it is assumed that a signature of the structure in its safe state is available. The damage detection algorithm processes new data by first generating a residual, and computing its sensitivity with respect to damages.

The purpose of this work is to describe the damage detection method and apply this method to assess the composite structure filled with fluid. In the study, the crack damage is simulated in a finite element model. Because these pressure vessels are normally filled with fluid, the interaction between the fluid and composite shell structure is considered. The results of identification and damage detection will be presented.

6934-12, Session 2

Single-crystal piezoelectric composite transducers for ultrasound NDE applications

X. Jiang, K. A. Snook, T. Walker, W. S. Hackenberger, TRS Technologies, Inc.

In this paper PMN-PT single crystal 1-3 composite transducers with frequencies ranged from 10 MHz to 75 MHz are developed for ultrasound NDE applications because of their short pulse, wide bandwidth and high sensitivity. In specific, 10 MHz and 15 MHz 1-3 composites were fabricated using conventional dice-and-fill technique, the kerf width is about 21 μm and 14 μm for 10 MHz composites and 15 MHz composites, respectively. The measured electromechanical coupling coefficients are 0.76-0.79. High frequency (60-75 MHz) 1-3 composites were fabricated using PC-MUT technology, the kerf width of a 60 MHz composites is about 4 μm , and the electromechanical coupling coefficient is about 0.66. Transducers at these frequencies are being assembled and characterized for SiC mirror NDE experiments to detect surface and sub-surface defects and damages.

LCR wave setup for stress measurement are developed for measurements of internal stress in SiC mirrors. The results on transducers characterization and NDE experiments will be presented in the full paper.

6934-13, Session 2

Development of acoustic-ultrasound methods for damage detection in fiber metal laminate structures

N. P. Salowitz, F. Chang, Z. Wu, Stanford Univ.

Bonded layered structures are becoming increasingly common in aircraft as a means of saving weight and reducing fasteners in metal structures. Fiber Metal Laminates (FMLs) like GLARE are the epitome of this technology and are reaching mainstream utilization in the aerospace field. Aircraft like the Airbus A380 have substantial structure made of GLARE. However, the properties and failure modes of FMLs present unique problems for standard inspection and NDE techniques. Therefore methods need to be developed to monitor the structural integrity of FMLs. This paper presents preliminary studies, testing and results in the use of Acoustic Ultrasound based Structural Health Monitoring (SHM) techniques in GLARE as a means of detecting and quantifying internal damage in FMLs.

FMLs like GLARE are particularly prone to internal hidden fatigue damage. Fatigue cracks form in the thin internal layers of aluminum earlier than an equivalent monolithic aluminum counterpart due to their closer realization of plane stress. As cracks grow crack bridging occurs which forms delaminations between the layers. In most instances this all occurs in the thinner internal layers of the laminate structure, keeping the damage hidden from surface inspection.

NDE techniques have been developed to detect various types of structural failures however any given traditional technique typically will not be capable of detecting both cracks and delaminations. FMLs can exhibit both forms of damage individually or together. Through penetration C-Scan is well suited for detecting delaminations but not cracks. Conversely, eddy current evaluation is well suited to detect cracks but not delaminations. Other methods like X-Rays do not work on thick metal structures

Acoustic Ultrasound SHM techniques have shown sensitivity to both cracks and delaminations. This capability combined with the high sensitivity of Acoustic Ultrasound makes it ideal for this application.

An initial round of testing has been performed wherein GLARE layups with piezoelectric transducers mounted on the surface and embedded within specimens were fatigued until surface cracks were visible. Acoustic Ultrasound data was taken at intervals, the analysis of which suggests that significant damage occurred before surface cracks became visible. In addition the damage location was where the surface cracks would eventually occur. Traditional NDE techniques were then utilized to help assess internal damage. This testing confirmed that Acoustic Ultrasound techniques have the potential to be applied to FMLs and detect internal damage before it appears on the surface. This testing also provided information about the effects of through structure sensor location and

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waveform effectiveness.

The results of this testing provide a basis on which to develop techniques for real time detection of internal damage before it appears on the surface of an FML, embedding piezoelectrics into FML structures and quantification of damage in FMLs.

6934-14, Session 2

Acoustic emission analysis of full-scale honeycomb sandwich composite fuselage panels

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Tests were conducted to evaluate the acoustic emission (AE) analysis of damaged honeycomb sandwich panels. The objective of this evaluation was to correlate this method with other methods of detecting damage in sandwich panels. This evaluation is part of a study investigating the damage-tolerant characteristics of several honeycomb sandwich composite curved aircraft fuselage panels subjected to quasi-static pressurization and axial loading. The evaluation was conducted using the Full-Scale Aircraft Structural Test Evaluation and Research (FASTER) facility located at the Federal Aviation Administration William J. Hughes Technical Center in Atlantic City, NJ. The overall program objective is to investigate the effects of holes and notches on the residual strength of full-scale composite curved aircraft fuselage panels and the evolution of damage under quasi-static loading up to failure.

Background: The sandwich structural configuration in a typical airframe experiences a combination of in-plane loads, and damaged regions may experience localized out-of-plane bending and bulging due to pressurization loading. The FASTER fixture is capable of testing full-scale fuselage panel specimens under conditions representative of those seen by an aircraft in actual operation.

The acoustic emission method was implemented in this test program to monitor for real-time damage initiation and growth and serve as an early warning for imminent fracture. Altogether, six panels were tested. The first panel was undamaged, used to obtain baseline data. Various damage scenarios, were considered in subsequent tests including a 10_ through-the-thickness longitudinal notch, a 10_ through-the-thickness circumferential notch, and a 10_ diameter hole through the exterior (convex side) facesheet.

Loads were applied quasi-statically in ten equal steps, up to the maximum load. Each panel was instrumented with eight acoustic emission sensors, circling the damage at 45 degree intervals at a radius between 15 and 25 inches, depending on the specific damage case. Several AE sensors were used during the different tests, including the Physical Acoustics Corporation R6, R15, and WD sensors. Special attention was given to the emission generated by the fretting among the many fracture surfaces formed during damage progression. This was accomplished by subjecting the panels to several loading/unloading cycles, at load levels below the previously maximum attained loads. This process was repeated several times, at different states of damage. The intensities of the acoustic emission events recorded during these load cycles were analyzed and quantified.

Extensive data analyses were conducted, characterizing the acoustic emission events generated during the test. The results obtained from these tests show that damage initiation at the tip of the notches and its progression along the panel could be monitored. Further, the AE results could locate internal disbonding caused during panel fabrication. The acoustic emission results were correlated with the deformation and strain fields measured, throughout loading, at the vicinity of these notches through digital image correlation and with the changes in the frequency response of the panel.

6934-15, Session 2

Determination of crystallographic texture in metal sheets using ultrasound and EBSD

S. B. Palmer, S. M. Dixon, M. Potter, S. Essex, The Univ. of Warwick (United Kingdom)

The quantitative measurement of crystallographic texture through determination of the Orientation Distribution Coefficients (ODCs) can provide critical information on a sample's suitability for being utilised in a particular manufacturing process or can be used to measure changes in the microstructure of components in service. Ultrasonic techniques have been developed by previous workers that measure three of the ODCs that describe the orientation probability distribution function for an aggregate of cubic crystallites. Electron Backscatter Diffraction (EBSD), a microscopic technique that measures the crystallographic orientations of individual crystals, has been utilised to offer an alternative method to measuring the complete range of ODCs. As a technique, EBSD provides a much more detailed measurement of texture than ultrasonic measurements ever could. Ultrasonic methods are however non-destructive, can be used on components in service and are quicker in use and are less expensive to implement than EBSD measurements. EBSD is a valuable method in validating ultrasonic measurements, and can help to guide us in determining the limitations of the ultrasonic measurements. Ultrasonic measurement of texture is and will continue to be a useful approach to measuring texture but it does have its limitations for application to real samples. Equally, one has to use EBSD properly if one is to obtain accurate and representative data for the entire sample.

6934-16, Session 2

Simulation of AE from delaminations and cracks in composites

B. R. Tittmann, The Pennsylvania State Univ.; S. Fladischer, Technische Univ. Graz (Austria); S. Jayaraman, M. J. Guers, The Pennsylvania State Univ.

During the manufacture of composites a major concern is the formation of delaminations which in most cases render the component useless. Early recognition of these would promote quality control and save processing time and expenses. The detection is made difficult by the formation of microcracks which are filled-in in further treatments. The objective of this work is to distinguish the acoustic emissions (AE) from these two flaw types. Finite Element Methods were used to simulate AE using sources represented by piezoelectric wafers embedded in the composites. Flat panels of different lateral and thickness dimensions and of different materials were considered. The simulated AE show distinct differences in the amplitudes, durations and frequency content of the waveforms. This paper presents both the simulation results and experimental AE for First Carbonization of carbon-carbon composite. The AE from delaminations are characterized by high amplitude, short duration waveforms in contrast to the long duration, low amplitude waveforms from micro-cracks.

6934-17, Session 2

Failure progression monitoring of advanced composite bridge components using acoustic emissions sensors

J. B. Kosmatka, D. J. Klein, M. J. Robinson, E. Velazquez, Univ. of California/San Diego

Acoustic Emissions (AE) has been successfully used with composite structures to characterize progressive failure from initial matrix cracking to fiber failure. The current experimental study uses AE to monitor large-scale composite modular bridge components that are being developed for the US Military. The components consist of carbon/epoxy deck and beam structures as well as both bonded and mechanically fastened joints. Individual components (5 m in length) are assembled to create a 40 m long bridge capable of supporting vehicles having Military Load Class (MLC) of 100 (100 ton). Bonded joints consist of double lap aluminum splice plates bonded and/or bolted to the tension flange of the beams. AE sensors are used to locate and characterize damage as the joints are loaded to failure. The location of damage is interpolated from the time of arrival of the

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acoustic signals. To characterize the damage, we look at several features in the AE data such as Cumulative Acoustic Emission counts (CAE) that give an estimate of the severity and rate of damage accumulation, as well as Incoming Wave FFT (IWF) to differentiate the type of damage (fiber breakage, matrix cracking, adhesive disbonding). During the design and testing of the bolted and bonded joints, the AE data was used to interpret the source and type of damage that induced failure in the joint. These results were used to improve the joint design. A four-point bending test on a five-meter long carbon/epoxy composite bridge beam/deck assembly is currently underway. The AE system is being used to detect, locate, and characterize damage as the deck/beam system is loaded to working load, fatigue cycled and then loaded to failure.

6934-18, Session 2

Applications of acoustic emission for civil infrastructure

P. H. Ziehl, Univ. of South Carolina

Acoustic emission is a useful and accepted method for evaluation of fiber reinforced polymers and has been used in the pressure vessel industry for over 20 years. However, its adoption for the evaluation of civil infrastructure (buildings and bridges) has been considerably less rapid.

This presentation describes several case histories of both building and bridge evaluation with acoustic emission data. Challenges as well as opportunities are discussed.

6934-19, Session 2

Acoustic emission monitoring and critical failure identification of bridge cable damage

D. Li, Dalian Univ. of Technology (China)

Acoustic emission (AE) characteristic parameters of bridge cable damage were obtained on tensile test. The testing results show that the AE parameter analysis method based on correlation figure of count, energy, duration time, amplitude and time can express the whole damage course, and can correctly judge the signal difference of broken wire and unbroken wire. It found the bridge cable AE characteristics aren't apparent before yield deformation, however they are increasing after yield deformation, at the time of breaking, and they reach to maximum. At last, the bridge cable damage evolution law is studied applying the AE characteristic parameter time series fractal theory. In the initial and middle stage of loading^{1/4} the AE fractal value of bridge cable is unsteady. The fractal value reaches to the minimum at the critical point of failure. According to this changing law, it is approached how to make dynamic assessment and estimation of damage degrees.

6934-20, Session 3

Investigation of fiber waviness in a thick glass composite beam using THz NDE

R. F. Anastasi, NASA Langley Research Ctr.

Fiber-waviness in laminated composite material is introduced during manufacture because of uneven curing, resin shrinkage, or ply buckling caused by bending the composite lay-up into its final shape prior to curing. The resulting waviness has a detrimental effect on mechanical properties, therefore this condition is important to detect and characterize. Ultrasonic characterization methods are difficult to interpret because elastic wave propagation is highly dependent on ply orientation and material stresses. By comparison, the pulsed terahertz response of the composite is shown to provide clear indications of the fiber waviness. Pulsed Terahertz NDE is an electromagnetic inspection method that operates in the frequency range between 100 GHz and 2 THz. Its propagation is influenced by refractive index variations and interfaces. This work applies pulsed Terahertz NDE to the inspection of a thick composite beam with fiber waviness. The sample is a laminated glass composite material approximately 15mm thick with a 90-degree bend. Terahertz response from the planar section, away from the bend, are indicative of a homogeneous material with no major reflections from internal plies, while the multiple reflections in the response at the bend area correspond to the fiber waviness. Results of these measurements are presented for the planar and bend areas.

6934-21, Session 3

Through-wall electromagnetic imaging for infrastructure evaluation

B. J. Tucker, D. L. McMakin, Pacific Northwest National Lab.

The presence of moisture in wood-framed building cavities can have important implications on both structural performance and human health. Moisture can encourage corrosion of fasteners or fungal decay, greatly affecting the structure's performance. Unfortunately, this might not be apparent until an earthquake, hurricane, or other high-loading event. The presence of moisture can also lead to the growth of molds and fungi, which has caused increased health concerns. Forensic investigation of moisture in a wall cavity is difficult due to the numerous layers of building materials, requiring costly removal for visual inspection. Recently developed technology at the Pacific Northwest National Laboratory (PNNL) has the potential to accurately locate moisture in wall systems using electromagnetic imaging. This technology, originally developed for national security purposes, has far reaching applications in the forest products industry. For imaging moisture in wall systems and individual members. Portable systems could be employed by building inspectors for imaging moisture in wall systems. More advanced stationary systems could be used by wood products manufacturers for imaging of moisture in lumber before, during, and after drying. A brief synopsis of the technology and preliminary test results on wall systems will be presented.

6934-22, Session 3

Inductive thermal excitation for NDE of conductive media in composite structures

G. E. Georgeson, The Boeing Co.

This paper describes the utilization of induced radio frequency thermal excitation in conjunction with infrared (IR) imaging for the detection of discontinuities in embedded metal conductive mesh on composite structure. An electric current is inductively generated in the conductive media of the composite using a radio frequency coil held above the surface. As the generated current moves through the composite structure, any perturbation in the current flow caused by discontinuities in the grid or highly resistive areas becomes heated slightly above surroundings. This small temperature variation is detected in real-time by means of an IR imaging system that includes an IR camera, a computer, and imaging software. The data is depicted as a thermogram on the computer monitor, and can be analyzed using specialized system software. From the detected thermal variations, one can determine electrical conductivity characteristics of the conductive layer.

6934-23, Session 3

Ear recognition based on the edge information of the auricle contour

J. Liu, L. Wang, Chongqing Univ. (China); T. Ma, Univ. of Hawai'i at Manoa; Y. Lan, Chongqing Univ. (China)

Ear recognition is a new technology of biometrics. Ear recognition involves many domains such as feature extract, computer vision, image processing, pattern recognition and identity authentication etc. Although there are many algorithms about ear recognition now, ear recognition employing the spatial information of edge map associated with optimal information remains an interesting research area. The basic theory and method of edge information used in ear recognition is studied in this paper.

Ear image denoising plays an important role in ear recognition system. In this paper, an ear image denoising and inpainting approach based on skin color detection is proposed. This method employs skin color detection to segment images into skin color and non-skin color regions in HSI color space. Those non-skin color regions surrounded by skin color pixels will be considered as noise regions, then these noise regions are inpainted by a new image-inpainting algorithm. When the image-inpainting algorithm is carried out, non-skin color pixels in noise regions will be replaced by skin color pixels around the non-skin noise region. The experimental results with ear images demonstrate that the proposed method is very simple and works well and fast for image denoising while some important information like edges is substantially retained.

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Most of the classical methods of edge detection are either based on various differential operators combined with the methods of threshold ranking or smoothing or template matching, or some optimized arithmetic operators based on the classic differential operators. The applications of the above methods have some disadvantages such as sensitivity to noise, loss of edge detection. In this paper, gray-scale morphology is applied to edge detection. An improved edge detection operator is proposed that uses morphological operations such as dilation, erosion, opening, closing and their combination. The method can accurately detect and catch the position of edge points and has satisfied filtering results. Experiments demonstrate that compared with traditional edge detectors, this edge detector has a good performance of noise reduction and requires fewer calculations, which enhances its practicality and feasibility.

The Hausdorff distance between planar sets of points is known as a good method to compare binary images. In this paper, a new modified Hausdorff distance using standard deviation and difference in length of edge lines is proposed, which could attain more accurate measurement of the differences between the edge lines. It reduces the errors that induced by noise, pseudo edge segments and outlier points. Finally, SVM is employed for ear recognition. Experimental results show that the modified algorithm can get high recognition rate of 94.4% based on 320 ear images in the database.

6934-24, Session 3

Ultrasonic phased array inspection imaging technology for NDT of offshore platform structures

B. Shan, H. Wang, Z. Duan, Harbin Institute of Technology (China); J. Ou, Dalian Univ. of Technology (China)

Offshore platform structures operate in a harsh environment and are subjected to a variety of cyclic loads such as wind and waves. This can, in some cases, lead to degradation due to fatigue, and flaws are usually easy to come into being in welded tubular joints. In order to improve inspection result repetition and flaw ration veracity of manual ultrasonic inspection of offshore platform structure, an ultrasonic phased array inspection imaging technology for NDT of offshore platform structures is proposed in this paper.

Aimed at the practical requirement of tubular joint welds inspection of offshore platform structures, an ultrasonic linear phased array is designed, and the operating frequency, piezoelectric material and geometry parameters of transducer are confirmed. According to the inspection requirement of tubular joint, the coordinate system of offshore platform structure inspection algorithm is defined; the inspection zone selection rule of tubular joint weld is illustrated. Scanning method of ultrasonic phased array technology inspecting tubular joint weld is brought forward, ultrasonic phased array technology imaging principle from A-scan data into B-scan, C-scan and D-scan, flaw evaluation and analysis method of offshore platform structure ultrasonic phased array technology are also researched.

Based on the study of inspection algorithm of offshore platform structures, the integrated design of ultrasonic phased array inspection imaging system for offshore platform structure is developed, the ultrasonic phased array inspection imaging system for offshore platform structure is integrated on the basis of the each module and the exploitation of subsystem, which is made up of computer, ultrasonic circuit system, scanning device, phased array transducer and inspection imaging software system. The fabrication technique of ultrasonic linear phased array is introduced, and the detection result of performance index of the transducer fabricated practically arrives at the design requirement. The ultrasonic phased array circuit system supports 64 elements phased array transducer. Scanning device composed of electric control system, scanner mechanism and clear water vision system could satisfy the inspection requirement in turbid water. The inspection imaging software system is compiled according to the inspection algorithm, which implements the ultrasonic phased array inspection of offshore platform structure.

The ultrasonic phased array inspection experiments of tubular joint model are performed with phased array system, the flaws characteristic could be exactly estimated and the flaws size could be measured through ultrasonic phased array inspection imaging software system of offshore

platform structures. Experiment results show that the ultrasonic phased array inspection algorithm for offshore platform structures is feasible, the ultrasonic phased array inspection imaging system could detect flaws in tubular joint model, the whole development trend of flaws is factually imaging by the ultrasonic phased array inspection imaging technology of offshore platform structures.

6934-25, Session 4

Highly nonlinear waves' sensor technology for highway infrastructures

D. Khatri, C. Daraio, California Institute of Technology; P. Rizzo, Univ. of Pittsburgh

This paper describes preliminary results towards the development of an innovative NDE scheme for material characterization based on the generation of highly nonlinear solitary waves (HNSWs). HNSWs are stress waves that can form and travel in highly nonlinear systems (i.e. granular, layered, fibrous or porous materials) with a finite spatial dimension independent on the wave amplitude. Compared to conventional linear waves, the generation of HNSWs does not rely on the use of electronic equipment (such as an arbitrary function generator) and on the response of piezoelectric crystals or other transduction mechanism. HNSWs possess unique tunable properties that provide a complete control over tailoring: 1) the choice of the wave's width (spatial size) for defects investigation, 2) the composition of the excited train of waves (i.e. number and separation of the waves used for testing), and 3) their amplitude and velocity. HNSWs are excited onto concrete samples and steel rebar. The characteristic of the pulses traveling along these systems is studied experimentally. The presence of pulse's features sensitive to geometrical and mechanical material properties is studied and discussed.

6934-26, Session 4

MEMS microphone sensor for roadway safety monitoring

G. Feng, National Chung Cheng Univ. (Taiwan); H. Chung, ImageCat, Inc.

A micro-machined piezoelectric microphone system is developed for use of roadway safety monitoring. A series of MEMS microphone designs have been fabricated in an earlier investigation. Designs in variable piezoelectric active region geometries showed usefulness and different sensitivities in detecting a series of system parameters for roadways condition monitoring. Piezoelectric sensors have been employed to quite a few structural health monitoring studies by having their practical designs and applications. Most of the developed ones are emphasized on the acceleration and/or displacement measurements. The nature of the piezoelectric sensors is a low-cost, low-power activated, and easily implemented to a sensing network. This study focuses on the non-intrusive sensing array system for detection of abnormal conditions of structures.

The micro-machined microphones are made by silicon bulk-machining. Using a silicon dioxide or silicon nitride as a supporting layer, the sandwiched structure of piezoelectric (ZnO/PZT) active region is formed by evaporation, sputtering, wet etching and necessary photolithography processes. Due to the batch fabrication process, the micro-machined microphone possesses highly uniform quality between individual devices. Thus, they are feasible to make a sensor array and effectively process signal for a structural health monitoring.

The sensor is firstly used in a proof-of-concept experiment of using ambient vibration testing for a structural member, such as a beam member with slender geometrical cross-section. Further testing of a realistic scale for a complex structural system will be investigated in near future. The preliminary results of this research show that effectiveness and usefulness of micro-machined microphones is promising with its anticipated performance in roadway inspection and safety monitoring within an advanced highway management system.

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6934-28, Session 4

Fast EM stress sensors for large steel cables

Y. Zhao, Intelligent Instrument System; M. L. Wang, Univ. of Illinois at Chicago

Monitoring stress in a steel tendon dynamically is one of the challenges to engineering community. High stress strands and wires have many structural applications in the form of tendons, cables, and ropes. These applications include pre-tensioned and post-tensioned concrete bridges and buildings, pipelines, cable-supported bridges, and ground anchors. Structures and facilities deteriorate over a period of years or decades and eventually become unsafe. Moreover, observing and predicting the onset of dangerous structural behavior induced by hurricane, collision, explosion, and earthquake will provide advance warning to prevent the loss of life. It prompts the commencement of mitigating control or removal of the structure from service.

Magnetoelastic (EM) stress sensors function by utilizing the direct dependence of the magnetic properties of structural steels on the state of stress. These properties are measured by subjecting the steel to a pulsed or periodic magnetic field, which can be accomplished without any contact. Changes in magnetic flux in the steel allow those magnetic properties to be sensed and deduced through Faraday's law. EM sensors can be designed for all sizes of prestressing steel, strands, cables, and tendons. They are suitable for measuring quasi-static loads under any environmental conditions. The sensors can be embedded in concrete or fabricated in situ for exposed cables. The sensors are entirely suitable for sheathed cables and require no physical contact with the cable itself. In order to meet the requirement of observing structure behavior under extreme events, a high sampling rate of EM technology has been developed. The sampling rate of the EM sensor can be as high as 0.1 Hz which is 10 times faster than the current available technology for sensor size of up to 250mm. Both laboratory and field calibrations were conducted. The relationship between the relative incremental permeability and tensile stress is derived from these calibrations. Field measurements on tendons for Stonecutters Bridge in Hong Kong demonstrate the reliability and accuracy of the EM stress sensors using the updated technology.

6934-29, Session 4

Application of time-frequency analysis in data processing using impact echo on soil nail

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Sinotech Engineering Consultants, Inc. developed the new impact echo system (US. Patent No.09/722,098) and has been applied in many quality investigation of infrastructures. This instrument was also applied in the quality checking of soil nails. The existing soil nails were investigated for buried length and grouting quality. After collecting and processing many data acquired in the fields, the echo of soil nail seems strong related to the grouting quality. The suitable physical models were built for verifying the relations. The echo of partial-grouted soil nail was almost the same with the steel bar but with the reverse phase, and there was no echo of full-grouted soil nail. The spectrograms also showed the different characteristics.

6934-30, Session 4

Structural damage detection for long-span cable-stayed bridge under varying temperature and humidity conditions

W. Zhou, Harbin Institute of Technology (China); H. Nasser, Ctr. de Recherche Public Henri Tudor (Luxembourg)

The vibration-based method has been developed in the past few decades to monitor structural condition and identify structural damage, because structural properties such as stiffness and damage are closely related to structural vibration parameters, e.g., frequency, mode shape and damping. The method has been successfully applied in mechanical and aerospace

engineering. How application of the method to monitor civil engineering structure conditions and detect damage is more complicated because of their large dimensions and the associated uncertainties. In particular, the uncertainty comes from inevitable finite element modeling error, instrument noise, and the influence of changing environmental conditions on structural properties. For civil engineering structures, the complex external environment results in the structural vibration properties varying with external conditions, such as humidity, traffic and temperature, which may mask the changes caused by structural damages. For the vibration-based structural health monitoring techniques, for example damage identification, modal updating and so on, above characteristics will make the vibration-based techniques invalid. Other researchers have reported that modal frequencies varied significantly due to temperature change, but the coupling humidity and temperature affect structural vibration properties in a more complicated manner, and hardly researchers work on it.

In this paper, we firstly discuss the variation of frequencies and mode shapes with respect to humidity and temperature changes for concrete structures, for which the changing of moisture will affect the density of materials, and the changing of temperature will affect the stiffness of structures. For the concrete, which is a porous material, the change of the humidity of air will lead to the change of moisture on surface and interior of the concrete materials. Rigorous investigations have been conducted by early researchers. This work considers the isothermal moisture transport and heat induced moisture transports, which will change the mass and stiffness of concrete structures, and models these two factors with finite element model approach based on the theoretical analysis.

Then we will present a statistical damage detection method, which is based on a residual generated from a subspace-based identification method. Then, a statistical nuisance rejection approach with respect to varying mass and stiffness condition is proposed. This technique assumes that several datasets are recorded on the safe structure at different and unknown mass changes, and computes an extended Jacobian w.r.t the new parameter set.

At last, based on above analysis, the structural vibration responses for a long-span cable-stayed bridge under the varying temperature and humidity conditions, and also the damage case, will be simulated for damage detection. The detailed numerical results obtained on the finite element model of this bridge will be reported.

6934-51, Session 4

An image reconstruction method by deconvolution for ECT

A. Sasamoto, T. Suzuki, Y. Nishimura, National Institute of Advanced Industrial Science and Technology (Japan)

In previous 2007 conference, we showed the possibility of simple inverse method that is based on deconvolution of signal. The reconstructed image is more finer than the original experimental one. The method needs short computational time with FFT. Those detail was shown by applying it to the actual experimental data (Proc. of SPIE Vol.6531, 653118, (2007)). However, there was room to be improved. The original data has been contaminated some noise. The deconvolution method may be a classified in ill-posed problem that means small noise in signal brings about large error in output image. The regularized process that we employed in previous work made weaken the ill-posedness and recover the quality of output image. The process uses some parameters. The method reproduced the good image well, but bad results are also obtained on the bad parameters choice. Those parameters were fixed by trial and error with some graphical fitting that are some ambiguous, not deterministic guide. To clarify this guide, we considered two methods. First is 'eliminate the background spectrum frequency'. It is simple and easy method. Second is a algorithms which estimates noise characteristics related to signal character based on filter algorithms. Those 'deterministic' process does not require only graphical fitting but also trial error, and made good results. They must be complements of the previous proposed method.

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6934-31, Session 5

Advances in wireless sensor networks for distributed sensing, controls, and computing

J. P. Lynch, R. A. Swartz, Univ. of Michigan

Wireless sensors have emerged in recent years to offer impressive functionality for engineers engaged in structural monitoring applications. In particular, such sensors offer opportunities for wireless nodes to engage in sensing, real-time feedback control and distributed computing functions when installed in structural systems. This paper will explore recent advances in the design of a low-power wireless sensor node under development at the University of Michigan, termed Narada. Narada supports ad-hoc communication using a Zigbee-compliant wireless transceiver. In addition, embedded microcontrollers are integrated in the design of the wireless node to allow it to execute embedded data interrogation algorithms. Most recently, wireless sensors have been deployed in real-time feedback control systems so as to limit undesired structural deflections during dynamic excitation. The paper provides an overview of the design of the Narada unit in addition to showcasing its performance in a variety of applications, including testing in the laboratory and field environment.

6934-32, Session 5

A distant real-time radar NDE technique for the in-depth inspection of glass fiber reinforced polymer-retrofitted concrete columns

T. Yu, O. Buyukozturk, Massachusetts Institute of Technology

A novel real-time radar NDE technique for the in-depth inspection of glass fiber reinforced polymer (GFRP)-retrofitted concrete columns is proposed. In this technique, continuous wave radar signals are transmitted in the far-field region (distant inspection), and reflected signals are collected by the same signal transmitter. Collected radar signals are processed by tomographic reconstruction methods for real-time image reconstruction. In-depth condition in the near-surface region of GFRP-concrete systems is revealed and evaluated by reconstructed images.

6934-33, Session 5

Passive sensing and imaging for GIS-PMS: system concept and challenges

D. Boyajian, The Univ. of North Carolina at Charlotte; H. Chung, ImageCat, Inc.; S. Chen, The Univ. of North Carolina at Charlotte

GIS-based pavement management systems (GIS-PMS) have been proposed for pavement management due to the spatial capability in organizing diverse spatially referenced information. Such technology can be further enhanced by nondestructive distributed sensing techniques. To target a wide study area, this paper proposes a low-cost vibro-acousto passive sensing technique that can be embedded within pavements for long term sensing. Using state-of-the-art and self-sustaining MEM sensors, the proposed technology detects acoustic signals and use relative rating and kriging to discern good and bad pavements. The proposed detection technique echos the traditional chain-drag technology in that the same sound detection is deployed. Coupling with previously established AMPIS pavement imaging and distress detection technique, the proposed system can evolve to be a more powerful new-generation GIS-PMS. This paper introduces the system concept and describes the philosophy behind the system and some of the challenges that we are currently attempting to solve.

6934-34, Session 6

On the feasibility of energy harvesting for health-monitoring sensors in the transport infrastructures

C. Tan, Wayne State Univ.

In recent years, wireless sensors technologies are getting wider applications in the structural health monitoring (SHM) of civil, mechanical and aerospace systems. One of the key challenges, in the wireless SHM sensor network, remained to be addressed is supplying of uninterrupted power for sensor nodes. Using batteries as a source of power for the system is not reliable as batteries can only provide power for short period of time, and it is hard to replace batteries attached to remote sensors, for example, sensors embedded inside bridge structures. As the system is based on wireless concept, providing power from the wired electric source is meaningless, uneconomical and not feasible. This study investigates the feasibility of energy harvesting from the ambient vibration of transportation infrastructures to power health monitoring sensors. Based on the vibration responses from simulation and field tests, two sources of ambient vibration for powering the wireless sensor network will be investigated, such as (1) vehicle induced vibration on pavement and bridge, (2) vehicle induced impact load on pavement. A prototype MEMS based energy harvesting device is manufactured to validate power output obtained from the theoretical studies. The expected results from this study will be demonstrated by avoiding complex wiring to the sensors by which the associated cost of wiring and batteries will be significantly reduced, and at the same time the technology can easily be deployed, meaning it is one step forward in improving the SHM applications.

6934-35, Session 6

Multimode piezoelectric energy harvesters for wireless sensor network-based structural-health monitoring

Y. Zhang, Georgia Institute of Technology; W. He, Univ. of California/ Berkeley

There is a growing desire to employ wireless smart sensors for structural health monitoring (SHM) in order to economically monitor the integrity of civil infrastructures in real-time and provide for increased safety to the public. For sensor operation or remote interrogation of existing infrastructures, power is one of the key issues in wireless sensing technology. The novel energy harvesting technique and its integration with wireless sensing systems are vital to the next generation structural health monitoring systems. Energy harvesting devices convert the ambient energy surrounding the wireless sensors into electrical energy to extend the lifetime or reach unlimited lifespan of wireless sensors. Mechanical vibrations, existing almost everywhere, have been investigated as a promising energy source for wireless sensors in many applications. Several methods exist for converting the vibration energy into electrical energy, such as electromagnetic induction, electrostatic generation, and piezoelectric materials. Since electrostatic transducers require a separate voltage source (such as a battery) to begin the conversion cycle and electromagnetic transducers typically output AC voltages well below one volt in magnitude (extra electronics might be needed to boost the output voltage), piezoelectric generators are of primary interest. Most piezoelectric vibration energy harvesters studied so far are based on simple cantilever-based design with resonant frequency matching the environmental resonant frequency. However, the energy conversion efficiency of this type of vibration energy harvester drops dramatically if the environmental frequency and the frequency of the energy harvester are mismatched. This paper proposes a novel multi-mode piezoelectric vibration energy harvester that is suitable for structural health monitoring in an environment with multiple dominant vibration modes.

The multi-mode piezoelectric vibration energy harvester has distributed stiffness and mass and has multiple resonant frequencies adapted to the environmental vibration modes. A multi-mode energy harvester with two interested resonant modes is used as an example to demonstrate this new concept. The multi-mode energy harvester is modeled using Finite Element Method. Modal analysis is based on the numerical model. The efficiency of the multi-mode piezoelectric energy harvester is compared with that of existing cantilever-based piezoelectric energy harvester.

Different from cantilever-based single-mode piezoelectric energy harvester, it is difficult for designers to identify promising constellations in uncharted regions of the vast design solution space and to derive an intuitive analytical solution to guide the design of energy harvesters with complex configuration. An evolutionary design automation and synthesis method is proposed to facilitate the creation of multi-mode piezoelectric energy harvesters given the design objectives, application constrains and material properties.

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6934-36, Session 6

Monitoring damage propagation using PZT impedance transducers

Y. Yang, H. Liu, V. G. M. Annamdas, Nanyang Technological Univ. (Singapore)

Lead Zirconate Titanate (PZT) transducers have been extensively used in the electromechanical impedance (EMI) based structural health monitoring (SHM). Many EMI models have been developed for damage assessment, mostly focusing on single damage identification. However, in real life, structures are frequently subjected to multiple or progressive damages. To effectively monitor the structural health, the issue of monitoring damage propagation in the structure needs to be addressed. In the present paper, EMI technique using surface bonded PZT transducers is employed to obtain the structural health signature. Experimental tests are carried out to study the damage propagation on aluminum plates, where damages are created progressively along the length, width and depth directions of the plates by drilling holes. Health signatures are obtained for each damage state and compared with the signature of non-damage state, followed by the discussion on the characteristics of damage propagation. In addition, for some damaged states, finite element modeling is carried out to verify the experimental signatures. The acquired numerical results are analyzed both qualitatively and quantitatively.

6934-37, Session 6

Quantitative characterization of materials using flash thermography

S. M. Shepard, Y. Hou, Thermal Wave Imaging, Inc.

The potential of thermography as a non-contact, wide-area NDT method has been widely recognized. However, until recently, its application has generally been limited to qualitative applications, where subsurface defects are identified by comparison to a defect-free background or reference standard. In this contrast-based mode, interpretation of data is somewhat subjective, and dependent on the availability and state of the defect-free reference.

Recently, quantitative methods for analysis and interpretation of thermographic data have been developed. In particular, the Thermographic Signal Reconstruction (TSR) method facilitates data interpretation without requiring a reference sample. The TSR method creates a noise-free replica of the data sequence for each pixel. While the replica removes temporal noise from each pixel time history, it does not substantially improve detection of subsurface features or quantitative analysis. However, the derivatives of the replica, taken with respect to $\ln(t)$, provide a significant degree of image enhancement, as well as invariant characteristics that are relatively immune to changes in emissivity, camera performance or ambient conditions. Unlike contrast methods, where an entire image must be viewed to interpret inspection results, a the TSR derivative of a single pixel time history provides a significant amount of information that can be extracted without viewing a reference sample, or even neighboring pixels.

While TSR does not require a reference standard for most NDT applications, if one is available then measurements can be calibrated using TSR derivative characteristics. For example, if the thermal diffusivity of a sample is known, its thickness (or depth of subsurface defects) can be measured. Conversely, if sample thickness is known at a particular location, a thermal diffusivity map can be created.

The TSR method has been successfully applied in composites, metals and ceramics, including complex and multilayer structures, such as the Reinforced Carbon-Carbon leading edge of the NASA Space Shuttle. Examples of applications and the characteristics of the TSR derivatives for several common defect types will be presented.

6934-38, Session 6

Quadrangular grid method for stress wave propagation in 2D orthotropic materials

D. Li, Beijing Jiaotong Univ. (China); T. Liu, Shenyang Jianzhu Univ. (China)

A quadrangular grid method is presented for simulating the propagation of elastic stress waves in two-dimensional orthotropic materials. The

investigated lumps in the orthotropic medium are constructed among the auxiliary quadrangular grids. The dynamic equation of the investigated lump is given by integrating the typical investigated lump. The algorithm is obtained by computing the nodal displacements and the central point stresses of the quadrangular grids alternately in time domain. The numerical results are compared with the corresponding solutions of the finite element method. The results show that the quadrangular grid method is of much higher calculational speed than the finite element method. The stress wave propagation in two layers of orthotropic media is studied and the results show the features of the reflected and refracted wave propagations. This method provides a new tool with substantially low computational cost for wave simulation in the composite of orthotropic media.

6934-39, Session 7

Through-container measurement of acoustic signatures for classification/discrimination of liquid explosives (LEs) and precursor threat liquids

A. A. Diaz, T. J. Samuel, B. J. Tucker, J. D. Valencia, K. L. Gervais, J. S. Thompson, Pacific Northwest National Lab.

Numerous industries, when dealing with sealed closed containers, have expressed the need to determine and or verify the contents of containers rapidly and accurately without opening the container. Domestic and international applications exist in law enforcement, border control, transportation, manufacturing, and shipping. Ensuring international treaty compliance, border control, training, and deterring illicit drug smuggling are also significant applications. Other applications include efforts to collect taxes and tariffs, to effectively maintain liquid inventories, and to monitor liquid process flows. Furthermore, material quality and process control are central to achieving high standards of product performance and safety in such industries as food processing and chemical inventory management. Government agencies and homeland security organizations are constantly searching for more effective approaches for dealing with the increasing requirements for inspections involving hazardous chemical and biological materials, including chemical warfare agents and liquid explosives (LEs). Due to the large number of both hand-held and cargo-sized containers being shipped worldwide, there is a need for technology that enables rapid and effective ways for conducting non-intrusive inspections of liquid-filled containers. Such inspections need to quickly identify/classify the liquids within the containers and also identify the presence of objects not expected to be in a container, including, e.g., smuggled contraband.

The Pacific Northwest National Laboratory (PNNL) has developed a methodology and prototype device for classification/discrimination of a wide variety of liquids (including threat liquids and their precursors), providing noninvasive container liquid classification/discrimination capabilities using nondestructive ultrasonic measurement technology that is rapid, accurate, and simple to operate. PNNL's prototype was developed using an optimized custom electronics platform, advanced ultrasonic wave propagation methods, and advanced signal processing techniques. In the winter of 2006, Department of Homeland Security (DHS) Science & Technology Directorate (S&T) requested the test results from a study PNNL conducted on a variety of commercial liquids in "off-the-shelf" containers using the PNNL Prototype container inspection system. Further, DHS-S&T provided PNNL with a list of commercially available commodities and specific guidance related to the type of containers to be measured. Subsequent measurements in 2007 on additional key precursor LE chemicals were conducted and are reported here.

The results of this work demonstrated that ultrasonic property measurements can be effectively employed for the rapid and accurate classification/discrimination of liquids in small, carry-on, standard "stream-of-commerce" containers. This paper focuses on laboratory measurements acquired with the PNNL prototype device as applied to several types of liquids (including threat liquids and precursor chemicals) to the manufacture of LEs in small commercially available containers. Results of work conducted in the laboratory will be presented and future measurement platform enhancements will be discussed.

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6934-40, Session 7

Enhanced measurement functionality and signal quality through advanced diplexer design for pulse compression acoustics

A. A. Diaz, J. D. Valencia, B. J. Tucker, Pacific Northwest National Lab.

The increase of terrorism and its global impact has made the determination of the contents of liquid filled containers a necessity. The ability to determine and verify the contents of a container rapidly and accurately is a critical tool in maintaining global safety and security. Due to the immense quantities and large variety of containers shipped worldwide, there is a need for a technology that enables rapid and effective ways of conducting non-intrusive container inspections. Such inspections can be performed utilizing "through transmission" or "pulse-echo" acoustic techniques, in combination with multiple frequency excitation pulses or waveforms. The challenge is combining and switching between the different acoustic techniques without distorting the excitation pulse or waveform, damaging or adding noise to the receive circuitry; while maintaining a portable, low power, low cost, and easy to use system.

The Pacific Northwest National Laboratory (PNNL) has developed a methodology and prototype device focused on this challenge. The prototype employs an advanced diplexer circuit capable of rapidly switching between both "through transmission" and "pulse-echo" detection. This type of detection requires isolation of the transmission pulse generated by the pulsing circuitry from the received signal obtained by the receiving circuitry to prevent damage and reduce noise.

The results of this work demonstrate that an advanced active diplexer circuit can be effective for this type of acoustic transmission, however some bandwidth issues exist. This paper focuses on the design, relevance and functionality of the diplexer in the context of rapid acoustic measurement platforms for employing multimodal data acquisition methods. Results and the impact of this diplexer on measurements conducted in the laboratory will be presented and future diplexer design enhancements will be discussed.

6934-41, Session 7

Contraband detection using acoustic technology

R. George, R. Gauthier, Space and Naval Warfare Systems Ctr., San Diego; A. A. Diaz, Pacific Northwest National Lab. and Dept. of Energy, National Security Directorate; K. Denslow, T. Cinson, Pacific Northwest National Lab.; M. Griffin, Spearhead Innovations and MGB, Ltd.

Maritime security personnel have a need for advanced technologies to address issues such as identification, confirmation or classification of substances and materials in sealed containers, during field and 1st response operations, both non-invasively and nondestructively. These materials/substances include items such as hazardous/flammable liquids, drugs, contraband, and precursor chemicals used in the fabrication of illicit materials (e.g. drugs, chemical weapons agents, liquid explosives, etc.). As a result, our efforts have focused on acoustic evaluation technologies with the goal of providing an enhanced, robust, portable detection capability directed at nondestructively sensing contraband in cargo/materials containers, without a need for opening the container, in a maritime environment. Initial field evaluations of a promising commercial portable acoustic detector technology were performed under operational conditions in such a maritime environment. Both technical and operational limitations were identified, associated with its use in a harsh maritime environment and operation by non-technical personnel. Technical efforts were subsequently initiated to incorporate application-specific enhancements that would address these limitations. Once technology enhancements were complete, detector performance was once again evaluated, and significant increases in operational performance were demonstrated. In this paper, application-specific technology enhancements and performance testing/evaluation results will be described. It is expected that the enhancements made to this technology will provide personnel/users of the detector a significantly more reliable method of screening materials for contraband items of potential concern that might be hidden in cargo containers.

6934-42, Session 7

Structure-health assessment and warning system (SHAWS)

D. M. Bock, K. Kim, Physical Optics Corp.

We are developing a Structure Health Assessment and Warning system (SHAWS). SHAWS will measure and predict the stability/instability of a building and determine whether it is safe for emergency responders to enter during an emergency. SHAWS incorporates remote sensing nodes (RSNs) installed on the exterior frame of a building. Each RSN will include a temperature sensor, a three-axis accelerometer making static-acceleration measurements, and a ZigBee wireless system (IEEE 802.15.4). We chose static-acceleration measurements because of the problems that drift poses in standard displacement measurements from accelerometers. Due to the double integration involved in the calculation, the error in any displacement measurement grows exponentially with time. By performing static measurements of the building angular movement relative to the local gravitational field, the system can be made immune to drift. According to device specifications, the noise floor of the accelerometers is 0.05 degrees below the building noise of 0.25 degrees due to wind and day/night transitions. Each RSN will be able to operate with only 10 mAh current, providing maximum lifetime in a 1.5 in. diameter spherical package. SHAWS will use a series of three primary RSNs per building to monitor motion. Each sensor will be deployed using an air-cannon-type system and will attach to the sides of the building. Once the building has moved past a threshold (-0.25 in./story of building), a warning will be issued to emergency responders. We will present initial results of SHAWS development and testing.

6934-43, Session 7

Health monitoring: asset damage detection

F. J. Mauss, B. K. Hatchell, J. R. Skorpik, K. L. Silvers, Pacific Northwest National Lab.

The Health Monitor is a low cost, low power, battery powered device that is capable of measuring temperature, humidity, and shock. Many mission critical items are susceptible to shock damage. To help prevent shock damage, assets are often placed in robust custom containers with shock damping and absorption devices. Assets are still at risk of damage while in their protective containers. Having a Health Monitor attached to an asset or container allows the status of the asset to be determined. The Health Monitor can measure, record, store, analyze and display to the user if a shock event has occurred that puts the asset at risk of failure. Extensive shock testing and algorithm implementation is required to develop a Health Monitor that uses a single point 3-axis accelerometer to determine a shock event's type, height, and severity.

A shock event can occur by many differently means-Handling, transportation, and use. To reduce variability in testing, the Health Monitor was tested with shocks occurring from bench top and vertical drops on 3/4" plywood over concrete. Plywood is used to represent packed dirt and provides a conservative, reliable, and repeatable drop surface. Drop testing was conducted by attaching a Health Monitor to the container, with an asset mass simulant, and then dropping the container on plywood. The Health Monitor was used to capture the shock events. Drop results were also verified by lab grade accelerometers. Initial drop tests with the Health Monitor were used to establish drop characteristics and general trends. The container was dropped in varying orientations ranging from front end flat pivot, aft end flat pivot, front end corner, and vertical drops. After initial testing it was possible, through analyzing the Health Monitors recorded data, to characterize each drop type. Attributes used to characterize the drop type are magnitude, direction, axis of excitation, and axis shock energy. The Health Monitor when mounted on the aft end of the container is able to determine that a front end drop has exceeded a defined threshold. Once a shock event has occurred, it is processed on-board by the Health Monitor electronics. When a shock event is higher than a defined threshold, an alarm light will be displayed when the containers status is evaluated. Each shock type can pose a different damage to the asset and because of the varying nature of each event the ability to apply individual alarm thresholds to each shock type is crucial.

This document focuses on drop testing results acquired with the Health Monitor. Results of the testing show the ability to determine drop type and

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severity using a single point 3-axis accelerometer. The future uses and enhancements will also be discussed.

6934-44, Session 8

Damping performance of colloidal dampers

G. Zhou, Univ. of California/Irvine; B. Johnson, Honda R&D Americas, Inc.; L. Sun, Univ. of California/Irvine

Nano-flow based colloidal damping methodology is a low-temperature and efficient technology. It utilizes porous particles and carrier fluids to compose damping medium. When the medium is subjected to cycle excitation, nano-flow in the channels of porous particles dominates damping effects. It is reported the temperature generation is very lower and is below 10% of the absorbed energy while the damping efficiency can achieve more than 90%. This paper compares the heat generation of the nano-flow based colloidal dampers to that of conventional hydraulic dampers as well as their damping efficiencies. This project was sponsored by Honda Initiation Grant (HIG) jointly run by Honda Research Institute USA and Honda R&D Americas, Inc.

6934-45, Session 8

Through-wall detection and location using ultra-wideband technology

X. Huang, Z. Wei, Stevens Institute of Technology; K. Wang, Monterey Bay Aquarium Research Institute; H. Cui, R. A. Pastore, Stevens Institute of Technology

Recently there is a lot of interest on see-through-wall application. There are a number of situations where the entering of a room or a building is considered hazardous and it is desired to inspect its interior from outside through the walls. Examples include the tracking of people in dangerous environments (for policeman, fireman, etc.), and so on. In these cases, ultra-wideband radar can provide significant help by detecting and localizing the targets. As the primary advantages of UWB for short-range radar include extremely fine range resolution in the order of sub-centimeter, high power efficiency, and low probability of detection.

One of the goals of this article is to illustrate the ability of the UWB radar to detect and localize a target behind walls. In addition, the reflected signals will also be compared with those obtained from the finite-difference time-domain (FDTD) technique.

The measurement setup consists of a UWB transmitter and a digital sampling oscilloscope as the receiver. A localization approach is used to estimate a target position. Suppose one antenna is used for transmitting signals (Tx), and two antennas are for receiving signals (Rx1, Rx2). The approach estimates the round trip time from the transmitter to a target and back to an antenna array element. Multiplying estimated round trip times by the velocity of the wave propagation provides the distances Tx-target-Rx1 and Tx-target-Rx2. These distances are related to axes of an ellipse around the transmitter-receiver antenna pair on which the target can be situated. The position of the target is determined by the intersection of two ellipses.

Two measurements are carried out. First one Tx antenna and one Rx antenna UWB measurement setup is used to obtain range information about a target behind barriers. The experiment is conducted in a typical sophomore laboratory which contains rows of tables. Two horn antennas are used. A steel sheet is placed behind two wooden boards and two carbon boards to extract its range. The range obtained from measurement shows good agreement with the theoretical value. The second measurement is carried out using one Tx antenna and two Rx antennas to extract target position. Also will be done is the comparison of the reflected signals from measurement and that obtained from FDTD.

Experimental investigations on the use of UWB signals for through-wall detection and localization have been discussed. The measurement results demonstrated how it is possible to detect and localize the targets behind walls with UWB signals. One can design a more efficient system for through-wall detection by means of this approach and the proper data processing techniques.

6934-46, Session 8

Design and application of an interdigitated PVDF transducer

H. Gu, Univ. of Illinois at Chicago

The employment of Lamb waves in nondestructive testing has been recognized to have many advantages over the conventional ultrasonic methods. A monolithic interdigitated PVDF transducer (PVDF IDT) has been developed in this study for generating and receiving Lamb waves for structural health monitoring. A design guideline for the applications of the interdigitated transducers on isotropic materials has been derived and verified. This design guideline simplifies the design procedure by eliminating the need of the dispersion curves. It utilizes the fact that Lamb waves are material property dependent, and relates the desired wavelength with the material's Poisson's ratio.

Applications of this PVDF IDT on anisotropic materials have also been explored. Examples given here are the damage detection on carbon fiber reinforced polymer materials (CFRP) with a series of imbedded defects. Results have shown that these PVDF IDTs are capable of yielding responses comparable to both computer simulated and PZT-generated results. They are able to qualitatively identify the existence and the locations of defects by generating size-sensitive and location-sensitive outcomes.

6934-47, Session 8

Use of impedance measurements for crack detection in moderately soft piezoelectric ceramics

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The application of cyclic electric fields causes changes in impedance and shifts in resonance peaks in PZT piezoelectrics. These impedance changes can be correlated to the length of pre-existing cracks generated by Vickers diamond indents and to the growth of these cracks by low cycle electric fields. These findings demonstrate that impedance measurements can be used as the basis of a non-destructive test to cracks in piezoelectric sensors.

6934-48, Session 8

A multifeatured hardware platform for SHM

D. C. Zhang, S. J. Beard, B. Liu, X. P. Qing, A. Kumar, L. Ouyang, Acellent Technologies, Inc.

Structural Health Monitoring (SHM) that uses integrated sensor network to provide real-time monitoring of in-service structures can improve the safety and reliability of the structures significantly. Acellent Technologies' SHM systems based on SMART technology consists of the integrated sensor network, diagnosis hardware platform and the diagnosis software. This paper introduces the latest SMART damage detection hardware platform - ScanGenie and the new analysis software for damage detection in composite and metal structures. The ScanGenie is a portable high-performance hardware that provides many features such as through-transmission, pulse-echo, temperature measurement, self-diagnosis, sensor diagnosis, hot-spot monitoring, etc. The new analysis software is based on the ScanGenie hardware to provide functions such as temperature compensation, auto-gain adjustment, impedance-based diagnosis and probability of detection. The system can be used for damage detection in most composite and metal structures used in markets such as aircraft, spacecraft and civil infrastructures.

6934-49, Session 8

Experimental study on decision fusion of many damage-detection methods with multiresolution

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Conference 6934: Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security II

This paper describes the use of decision fusion strategies in damage detection. These techniques fuse multiple individual damage detection measures to form a detector with higher probabilities of correct detection than that attainable with any of the individual measures. In this paper, these techniques are applied to vibration-based damage detection methods. As a demonstration of the methodology, the first step was to fabricate an experimental fixture which the vibration properties of damaged and undamaged structures can be measured. The experimental results with the undamaged structural model provided information for producing an improved theoretical and numerical model of the mechanics via model updating techniques. Three common vibration-based damage detection methods using a varied multi-resolution on the experimental results were implemented to identify the damage that occurred in the structure. Finally, the strategy to join the information from the three methods with multi-resolution decision fusion rules is introduced. The fused results are shown to be superior to that from only one method.

6934-50, Session 8

Stochastic subspace-based damage localization: application to the ASCE benchmark structure

W. Zhou, Harbin Institute of Technology (China); L. Mevel, Institut de Recherche en Informatique et Systèmes (France)

The vibration-based structural health monitoring problem is addressed as the double task of detecting damages modeled as changes in the eigenstructure of a linear dynamic system, and localizing the detected damages within the monitored structure. This paper describes a damage localization algorithm that is based on a residual generated from a subspace-based covariance-driven identification method and on the statistical local approach to the design of detection algorithms. In this method, damage localization consists in determining which part of the structure has been affected by the damage, more precisely which (groups of) elements of the structural parameters matrices (e.g. M , C , K) have changed. This algorithm basically computes a global test, which performs a sensitivity analysis of the residual to the damage, relative to uncertainties and noise. The damage localization problem is addressed by plugging aggregated sensitivities of the eigenvalues and mode-shapes with respect to finite element model structural parameters. In the proposed damage localization algorithm, it is assumed that a signature of the structure in its safe state is available. This signature is usually identified using reference data, possibly recorded under an unknown non-stationary excitation. The damage localization algorithm processes new data by first generating a residual, and computing its sensitivity with respect to damages. The purpose of this work is to describe the damage localization algorithm and apply to assess the ASCE benchmark structure state. In this study, the undamaged data will be the reference output to obtain the test value (damage index) for the other damaged case. Moreover, the other three essential steps, modes matching, Jacobian fusion and the computation of sensitivities of analytical modes to structural parameters, are also described. The corresponding results are shown. At last, the results of identification and damage localization will be presented. These final results indicate that the algorithm is able to localize the damage in the example structure.

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6935-01, Session 1

Real-time dual-channel ultrasonic imaging of composite aircraft structures

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A commercial real-time ultrasonic imaging camera is integrated with an A-scan data acquisition channel for concurrent in-plane and in-depth real-time evaluation of large area composite aircraft structures. The combined instrument provides high-resolution in-plane images (X-Y plane) of the structures while simultaneously providing "in-depth" ultrasonic A-scans along the Z-axis.

The highest resolution and quality of the ultrasonic images are usually achieved at or close to the focal plane of the imaging device. Full coverage ultrasonic inspections of composite aircraft structures with variable thickness and unknown depth of potential defects would require continuous real-time refocusing of the imaging system. This very challenging imaging procedure will, in turn, necessitate development of complex and expensive hardware and software modules.

On the other hand, the integrated imaging/A-scan system can provide "on demand" refocusing of the imaging plane. Initially, the ultrasonic data are collected and analyzed by the "in-depth" acquisition channel. Without any flaw indications the "in-plane" imaging channel remains focused at a pre-selected depth. Any ultrasonic signal that can be qualified by the "in-depth" channel as a flaw indication will result in real-time automatic refocusing of the imaging channel in order to acquire high resolution defect images at the desired depth.

Additionally, the A-scan data acquisition channel is utilized as an independent inspection tool for quantitative evaluation of the detected abnormalities. Combination of the A-scan data with the two-dimensional ultrasonic images provides real-time three-dimensional information about condition of the composite aircraft components. This kind of information can be extremely important for rapid assessment of composites in both manufacturing and in-service maintenance of the aircraft structures.

Applications of the dual-channel real-time ultrasonic imaging system on composite aircraft structures with various internal manufacturing defects and low-velocity impact damage will be presented.

6935-02, Session 1

Detection of impact damage on thermal protection systems using thin-film piezoelectric sensors for integrated structural health monitoring

J. K. Na, S. J. M. Kuhr, Univ. of Dayton Research Institute; K. V. Jata, Air Force Research Lab.

Thermal Protection Systems (TPS) can be subjected to impact damage during flight and/or during ground maintenance and/or repair. AFRL/MLLP is developing a reliable and robust on-board sensing/monitoring capability for next generation thermal protection systems to detect and assess impact damage. This study was conducted on Ceramic Matrix-Composite (CMC) wrapped tiles and two classes of metallic thermal protection tiles to determine threshold for impact damage and develop sensing capability of the impacts. Sensors made of PVDF piezoelectric film were employed and tested to evaluate the detectability of impact signals and assess the onset or threshold of impact damage. Testing was performed over a range of impact energy levels. The signal levels detected by the sensors adhered to the back of the specimens were analyzed and then compared to assess damage obtained by other NDE techniques such as Computed Tomography (CT) X-ray and White Light Interferometry. Based on the current impact test results, an attempt is made to compare the impact damage thresholds for each type of TPS system.

6935-03, Session 1

Detection of disbonds in a honeycomb composite structure using guided waves

H. K. Baid, Univ. of California/Los Angeles; S. Banerjee, St. Louis Univ.; A. K. Mal, Univ. of California/Los Angeles; S. P. Joshi, NextGen Aeronautics, Inc.

Advanced composites are being used increasingly in state-of-the-art aircraft and aerospace structures. In spite of their many advantages composite materials are highly susceptible to hidden flaws that may occur at any time during the life cycle of a structure and if undetected, may cause sudden and catastrophic failure of the entire structure. An example of such a defects critical structural component is the "honeycomb composite" in which thin composite skins are bonded with adhesives to the two faces of extremely lightweight and relatively thick metallic honeycombs. These components are often used in aircraft and aerospace structures due to their high strength to weight ratio. Unfortunately, the bond between the honeycomb and the skin may degrade with age and service loads leading to separation of the load-bearing skin from the honeycomb (called "disbonds") and compromising the safety of the structure. This paper is concerned with the noninvasive detection of disbonds using ultrasonic guided waves. Laboratory experiments are carried out on a composite honeycomb specimen containing localized disbonded regions. Ultrasonic waves are launched into the specimen using a broadband PZT transducer and are detected by a distributed array of identical transducers located on the surface of the specimen. The guided wave components of the signals are shown to be very strongly influenced by the presence of a disbond. The experimentally observed results are being used to develop an autonomous scheme to locate the disbonds and to estimate their size. In addition, a theoretical model is being developed in an effort to understand the characteristics of guided wave modes in these novel structures.

6935-04, Session 1

Embedded nonlinear ultrasonics for structural health monitoring of satellite joints

A. N. Zagrai, New Mexico Institute of Mining and Technology; B. J. Arritt, Air Force Research Lab.; D. Doyle, New Mexico Institute of Mining and Technology

Responsive space satellites must be assembled and tested in extremely short time. Integrity of structural joints is one of major concerns during satellite assembly and qualification processes. A structural health monitoring (SHM) approach based on nonlinear ultrasonics is suggested for rapid diagnostics of structural connectors and joints. Embedded piezoelectric sensors are utilized to enable propagation of elastic waves through bolted aluminum panels. Signal parameters indicative of the nonlinear behavior are extracted from the received waveforms and are used for assessment of structural integrity. Experimental studies reveal variation of the nonlinear response of the joint due to applied structural loads. These changes are explored as diagnostic features of the method. We discuss theoretical aspects of the nonlinear wave propagation through joints and provide experimental data showing feasibility of the embedded nonlinear ultrasonics method for monitoring of structural integrity.

6935-05, Session 1

Enhanced damage detection of bladed disk structures with piezoelectric networks

R. C. Struzik, H. Yu, K. Wang, The Pennsylvania State Univ.

Damage detection in engine bladed disks is an extremely important task. Bladed disks operate in a harsh environment where loading fatigue and foreign object impact can induce crack damages and lead to catastrophic failure when undetected. Currently, damage detection of bladed disks is often exercised through ultrasonic and eddy current techniques. While these methods are reliable, they are also expensive in cost and maintenance time, and cannot be used for in-situ monitoring. Alternatively,

global vibration-based damage detection techniques are relatively simple and inexpensive to implement, and have the potential for real-time in-situ applications. However, vibration-based identification is in general not accurate due to its low sensitivity to damage. On the other hand, for a periodic structure such as the bladed-disk system, due to its unique localization characteristics, there is great potential in utilizing a vibration-response-based concept to effectively and accurately detect damage.

The goal of this research is to advance the state-of-the-art of damage detection of bladed disks by developing an innovative piezoelectric circuitry networking methodology that can temporarily induce or intensify structural vibration localization to amplify the damage effect on the system vibratory signature during the inspection stage. The concept is to form an electro-mechanical wave channel to enhance localization through energy redistribution and wave reflection. Under the temporarily intensified localization, a small damage can now cause drastic differences in the vibratory signature, thus making the system more sensitive to damage and enabling robust detection. In this research, enhanced localization and damage sensitivity is achieved by tuning the piezoelectric network parameters to yield an additional narrow vibration frequency passband. Monte Carlo simulations are performed to refine the network tuning and evaluate its effectiveness under a range of inherent mistuning levels, where promising results are illustrated.

6935-06, Session 2

Sensing and actuation of smart chiral honeycombs

F. L. Scarpa, Univ. of Bristol (United Kingdom); H. Abramovich, Technion-Israel Institute of Technology (Israel); K. Tee, Univ. of Bristol (United Kingdom); C. W. Smith, K. E. Evans, The Univ. of Exeter (United Kingdom); M. Burgard, M. Hoffmeister, Fraunhofer-Institut für Produktionstechnik und Automatisierung (Germany)

A novel concept of auxetic (negative Poisson's ratio) honeycomb for active microwave absorbers and structural health monitoring applications has been developed within the European FP6 project CHISMACOMB (CHiral SMARt honeyCOMB). The honeycomb concept is made of tessellating cylinders and joining ligaments to form a noncentrosymmetric structure, with PMC devices embedded in the core. The honeycomb features a negative Poisson's ratio effect, synclastic curvature, enhanced compressive strength properties and sensing and actuation characteristics because of the piezo elements embedded. A tetrachiral demonstrator is developed and manufactured, subjected to dynamic testing (modal analysis). The response of the piezosensors under broadband white noise excitation is measured to evaluate the sensing capabilities of the honeycomb. Actuation authority is probed using progressive voltage loading. Numerical models are developed to simulate the piezoelectric response of the smart honeycombs and their mechanical performance.

6935-07, Session 2

Recent advances on pipe inspection using guided waves generated by electromagnetic acoustic transducers

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For several years guided waves have been used for pipe wall defect detection. Guided waves have become popular for monitoring large structures because of the capability of these waves to propagate long distances along pipes, plates, interfaces and structural boundaries before losing their strengths. The current challenge is to detect small defects in the pipe wall using appropriate guided wave modes and to generate those modes relatively easily for field applications. Electro-Magnetic Acoustic Transducers (EMAT) can generate guided waves in pipes in the field environment. This paper shows how small defects in the pipe wall can be detected by appropriate signal processing technique applied to the signals generated and received by EMAT.

6935-08, Session 2

Passive-only wave-based structural health monitoring from ambient noise

K. G. Sabra, Georgia Institute of Technology; A. Srivastava, Univ. of California/San Diego; A. Duroux, Georgia Institute of Technology; F. Lanza di Scalea, I. Bartoli, Univ. of California/San Diego

A new passive imaging technique has been recently demonstrated in ultrasonics, underwater acoustics and seismology to extract Green's functions (impulse responses) from apparently-incoherent, diffuse noise fields. The Green's function emerges once the cross-correlation between noise recordings at two receivers is computed and averaged over time.

It is here proposed to apply this concept to the structural health monitoring (damage detection) of aircraft structures, such as wing skin panels. Random vibrations generated by air-turbulence and scattered waves will be examined as sources of diffuse noise fields. Guided stress waves propagating in simulated wing panels will be extracted from the diffuse noise recorded by pairs of receivers (thus in a passive-only mode). This method will allow eliminating (or keeping to a minimum) active sources while preserving the advantages of active-passive guided-wave monitoring (i.e. ability to detect existing damage, in addition to occurring damage). The passive-only structural monitoring array would require low-power supply lending itself, for example, to wireless transmission. Other advantages would include the possibility for monitoring several guided wave modes simultaneously (thus likely increasing the sensitivity to damage), and the exploitation of the inherent structural complexities of actual aircraft wings as scattering sources beneficial to the coherent wave extraction process.

In this paper the Green's function reconstruction will be demonstrated on laboratory specimens where theoretical impulse responses will be predicted by semi-analytical finite element methods. The potential for defect imaging from the noise-reconstructed waves will be also demonstrated by comparing the reconstructed wave interaction with defects to predictions from global-local wave propagation models. It will be shown that the passive-only imaging technique gives results comparable to those of conventional active-passive testing but without using coherent active sources.

6935-09, Session 2

Instantaneous crack detection using dual PZT transducers

S. B. Kim, Carnegie Mellon Univ.; H. Sohn, Korea Advanced Institute of Science and Technology (South Korea)

A new methodology of guided wave based NDT is developed to detect crack damage in metallic plates without using prior baseline data. In conventional guided wave based methods, damage is often identified by comparing the current data with the past baseline data collected at the pristine condition of a structure. However, this type of pattern comparison can lead to increased false alarms due to its susceptibility to varying operational and environmental conditions of the structure. In order to tackle this issue, a reference-free NDT technique is developed using dual PZT transducers. Crack formation creates Lamb wave mode conversion due to a sudden change in the thickness of the structure. Then, the proposed technique instantly detects the appearance of the crack from the measured Lamb waves. Numerical and experimental results are presented to demonstrate the applicability of the proposed technique to instantaneous crack detection.

6935-10, Session 2

Ultrasonic wireless sensor network and automated data analysis algorithms for health monitoring of structural components

S. Banerjee, B. Sholy, K. Mitchell, St. Louis Univ.

This work aims at developing a compact and mobile wireless structural health monitoring system (WSHM). The system retrieves ultrasonic wave propagation data remotely, and analyzes the collected data using three distinct but complementary analysis approaches. The analysis

provides an insight into the state of health of the structure under test as a function of time. The three approaches are designed to overcome the complexity and variability of the signals in the presence of damage as well as the geometric complexity of the structure, requiring minimal operator intervention. Each of the three methods relies on detecting changes in the dynamic and physical properties of structural components that are initiated by new damage or growth of existing damage. The methods establish a baseline drawn from measurements done on an undamaged or partially damaged structure. This baseline is used to monitor for changes in the health of the structure. Certain damage indicators, such as damage indices, system-difference norms and spectral amplitudes variation, are evaluated “instantly” by comparisons between the frequency response of the monitored structure and an unknown damage under the same ambient conditions. The methods are applied to identify several types of structural defects in steel girders and stiffened composite panels for different arrangements of the source and the receivers. The objectives are to deliver an early indication of the risk associated with the defect and to develop inspection and mitigation strategies to manage the risk using detailed, local, nondestructive evaluation of the areas identified with possible defects. The wireless data acquisition system and the automated data analysis tool developed under this work should improve the reliability of the defects detection capability and aid in the development of near real-time health monitoring systems for defects-critical structures.

The project is funded by the Missouri Transportation Institute (MTI) and is part of the ongoing activities of the Center for Sensors and Sensor Systems at Saint Louis University.

6935-11, Session 3

Design and characterization of the CLoVER transducer for structural health monitoring

K. I. Salas, C. E. S. Cesnik, Univ. of Michigan

Structural health monitoring (SHM) is the component of damage prognosis systems responsible for interrogating a structure to detect, locate, and identify any damage present. Guided wave (GW) testing methods are attractive for this application due to the ability of GWs to travel over long distances with little attenuation and their sensitivity to different damage types. Typically, GWs are excited using surface-bonded piezoelectric transducers. Among these, anisotropic piezocomposite transducers (APT) offer numerous advantages over conventional piezoelectric wafers, such as the ability to produce focused strain fields, enhanced surface conformability, and a larger strain energy density. However, state-of-the-art transducer configurations are unable to efficiently interrogate large structural surfaces for damage identification.

The proposed paper will introduce the Composite Long-range Variable-length Emitting Radar (CLoVER) transducer as an alternative concept for efficient damage interrogation and GW excitation in GW-based SHM systems. This transducer has an overall ring geometry, but is composed of individual wedge-shaped sectors that can be individually excited to interrogate the structure in a particular direction. Each wedge-shaped sector is made with piezocomposite fibers in an interdigitated electrode pattern. The multiple advantages over alternative transducer concepts will be examined in detail. The overall configuration of the proposed transducer concept allows the efficient generation of GWs, which is related to magnitude of the strains that the transducer can induce for a given input. Previous work by the authors has shown that due to the geometry of each sector, the expected GW amplitudes induced are at least 50 % larger than those obtained for a ring configuration using similar electric current inputs. Similar studies by the authors have shown that employing a CLoVER sector with a small azimuthal span, combined with the anisotropic actuation of the APT technology, produces directional wave fields that minimize losses by concentrating the actuation along a desired direction. Finally, due to the composite construction of this device, it is more resistant to damage than alternative configurations based on piezoelectric wafers.

The design and manufacture process of the CLoVER actuator will be presented in detail. An important feature of the transducer concept is its interdigitated electrode pattern. Each sector has been designed with two radial subdivisions that give the actuator the flexibility to act as a combined acting and sensing element. In addition, the subdivisions can be used to compensate for environmental conditions, or to modify the radial dimension of the sector according to the substrate thickness or damage

type to be detected. The CLoVER actuators were manufactured using an adaptation of the standard macro-fiber composite (MFC) fabrication procedure presented by NASA. This adaptation, particularly as it relates to the cure schedule and actuator polarization, will be described in detail, and supporting experimental studies will be presented.

The damage interrogation approach employed with the CLoVER transducer will also be described and experimentally implemented. The transducer is excited in a sequential manner with each sector acting independently. After one sector is excited, all CLoVER sensors are activated to receive reflections from any damage present. After a small time delay to complete this process, the next sector is excited. This process is repeated until the complete structural area has been covered. Results on the experimental implementation of this approach will be presented.

6935-12, Session 3

Lamb wave propagation in negative Poisson's ratio composites

C. Remillat, P. D. Wilcox, F. L. Scarpa, Univ. of Bristol (United Kingdom)

Negative Poisson's ratio (auxetic) composites have shown recently experimental evidence of enhanced damage tolerance characteristics under low kinetic energy impacts. In this work we investigate the Lamb wave propagation characteristics in auxetic laminates with negative through-the-thickness values manufactured using custom cross-ply stacking sequences. Analytical models are developed to describe the dispersion curves. The models are validated with time domain FE simulations, highlighting some very peculiar propagation of modes for the composites in the auxetic phase.

6935-13, Session 3

Structural health monitoring of aerospace applications with restricted geometry

R. T. Underwood, E. D. Swenson, S. Soni, Air Force Institute of Technology

Structural health monitoring (SHM) systems allow aircraft maintainers to monitor regions of an aircraft structure that have been known to fail, also referred to as “hot-spot” monitoring, especially inaccessible regions of the aircraft. The SHM approach evaluated here uses piezoelectric transducers to create Lamb waves, guided elastic waves, to detect through-thickness cracks using a multi-transducer “pitch-catch” technique. The Lamb waves are propagated or “pitched” by a single piezoelectric actuator and sensed or “caught” by multiple piezoelectric sensors to monitor a variety of paths in the “hot-spot” region. This SHM approach is developed for application on a bulkhead in a high performance aircraft with known cracks. This problem is challenging because the restricted geometry results in reflected Lamb waves arriving at the sensors near to or at the same time as the incident waves and the large thickness changes at the boundaries of the vertical plate cause mode conversion in the reflected waves. Therefore, the approach taken in this research is to collect data from three experiments in order to validate finite element (FE) models on which the SHM approach will be evaluated and compared to measured data.

The goal of the first experiment is to collect responses for validation of the FE modeling approach and achieve a better understanding of the propagation characteristics (dispersion, time-of-flight, mode amplitude, etc.) of Lamb waves in a simple plate of similar thickness as the vertical plate in the bulkhead. Two pairs of 0.25 in round piezoelectric actuators are attached 12 in apart on opposite sides and near the middle of a 36 in by 48 in flat plate (0.125 in thick 6061-T6 Al). The peak magnitudes of the S₀, first symmetric, or A₀, first anti-symmetric, modes are recorded and used for a “tuning” approach where the amplitude of either mode is maximized by selecting the best excitation frequency.

In the second experiment, 8 in by 12 in test sections are milled from the previously discussed large plate to represent only the vertical section of the bulkhead. Two rows of six sensors are mounted to this test section more than 2 in apart, from which Lamb waves are generated from one actuator and received at 6 sensors on the opposite side of the damage, which will be simulated using electrical discharge machine (EDM) cuts. The damage will be incrementally introduced to the test plate to simulate

a propagating crack starting midway between the rows of sensors. After each EDM cut, the amplitude of the S0 or A0 modes will be recorded using a "tuning" approach to detect damage and further validate the FE model.

The goal of the last experiment is to further validate the FE modeling approach using data from test specimens with real cracks. First, additional test sections are milled from the large test plate and fatigue cracks are propagated in the small plate using a 110 kip MTS 810 material test system. The piezoelectric actuators are mounted in the same configuration as the second experiment and responses are recorded in the same fashion.

FE models developed and validated using data from this stepwise experimental approach should result in an FE model that closely replicates the behavior of Lamb waves propagating in a damaged bulkhead. In the end, assessing the practicality of using FE models for designing SHM systems for damage detection problems with restricted and challenging geometry should prove useful.

6935-14, Session 3

Guided wave SHM with distributed sensor network

A. J. Croxford, P. D. Wilcox, B. W. Drinkwater, Univ. of Bristol (United Kingdom)

The detection of unanticipated localised damage at any location in a large structure is a generic challenge in structural health monitoring (SHM) that has applications across a wide range of industries. These include, the detection of impact induced delamination in aerospace composites, localized corrosion in petrochemical plant and malicious penetrations of shipping containers. Guided waves provide one of the only potential detection mechanisms for large area SHM using a sparse array of sensors, as they combine both significant propagation range and sensitivity to damage. The challenge in their application is discriminating between large signals from benign structural features (e.g. edges, stiffeners, welds) and small signals from damage. In the context of deployable guided wave NDE systems this limits applications to structures with low feature densities, such as pipes and rail. For a permanently attached system, the opportunity to compare measurements with a reference measurement potentially provides a solution to the problem of structural complexity. Typically, a reference measurement is subtracted from a current measurement to suppress the signals from structural features.

The remnant signal can then be used to indicate the presence of damage in the structure through the presence of large residuals. While providing information as to the presence of damage this does not initially give information as to the damage location. The arrival time of any residual signal can be used to generate an intensity map indicating a region of probability where the new signal may be. The shape of this region being determined by the nature of the signal processing applied. If this data is collected from several pairs of sensors, the intensity maps from each pair can be added together to triangulate the location of the damage, with three pairs of sensors being the minimum required.

In this paper two signal processing techniques are applied and their performance investigated. The first looks at the arrival time of a large residual. This arrival time can be equated to a propagation distance when plotted as a potential location this generates an ellipse with foci at the locations of the transmitting and receiving transducers. The second approach looks at the difference in the arrival times of a large residual between two pairs of transducers. This difference in arrival time can be used to plot a hyperbola indicating the damage location. The paper looks at the relative performance of each of these techniques for damage location, both within the area described by the sensors and outside of it. The paper investigates how these techniques can be used with multiple units of three sensors to allow detection of damage over a larger area. It discusses whether each pair of sensors should be confined to the detection of damage within its local individual unit or should be used to interrogate the entire structure. These investigations are carried out using both experimental data and analytical models of the guided wave system.

6935-15, Session 3

Coupled NDE-durability approach for predicting life of insulated wires

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Exposure of electrical wires to heat, flexing, vibration and cyclic thermo-mechanical loads are the main causes of degradation in the insulation materials of aircraft electrical systems. Damage of wiring insulation represents a serious risk for the air transportation industry. As a consequence there is currently the need for nondestructive techniques capable of discovering such critical defects.

The proposed paper focuses on the use of ultrasonic guided waves as a tool to detect damage in insulation of electric wires. The experimentation effort will attempt to identify guided mode-frequency combinations sensitive to defects. Experimental data will be used to validate a semi-analytical finite element method able to predict the propagation of stress waves in damaged insulated wires. The combined numerical experimental approach has the potential to help in the inspection of aircraft electrical systems, to assess the wire aging and predict when repair or replacement will be required.

6935-16, Session 3

Excited guided elastic waves of PZT fiber transducers and impact interaction in CFRP structures using 3D laser scanning vibrometry

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The paper presents the use of PZT fiber transducers to generate guided elastic waves in a CFRP plate. After the excitation of a fiber transducer, different elastic waves emerge in a plate. By using special 3D laser scanning software it was possible to specify the different wave modes. These wave modes have been described concerning parameters like velocity and intensity. After scanning a large area it was possible to quantify the occurring damping of each wave mode in the CFRP structure. Subsequently, some impacts were introduced in the structure. The interaction of different wave modes is shown. In some experiments, it was proven that impact locations can be derived from the detected Lamb waves. This work is continued to develop special structural health monitoring systems (SHM) for selected aircraft components (e. g. stringer elements, panels).

6935-17, Session 3

Quantification of environmental compensation strategies for guided wave structural health monitoring

P. D. Wilcox, A. J. Croxford, B. W. Drinkwater, Univ. of Bristol (United Kingdom)

The detection of unanticipated localised damage at any location in a large structure is a generic challenge in structural health monitoring (SHM) that has applications across a wide range of industries. These include, the detection of impact induced delamination in aerospace composites, localized corrosion in petrochemical plant and malicious penetrations of shipping containers. Guided waves provide one of the only potential detection mechanisms for large area SHM using a sparse array of sensors, as they combine both significant propagation range and sensitivity to damage. The challenge in their application is discriminating between large signals from benign structural features (e.g. edges, stiffeners, welds) and small signals from damage. In the context of deployable guided wave NDE systems this limits applications to structures with low feature densities, such as pipes and rail. For a permanently attached system, the opportunity to compare measurements with a reference measurement potentially provides a solution to the problem of structural complexity. Typically, a reference measurement is subtracted from a current measurement to suppress the signals from structural features.

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The remnant signals from structural features after subtraction are termed post-subtraction noise and determine the sensitivity of the system. The subtraction never provides perfect suppression in practice due to environmental changes such as temperature. Subtraction of reference signals without compensation leads to unacceptably high post-subtraction noise in the presence of modest environmental changes. Hence some form of compensation is necessary. In this paper, various compensation strategies are investigated and their performance quantified. Simply stretching or contracting the time-axis of a time-domain signal is shown to provide a first order compensation for small temperature changes but also introduces noise due to frequency distortion that increases with the amount of temperature change. Theoretically, superior performance is achievable over larger temperature changes by applying a correction for the frequency distortion, but the practical implementation of this approach is problematic. For this reason it is concluded that the best performance that can currently be achieved is by combining an ensemble of reference signals recorded at different temperatures with time-domain stretching. The procedure is to extract the best matched signal from the ensemble of reference signals to provide a coarse match to the current signal, and then to iteratively stretch or contract the time-axis of this signal to fine tune the match. This approach limits the maximum temperature change that needs to be numerically compensated for, and hence alleviates the problem of frequency distortion. Factors such as the length of time-window considered, sensor variations and inhomogeneous temperature variations are also addressed. The extension to sensor networks is discussed.

6935-82, Session 3

Wireless structural health monitoring for critical members of civil infrastructures using piezoelectric active sensors

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No abstract available

6935-18, Session 4

Damage diagnostics of metallic structures using magneto-mechanical impedance technique

A. N. Zagrai, H. Cakan, New Mexico Institute of Mining and Technology

The paper discusses application of a Magneto-Mechanical Impedance (MMI) technique for damage diagnostics in metallic structures. A magneto-elastic active sensor consisting of a coil and a permanent magnet is utilized for generation of elastic waves via the eddy current mechanism. The generated waves travel in the host structure and reflect off boundaries producing standing (modal) spatial patterns at respective resonance frequencies. Frequency dependent response to the applied excitation is obtained by the same sensor and is presented in terms of the dynamic impedance. It is shown that the impedance measured in the MMI technique reflects structural dynamic characteristics such as resonances and anti-resonances. Experimental studies involving simple and complex structural elements are presented that explore MMI spectral features for damage diagnostics. Comparison of the impedance data reveals shift and redistribution of impedance peaks in the MMI spectra associated with the damaged samples. We conclude that MMI technique can be employed for structural diagnostics in the embedded SHM or re-configurable NDE formats.

6935-19, Session 4

Modeling of elastic wave scattering by a hole in a half-space using distributed point source method

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In NDT (nondestructive testing) often a side-drilled hole (circular cavity) is used for calibration. In this paper scattering of ultrasonic waves by a circular hole is studied. The ultrasonic wave is generated by a transducer

of finite dimension. A newly developed semi-analytical technique called Distributed point source method (DPSM) has been adopted to solve this problem. Even though this is an old problem the complete picture of the scattered wave field due to a hole in a half space near its boundary has not been shown in the literature yet. The scattered ultrasonic field (stress and displacement) is computed using DPSM and presented in the paper. Solution of this problem will also help us to understand the distortion of the ultrasonic field in the half-space due to the presence of a circular anomaly (cavity or inclusion) which plays an important role in structural health monitoring.

6935-20, Session 4

Microcapacitive sensor for delamination monitoring

B. Sun, Cape Peninsula Univ. of Technology (South Africa)

The paper present a novel technology on the delamination detecting by using a micro capacitive sensor with self power supply generated by PVDF sensor.

The delamination of composites is a dominate damage, its detecting is a quite difficulty problem for industry specially in the case of military application. The real-time of delamination detecting without external power supply is even more attractive.

The delamination will always cause the debonding of layer, which will generate a distance change of the two attached layers, by using the capacitive sensing technology will sensing the change of the distance. It can be very sensitive. The power supply will given by a PVDF sensor which deformed with the composites.

6935-21, Session 5

Active ultrasonic joint integrity adjudication for real-time structural health monitoring

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Recently, the Department of Defense unveiled its Operationally Responsive Space (ORS) initiative to ensure US space superiority well into the future. The ORS strategy hinges, in part, on realizing technologies which can facilitate the rapid development and deployment of satellites. Presently, structural flight qualification testing and vehicle integration processes are time consumptive and pose as two significant hurdles which must be overcome to effectively enhance US space responsiveness. As such, there is a growing demand for innovative embedded Structural Health Monitoring (SHM) technologies which can be seamlessly integrated onto space hardware and function in parallel with satellite construction to mitigate lengthy "check out" procedures.

In this effort, the primary thrust of our work is focused on the development of a joint connectivity monitoring algorithm which can detect, locate, and assess preload in bolted joint assemblies. This algorithm inherently relies upon novel guided wave strategies and state space reconstructed features. We test this algorithm in a series of numerical simulations and in two experimental test configurations with both single and multiple joint structures. We conclude with a discussion surrounding further development of this approach into a commercial product as a real-time flight readiness indicator.

6935-22, Session 5

Nonlinearity detection in multiple degree-of-freedom systems using the auto-bispectral density

J. M. Nichols, Naval Research Lab.; P. Marzocca, A. Milanese, Clarkson Univ.

Higher-order spectra (HOS) appear often in the analysis and identification of nonlinear systems. The auto-bispectrum is one example of a HOS and is frequently used in the analysis of stationary structural response data to detect the presence of structural nonlinearities. In this work we derive an expression for the auto-bispectrum of a multi-degree-of-freedom structure

with quadratic nonlinearities. A nonlinearity detection strategy, based on estimates of the bispectrum, is then described. The performance of this detector is quantified using a Receiver Operator Characteristic (ROC) curve illustrating the trade-off between Type-I error and power of detection (1-Type-II error). Theoretically obtained ROC curves are compared to those obtained via simulation.

6935-23, Session 5

Trispectrum analysis to detect cubic nonlinearities in structural systems

J. M. Nichols, Naval Research Lab.; A. Milanese, P. Marzocca, Clarkson Univ.

Non-linear interactions between vibration modes in mechanical systems have been recently studied in the context of structural health monitoring, in particular when damage appears as a nonlinearity. High order spectral analysis techniques provide insight into the origin and role of the interaction process, and may be used to predict various aspects of nonlinear behavior. This can finally prove useful in detecting and quantifying damage. The bispectrum and trispectrum, in particular, are recognized as useful tools in testing for the presence of quadratic and cubic nonlinearities, based on a response of the system to a stationary stochastic excitation. In this work, a special class of mechanical systems that may be represented by a Duffing oscillator is considered. Analytical expressions for the third order auto- and cross-spectra are determined using a Volterra functional approach. The presence and extent of nonlinear interactions between frequency components are identified, and the rich underlying structure of such spectra is shown. Numerical simulations accompany the analytical solutions. Finally, it is shown how these results can be used to identify the source of nonlinearity, that in many applications can be related to the appearance of a structural damage.

6935-24, Session 5

Implementation of nonlinear acoustic techniques for crack detection in a slender beam specimen

M. Haroon, D. E. Adams, Purdue Univ.

Techniques that analyze nonlinear transformations of high frequency vibration signals, such as harmonic distortions and frequency modulations, termed nonlinear acoustic techniques (NAT), offer unique advantages in detecting and characterizing structural damage. Linear techniques are limited in the ability to detect small incipient damage and false indications caused by environmental variability and structural features of comparable size to damage. Defects with contact surfaces, such as cracks and delaminations, lead to strong nonlinear behavior in the form of nonlinear frequency interactions. The advantage of NAT over traditional linear techniques in detecting incipient small-scale nonlinear damage is demonstrated by initiating and identifying a fatigue crack in notched beam specimens. Vibro-modulation (VM) and impact modulation (IM) are utilized to identify frequency modulation caused by the initiation of fatigue cracks. Piezo-stack actuators and modal impact hammers are used to generate structural excitations measured using high frequency accelerometers. Practical implementation issues of NAT are discussed, such as characterizing the inherent nonlinearities of actuators, bonds and sensors for reliable defect characterization.

6935-25, Session 5

Damage detection in structures through nonlinear excitation and system identification

M. R. Hajj, G. G. Bordonaro, A. H. Nayfeh, B. K. Hammad, J. C. Duke, Jr., Virginia Polytechnic Institute and State Univ.

This work aims at the assessment of a procedure based on nonlinear excitation and system identification for damage characterization in structures. Two systems representative of different structural elements and damage conditions are considered. The first experimental subject consists of a slender beam carrying a lumped mass. For this element,

damage was induced by subjecting it to large amplitude oscillations through a parametric excitation. These large oscillations caused the beam to be fatigued. The second experimental subject is a frame that consists of three beams attached to a base and two corner masses. The damage to the three-beam frame is introduced by loosening the screws connecting the masses to the horizontal beam and is representative of a fastener failure as would be observed in many applications. The damage identification procedure is based on comparing sensitivities of different system parameters including natural frequency, linear and nonlinear damping, and nonlinear parameters to damage over its successive stages. These system identification techniques are based on a combination of perturbation analysis of governing equations for the structural response and higher order spectral analysis of measured data.

For the beam-mass system, frequency sweeps were performed whereby the system was excited over a small range near twice its natural frequency. Variations in the steady-state amplitude as a function of the frequency of the excitation were then recorded. The results show an increase in the response amplitude as the excitation frequency is decreased to approach twice the natural frequency. Further decrease in the frequency of the excitation caused a sudden jump to near zero levels in the response. As the excitation frequency was decreased further, the response amplitude increased again indicating a change in the natural frequency. Our initial assessment is that this change was caused by fatigue induced into the beam through the extremely large amplitude oscillations encountered when the system was excited near twice its natural frequency.

The three-beam frame is excited harmonically with the excitation frequency set at 7.16 Hz; i.e. near twice its natural frequency. The damage to the three-beam frame is introduced by loosening the screws connecting the masses to the horizontal beam and is representative of a fastener failure. Data collected from a series of experiments under different screw loosening conditions are analyzed. The results show significant variations in the amplitudes and frequencies in the response. Particularly, the frequency of the response decreased with a significant drop in its magnitude.

In the full paper, we present a comprehensive analysis of the sensitivity of the frequency response of both structural elements to the induced damage. Particularly, we present more extensive results about the sensitivity of the damping and nonlinear parameters to the damage. The results show the effectiveness of nonlinear excitation for assessment of damage conditions and the higher sensitivity of the nonlinear parameters to the state of damage than their linear counterpart.

6935-26, Session 6

Monitoring forces in bridge steel cables using a wireless monitoring system

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Bridge cable forces are important parameters for the safety of bridges. Some techniques have been developed for the measurement of bridge steel cable forces. For bridges in service, steel cable forces are usually monitored by the technique based on the vibration frequencies of cables. In recent years, a useful alternative technique based on the magnetoelastic sensors (ME or EM stress sensors) has been proposed. However, all the systems current available for monitoring bridge cable forces are wired-based. Installation and maintenance of such wired-based monitoring systems for large span bridges is time consuming and expensive. With recent developments of wireless sensing, wireless monitoring systems have been developed to eradicate the extensive lengths of wires in the tethered systems. In this paper, the wireless monitoring system with local data processing functionality developed by researchers at Michigan University and Stanford University is employed to monitor steel cable forces in a bridge in Xiamen, China. Both the vibration frequency technique and the method based on EM stress sensors are utilized for measuring cable forces. In the vibration frequency technique, local computational capacity of the wireless sensing system can perform the Fourier spectrum of the measured acceleration signals on board. Cable forces are then estimated from the frequency spectrum on line. In the measuring method based on EM stress sensors, EM sensors are incorporated as the sensing interface of the wireless sensing system. Comparative studies of the two measuring technique results are performed. To validate the performance of the wireless sensing system for monitoring bridge cable forces, traditional wire-based monitoring systems are also employed for the bridge cable forces. Measurement results of cable forces based on the wireless sensing

system are compared with those obtained by the wire-based systems. It is shown that the wireless sensing system can provide a low-installation cost and efficient technique for monitoring bridge steel cable forces.

6935-27, Session 6

Wave propagation models for quantitative defect detection by ultrasonic methods

A. Srivastava, I. Bartoli, S. Coccia, F. Lanza di Scalea, Univ. of California/San Diego

Ultrasonic guided wave testing necessitates of quantitative information on flaw size, shape and position. This quantitative diagnosis ability is necessary to provide meaningful data to a prognosis algorithm for remaining life prediction. Quantitative diagnostics needs models able to represent the interaction of guided waves with various defect scenarios. One such model is the Global-Local (GL) method, which uses a full finite element discretization of the region around a flaw to represent wave diffraction and a set of wave functions to simulate regions away from the flaw. The GL method is expanded to take advantage of the Semi-Analytical Finite Element (SAFE) method in the global portion of the waveguide. An added feature of the SAFE technique used here is accounting for material dissipation and thus extracting attenuation data for waves. This GL method is applied to predicting quantitatively the interaction of guided waves with defects in aluminum and composites structural components.

6935-28, Session 6

Decentralized wireless structural sensing and control with multiple system architectures operating at multiple sampling frequencies

Y. Wang, Georgia Institute of Technology; R. A. Swartz, J. P. Lynch, Univ. of Michigan; A. C. Askin, K. H. Law, Stanford Univ.; C. Loh, National Taiwan Univ. (Taiwan)

Recent years have seen growing interest in applying wireless sensing and embedded computing technologies into structural control. The major advantages include greatly reducing system cost by eliminating expensive cables, and allowing highly flexible system architectures. Previous research has demonstrated the feasibility of decentralized wireless structural control through numerical simulations and preliminary laboratory experiments. This paper describes a complete suite of laboratory experiments that are designed to thoroughly evaluate the performance of decentralized wireless structural control on a six-story laboratory structure. One magnetorheological (MR) damper, which is commanded by one wireless control unit, is installed between every two neighboring floors of the structure. Six different centralized/decentralized control architectures have been tested, in combination with three different sampling frequencies. This exhaustive set of experiments offers valuable insight in applying decentralized wireless control to larger-scale civil structures.

6935-29, Session 6

Passive and active corrosion sensing for concrete reinforcing steel using GMR sensors

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Steel reinforcement corrosion is a significant problem for the US concrete infrastructure, and accurate and continuous corrosion sensing methods would help reduce this cost and enable effective health monitoring and service life prediction. In this paper recent efforts to apply giant magneto-resistive response (GMR) sensors for corrosion sensing is described. The GMR sensors are applied in passive and active sensing configurations, neither of which require excavation of the concrete so remote sensing at a surface and internal sensing with an embedded unit are possible. The passive and active testing configurations are described. Then experimental results from each are presented, with the aim of identifying

existing corrosion state to date and rate of active corrosion at time of sensing. Suggestions for effective implementation in structures are finally presented.

6935-30, Session 6

Bio-inspired molecular photonic devices and nanodevices

G. C. Giakos, Univ. of Akron

The interaction of biological material with light integrates major technologies such as photonics, nanotechnology, and biotechnology, leading to the shaping of new research frontiers such as biophotonics and biomolecular nanophotonics. Based on preliminary experimental studies [1], interaction of light photons with aqueous-insulin molecules, yield to a dramatic light signal-to-noise enhancement of the order of 25-30. In fact, proteins in solutions produce remarkably large increments in the dielectric constant of water. These increments are attributed to large permanent dipole moments, which are partially oriented by an external electric field. For liquid solutions of high dielectric constant the dielectric constant D and the molar polarizations P_j of the several components, are given as [9]:

respectively, where ∞ is the optical polarizability and $\langle \mu \rangle_{av}$ is the mean square of the dipole moment of a molecule of type j . It appears that the electric behavior of solutions of insulin, as with other globular proteins, can be accounted for by the rotation of permanent dipoles.

If so we anticipate that innovative integration of photonics with molecular biology and nanomaterials may lead to the design of new classes of greatly improved sensing and imaging systems. Ultimately, these biological principles will improve our current capabilities to fabricate optical devices and contribute to the construction of novel, adaptive, micro-scale optical devices and techniques for medicine, biology and homeland security applications.

References

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6935-31, Session 7

Health monitoring of plate structures using guided waves

P. Fromme, Univ. College London (United Kingdom)

Structural health monitoring using permanently attached, distributed sensors for guided waves offers an efficient methodology for the long-term monitoring of large technical structures. The measurement concept involving baseline subtraction has been demonstrated for plate structures and shown to be able to localize defects under laboratory conditions. For the application to real technical structures it needs to be shown that the methodology works equally well in the presence of structural features. Structural features, e.g. stiffeners, have been identified as safety-critical areas for the development of fatigue and corrosion damage. Problems employing this structural health monitoring concept can occur due to the presence of additional changes in the signal reflected at undamaged parts of the structure. This can be either due to environmental changes affecting the wave propagation characteristics or secondary changes in the signal due to a defect at a different position in the ultrasonic propagation pathway.

In this contribution different signal processing options to reduce these detrimental effects are compared, including the automatic identification of defect signals and truncation of secondary pulses. The influence of the signal processing parameters and transducer placement on the damage localization accuracy is discussed. Results are presented using experimental and simulated signals for large structures with features such as stiffeners and crack-like defects.

6935-32, Session 7

Defect characterization using ultrasonic arrays

P. D. Wilcox, J. Zhang, C. Holmes, B. W. Drinkwater, Univ. of Bristol (United Kingdom)

Ultrasonic arrays comprise a multiplicity of individually addressable elements in a single package. In non-destructive evaluation (NDE), one-dimensional linear arrays are the most common type, typically comprising 32-64 identical rectangular elements arranged in a straight line. There has been a massive increase in the use of ultrasonic arrays for NDE in recent years, with two-dimensional arrays just starting to become routinely available. However, any study of the history of array technology reveals that the key developments were made in the medical field and that this technology was then transferred to the NDE community, where the main use of arrays has mainly been to perform existing ultrasonic inspections more rapidly. This paper seeks to address the question of how an array system designed specifically for NDE would differ from current systems and what benefits arrays can provide beyond emulation of existing inspections.

Firstly, the separate requirements of the medical and NDE fields are discussed followed by a description of two possible array system architectures. It is shown that the need to imaging non-stationary targets in medicine places fundamental limitations on system architecture that do not exist in NDE. Coherent imaging of a (randomly) moving target can only be achieved if the movement of the target over one data acquisition cycle is less than half a wavelength, and this forces medical array systems to adopt a parallel firing approach. However, in NDE where the targets are stationary or (in the case of scanned systems) moving at a uniform known speed the requirement for parallel firing no longer exists. Instead, each element can be fired sequentially and all beam-forming performed in post-processing. In terms of flexibility and data analysis, this is the preferred approach since all possible information can be extracted from the array. In the first instance, this enables techniques such as the Total Focusing Method (TFM) or Fourier domain imaging to be used where the complete array aperture is effectively focussed at every image point in both transmission and reception. As such, these imaging algorithms always provide the highest possible imaging resolution that can be obtained by linear processing. However, an array also provides information that can characterise sub-wavelength defects, even though such detail is below the diffraction limit and cannot be seen in conventional images. Specifically this information is obtained by using multiple sub-apertures in an array to probe the scattering matrix of a point in an image where a scatterer is indicated. It is shown that for crack-like defects, the experimentally obtained portion of the scattering matrix agrees well with analytical predictions. A strategy for determining the size and orientation of such defects from experimental data is then presented.

6935-33, Session 7

Experimental verification of a Kalman filter approach for estimating the size of fastener hole fatigue cracks

A. C. Cobb, J. E. Michaels, T. E. Michaels, Georgia Institute of Technology

Ultrasonic methods have been proposed and implemented in the laboratory for in situ detection and sizing of fatigue cracks initiating at fastener holes. These techniques, however, only provide an estimate at the time of the measurement and cannot predict the remaining life of the structure. In comparison, a statistical crack propagation approach models the expected fatigue life based on an assumed initial material state and fatigue history, but does not incorporate any measurement data. To maintain the safety of the structure, the crack propagation approach requires worst-case assumptions of both the initial flaw size and structural usage. The authors have recently developed a Kalman filter-based method for integrating ultrasonic measurements with crack growth laws. Fastener holes were interrogated using ultrasonic shear wave, angle-beam transducers in a through transmission configuration. An energy-based feature of the ultrasonic waveforms, specifically the ratio of received energy from an open crack to that from a closed crack, has been shown to reliably indicate the presence and size of cracking near the

fastener hole. This ultrasonic feature, combined with a simplified energy-based wave propagation model, serves as the measurement model for the state estimation approach. Using an assumed fatigue history and known material properties, a Paris's law approximation of crack propagation was chosen as the system model for state estimation. Simulated data were generated using crack propagation equations and the measurement model for cracks with a range of aspect ratios and locations in the thickness direction. Further, differing amounts of noise were added to the simulated ultrasonic responses to represent typical measurement variations. For this synthetic data, the Kalman filter crack size estimates were more accurate than either the ultrasonic measurement technique or the crack growth approach alone, while showing little degradation in the presence of realistic noise levels. The study presented here is a continuation of this Kalman filter methodology, where experimental results are evaluated to assess performance on both 7075 and 7050 aluminum alloys and various transducer configurations. It is demonstrated that the Kalman filter approach is able to provide reasonable crack size estimates for a variety of experimental test configurations.

6935-34, Session 7

Adaptive beamforming using ultrasonic arrays

A. J. Hunter, P. D. Wilcox, B. W. Drinkwater, Univ. of Bristol (United Kingdom)

Standard ultrasonic NDE is based on knowledge of material properties and specimen geometry, and inspection angles are calculated using Snell's law. In the simple case of oblique shear wave inspection through a plane interface, this means computing the required angle of incident longitudinal wave and orientating a transducer accordingly. For a singly or doubly curved interface, the calculations are more complex and it may be necessary to construct specially shaped transducers, but fundamentally the problem is tractable if the specimen geometry is known. For inspection with an ultrasonic array, the same calculations can be used to compute the necessary element delay laws, and the problem of having to manufacture special transducers is avoided. The problem with the calculations in these examples is that they require the geometry and material properties to be precisely known. However, with an array beamforming based on adaptive approaches becomes viable. The general approach is to acquire the data from every possible transmitter-receiver combination in the array, and then to apply the adaptive beamforming in post-processing. Adaptive beamforming is of great practical interest, as there are many situations where precise material properties and specimen geometries are unknown. In the synthetic aperture sonar and radar communities, adaptive focusing is routinely used and this paper explores how this technology can be exploited in NDE. In particular, the applicability of wide-beam approximations, coherent shear averaging and incoherent shear averaging techniques is investigated. The NDE applications will include both conformable flexible arrays directly coupled to wavy surfaces and rigid arrays liquid coupled to wavy surfaces. Simulated and experimental results are presented that show how adaptive beamforming can be applied to significantly improve the imaging of target reflectors in a test-piece with a wavy surface. The necessary artefacts that must be present in an image to enable successful adaptive beamforming to be performed are also discussed. The paper also includes a quantitative comparison of the computational requirements of time and Fourier domain imaging algorithms and an assessment of the most appropriate to use with adaptive beam-forming.

6935-35, Session 7

Effectiveness of in-situ damage localization methods using sparse ultrasonic transducer arrays

J. E. Michaels, Georgia Institute of Technology

Sparse ultrasonic sensor arrays, which are spatially distributed over a large area of a structure, have been proposed and tested under laboratory conditions for in situ detection and localization of damage. Detection algorithms are typically based upon comparison to a baseline, where any differences not explained by benign environmental effects are interpreted as damage. Localization of the suspected damage is then desired, either to identify regions for follow-up inspection or as the first step of an in

situ damage characterization process. Most of the proposed localization methods are either based upon an arrival time analysis of differenced signals or spatial distribution of a damage index. Triangulation and delay-and-sum type algorithms fall into the first category, which considers the short time behavior of the differenced signals and, under ideal circumstances, can very accurately locate discrete damage such as a single crack. Algorithms in the second category typically consider longer time regimes, but are limited in their ability to precisely locate discrete damage.

This paper evaluates the effectiveness of both types of algorithms for locating discrete damage, and in particular considers the degradation in performance due to errors in both transducer locations and wave speeds. In the first category, two types of delay-and-sum imaging algorithms are considered, one based upon RF (unrectified) waveforms, and the other on envelope-detected waveforms. It is shown that images based upon RF waveforms can better localize discrete scatterers than those based upon the envelope-detected signals, but at the expense of a more complicated set of artifacts. Both methods are relatively insensitive to small errors in wave speeds and transducer locations, with some image degradation and expected localization errors. In the second category of localization algorithms, two correlation-based damage indexes are considered - one calculated in the time-domain and the other in the frequency domain. Their ability to localize damage depends upon the density of the transducer array, but their performance is relatively insensitive to even significant errors in transducer locations. For all algorithms, results are generated for aluminum plate-like components using both simulated and experimental ultrasonic data sets.

6935-36, Session 7

Concurrent optimization of input and output for feature extraction in structural health monitoring

L. A. Overbey, C. C. Olson, M. D. Todd, Univ. of California/San Diego

Previous work has developed advanced nonlinear time series analysis based techniques for feature extraction in structural health monitoring. Effective algorithms include the use of state space based methods like nonlinear prediction error and generalized state space interdependences. These features are effectively able to detect minute dynamical changes in a structural system without relying on model-specific forms or assumptions such as linearity. However, sensitivity of these features can be further improved by determining the excitation that will optimally produce the greatest difference between an undamaged and damaged state for a specific structure. Additionally, for a certain structure, there are ideal parametric choices which will fully exploit the potential of these feature algorithms. This work employs evolutionary algorithms to simultaneously optimize the excitation and feature parameters to produce high-sensitivity state space based features. Evaluations are conducted on nonlinear prediction error and generalized interdependence features by optimizing their algorithmic parameters, with particular emphasis on finding regions in phase space with a high sensitivity to damage-induced changes. Furthermore, the optimization scheme concurrently produces a structure-specific forcing that will enhance dynamical differences. Verification is conducted on a simulated dynamic oscillator.

6935-37, Session 7

A nonlinear acoustic technique for crack detection in metallic structures

D. Dutta, Carnegie Mellon Univ.; H. Sohn, Korea Advanced Institute of Science and Technology (South Korea); K. A. Harries, Univ. of Pittsburgh

A guided wave based crack detection technique using the principles of nonlinear acoustics is developed in this study. Lead Zirconate Titanate (PZT) materials are used for exciting and sensing acoustic waves. Acoustic waves at a chosen frequency are generated using an actuating PZT-transducer, and they travel through the target structure before being received by a sensing PZT-transducer. Unlike an undamaged medium, a cracked medium exhibits high acoustic nonlinearity which is manifested as harmonics in the power spectrum of the sensed signal. Experimental results also show that the harmonic components increase non-linearly

in magnitude with increasing amplitude of the input signal. Theoretical justification of the above effects has been provided using a simplified mechanical model (viz. a non-linear spring - mass system). The proposed technique attempts to identify the presence of cracks by examining the aforementioned features. The goodness of the technique was tested by conducting experiments on two specimens: an aluminum beam with a rectangular cross-section and a steel I-beam.

Most of the existing damage-detection techniques suffer from one or more drawbacks viz. dependency on prior baseline data from undamaged condition that require huge memory space, use of bulky equipment, unsuitability of automation, and requirement of interpretation of data or image by trained engineers. These shortcomings make the existing methods less attractive for online continuous monitoring. Moreover, changing environmental conditions may alter the baseline results thus making its comparison with damaged-state data dubious. The uniqueness of the present study lies in the authors' effort to overcome the aforementioned drawbacks by developing a baseline-free crack detection technique using PZT wafers (which can be easily surface mounted or embedded in the structure) and defining a damage index that can be computed automatically.

It is well known that crack in a structure causes nonlinear wave interaction leading to production of harmonics among other effects. The intended baseline-free crack detection technique discussed in this paper is based on the assumption that an undamaged structure will behave perfectly linearly while a crack in a structure will produce acoustic nonlinearity. The presence of harmonics in the output signal will therefore indicate a crack notwithstanding how the baseline data for the same specimen in undamaged condition looked like. The test for presence of harmonics can be easily automated using existing signal processing techniques like Fast Fourier Transform.

Experimental results show that the harmonic contents of the output signal are much more prominent in the cracked condition than in the pristine condition of the same specimen. However, contrary to the assumption that undamaged structures should behave perfectly linearly, responses from the undamaged specimens also contain harmonics although their magnitudes are small. This can be attributed to circuit-nonlinearity and other unknown sources of nonlinearity. However small the magnitudes of these harmonics are, this imposes limitation to the baseline-free approach of the proposed technique. The original intention was to classify damaged and undamaged specimens based on the presence or absence of harmonics. Presence of harmonics in the response signal from an undamaged structure might lead to false alarms unless an effective statistical classification scheme is developed in the future.

6935-83, Session 7

Mapping some functions and four arithmetic operations to multilayer feedforward neural networks

J. Pei, E. C. Mai, Univ. of Oklahoma; J. P. Wright, Weidlinger Associates, Inc.

This paper continues the development of a heuristic initialization methodology for designing multilayer feedforward neural networks aimed at modeling nonlinear functions for engineering mechanics applications as presented previously at SPIE 2003, and 2005 to 2007. Seeking a transparent and domain knowledge-based approach for neural network initialization and result interpretation, the authors examine the efficiency of linear sums of sigmoidal functions while offering constructive methods to approximate certain functions and operations. This study provides details and results of mapping the four arithmetic operations (summation, subtraction, multiplication, division) as well as other functions including reciprocal, absolute value and the product of absolute value and a first-order polynomial, Gaussian and Mexican hat functions into multilayer feedforward neural networks with one hidden layer. The approximation and training examples demonstrate the efficiency and accuracy of the proposed mapping techniques and details. Future work is also identified. This effort directly contributes to the further extension of the proposed initialization procedure in that it opens the door for the approximation of a wider range of nonlinear functions.

6935-78, Poster Session

A new method for SAR measurement in MRI

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During an MR procedure, the patient absorbs a portion of the transmitted RF energy, which may result in tissue heating and other adverse effects. The Specific Absorption Rate (SAR) is the RF power absorbed per unit mass of tissue that acts as a guideline for MRI safety. The phase transition method is a new method to measure SAR in MRI which has the advantages to be very simple and to overcome all the typical calorimetric method problems. It does not require temperature measurement, any specific heat or heat capacity knowledge, but only mass and time measurement. It is based on the stationary heat equation solution properties and on the transition phase heat exchanges, allowing a direct measurement of the absorbed energy transferred by RF pulse to a tissue equivalent solution. Preliminary results, obtained on two Philips Intera scanners at 1.5 T, show how the measured SAR is consistent with the expected SAR value as calculated by the scanner software.

6935-79, Poster Session

Research on human physiological parameters intelligent clothing based on distributed fiber Bragg grating

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A human physiological parameters intelligent clothing is researched with FBG sensor technology. In this paper, the principles and methods of measuring human physiological parameters including body temperature and heart rate in intelligent clothing with distributed FBG are studied, the processing method of body temperature and heart rate detection signals is presented, human physiological parameters detection module is designed, the interference signals are filtered out, and the measurement accuracy is improved. The intelligent clothing can implement real-time measurement, processing, storage and output of body temperature and heart rate. It has accurate measurement, portability, low cost, real-time monitoring, and other advantages. The intelligent clothing can realize the non-contact monitoring between doctors and patients, timely find the diseases such as cancer and infectious diseases, and make patients get timely treatment. It has great significance and value for ensuring the health of the elders and the children with language dysfunction.

6935-80, Poster Session

Thin foils as acoustic windows and substrates for scanning acoustic microscopy: applications in live cell imaging

M. von Buttler, E. Twerdowski, H. Voigt, R. Wannemacher, W. Grill, Univ. Leipzig (Germany)

Cell culture requires strict aseptic conditions. The focusing transducers of scanning acoustic microscopes are currently often in direct contact with the cell-culture medium which simultaneously serves as the coupling fluid. An acoustic window between the focusing transducer and the medium in which the cells are immersed can act as a barrier to contaminants and gases while allowing the acoustic waves to pass. We investigated polymer foils made of polyethylene terephthalate (PET) and polyethylene naphthalate (PEN) with thicknesses in the range of 0.5-12 μm as possible acoustic windows at 1.2 GHz. The acoustic properties were determined by a phase-sensitive scanning acoustic microscope. Images obtained with and without the acoustic window are compared in terms of resolution and contrast. Polymer foils can also be used as substrates for culturing cells. The acoustic magnitude and phase contrast of cells on such substrates can differ significantly from that of cells on standard Petri dishes or glass substrates. The contrast in reflection can be varied by modifying the fluid on the back side of the foil. The good optical properties of some foils allow simultaneous confocal laser scanning and acoustical imaging of cells.

6935-84, Poster Session

Ultrasonic characterization of interfaces at Brewster angle reflection

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Ultrasonic wave reflection at Brewster angle is proposed as a means to characterize the interfacial boundary between two elastic materials as well as the limiting case of the free boundary of an elastic material. For isotropic materials, the Brewster angle is defined as the angle of incidence for which the ratio of the amplitudes of the reflected longitudinal (P) and vertically polarized (SV) waves is independent of the ratio of the amplitudes of the corresponding incident waves. For a bi-material interface and wave reflections at Brewster angle, the reflectivity vanishes. However, for free boundaries where the reflectivity is non-vanishing, the Brewster angle defines the complete mode conversion (P to SV or SV to P). It is shown that Brewster angle reflections and surface Rayleigh waves are in fact derived from the same equation, being complementary solutions. The Brewster angle concept is extended to include SH waves, in which case it is defined as the angle of incidence for which the reflected wave vanishes. Regions of existence of Brewster angle(s) are established with respect of the mechanical material parameters. There are materials and material combinations for which there are two Brewster angles, one Brewster angle or none. The results are generalized to include anisotropic materials as well.

6935-85, Poster Session

Uniform circular array for structural health monitoring of composite structures

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Composite structures are susceptible to catastrophic failure without noticeable forewarnings. One possible way of preventing catastrophic failures is integrating health monitoring systems in the critical composite structures of the aircraft.

Phased array with all-azimuth angle coverage would be extremely useful in structural health monitoring (SHM) of planar structures. One method to achieve the 360° coverage is to use uniform circular arrays (UCAs). Circular arrays have been studied extensively because of their simple structure and the unique features they offer, among those the most important is that beam shapes in the plane of the array (the azimuth plane) are essentially independent of the steering angle. The desired beam shape can be achieved if the outputs of all array elements are fed to a structure, referred to as beamformer. Modern beamformers can take the form of parallel algorithms for processing digitized signals from the elements. If the excitation of each array element is first theoretically determined for a desired beam shape, the conventional beamformer circuit then consists of phase shifters (or delays) and attenuators (weight coefficients) inserted in all feed lines, and a combiner for all the line outputs.

In this paper we present the concept of UCA adapted for SHM applications. We start from a brief presentation of UCA beamformers based on the principle of phase mode excitation. UCA performance is illustrated by the results of beamformer simulations performed for the narrowband and wideband ultrasonic signals. Experimental results obtained for a 32 element UCA used for the reception of acoustic emission signals propagating in an aluminum plate are also presented.

6935-86, Poster Session

Remote personal health monitoring with radio waves

A. Nguyen, Univ. of California/Irvine

Medical costs in the United States have risen rapidly and substantially, making health care expenditure one of the most troubling economic and social problem for the U.S. government, private companies, and individuals. Adding to this health-care cost problem is the growing numbers of elderly adults, population, increased longevity, and more demand for different health care services resulting from changes in life styles. Implementing advanced technologies for medical practices and health treatments not only will help reduce medical costs, but also improve the treatment for patients from medical professionals.

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We will present several techniques utilizing radio-frequency identification (RFID) technology for personal health monitoring. One technique involves using RFID sensors external to the human body, while another technique uses both internal and external RFID sensors. Another technique involves simultaneous monitoring of many patients in a hospital setting using networks of RFID sensors. All the monitoring are done wirelessly, either continuously or periodically in any interval, in which the sensors collect information on human parts such as the lungs or heart and transmit this information to a router, PC or PDA device connected to the internet, from which patient's condition can be diagnosed and viewed by authorized medical professionals in remote locations. Instantaneous information allows medical professionals to intervene properly and timely to prevent possible catastrophic effects to patients. The continuously monitored information provides medical professionals more complete and long-term studies of patients. All of these result in not only enhancement of the health treatment quality but also significant reduction of medical expenditure. These techniques demonstrate that health monitoring of patients can be done wirelessly at any time and any place without interfering with the patients' normal activities. Implementing the RFID technology would not only help reduce the enormous and significantly growing medical costs in the US, but also help improve the health treatment capability as well as enhance the understanding of long-term personal health and illness.

6935-38, Session 8

Structural health monitoring

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The Department of Defense is working to develop an Operationally Responsive Space (ORS) capability, and has recently stood up the ORS Joint Program Office, at Kirtland AFB, NM, in support of that goal. As stated in the Plan for ORS [1], "ORS is focused on the timely satisfaction of the urgent needs of the JFC (Joint Force Commander) and other users." The Plan for ORS also describes a three-tiered approach to delivering these capabilities to our combatant commanders:

Tier 1: Utilizes existing, or on-orbit capabilities to provide the required space-based capability within days from establishing the need.

Tier 2: Utilizes field-ready, or nearly field-ready capabilities to satisfy warfighter needs within days-to-weeks of establishing the need.

Tier 3: Development of an entirely new, or unforeseen capability, within a year.

In order to meet the unique demands of this approach, the DOD research community has invested heavily in technologies that allow satellites to be designed and assembled via more modular schemes. At the Air Force Research Laboratory/Space Vehicles Directorate (AFRL/VS), there are many technology development efforts aimed at enabling these modular satellite architectures, to include: Space Plug-and-play Avionics [2], reconfigurable thermal management systems [3], autonomous satellite operations [4], satellite design tools, modular flight software, and configuration-flexible structural architectures.

However, all of these efforts at rapid satellite integration are for naught if we are forced to follow the current structural surety process. This paper discusses AFRL/VS's efforts to enable rapid satellite structural check-out, through the use of Structural Health Monitoring (SHM).

6935-39, Session 8

Evaluation of bonded piezoelectric AE sensors for structural health monitoring applications

M. J. Sundaesan, North Carolina A&T State Univ.

Bonded acoustic emission sensors have been used in our studies in the past to monitor damage growth in composite materials as well as aluminum. In these studies the performance of the individual nodes of the continuous sensors were evaluated through comparison with commercially available acoustic emission sensors. Individual bonded

sensor nodes were found to be comparable in terms of sensitivity to the commercially available resonant frequency sensors. In addition, they were found to have wider bandwidth, which is advantageous in differentiating the sources of acoustic emission signals. The current studies attempt to generate quantitative evaluation of the sensor nodes through comparison with waveforms detected by a Laser interferometer. Here the interest was mainly in detecting the fidelity of reproduction of the frequency spectrum and waveform. The calibration was performed by observing the stress waves propagating in aluminum plates. The resulting waveforms from this single node sensor were compared to the corresponding waveforms detected by Laser interferometer. The performance of the bonded acoustic emission sensor in detecting different types of acoustic emission events is compared. These acoustic emission events were also simulated using finite element technique. The waveforms from the finite element simulations were also found to closely resemble the waveforms experimentally detected from the sensors.

The implications of the sensor performance on the success of acoustic emission technique as a structural health monitoring tool are discussed. These parameters include the source to sensor distance, the sensor frequency response, attenuation characteristics in the material, and the prevailing noise level.

6935-40, Session 8

Resin flow front tracking of vacuum assisted resin transfer moulding (VARTM) using single-mode optical fiber (SMF) and real-time monitoring of resin cure and residual strain using FBG and EFPI sensors

J. K. Gope, M. G. Godbole, Research and Development Establishment (Engineering) (India)

Process monitoring that involves monitoring of extent of resin fill and resin cure is important to improve quality of products and reduce manufacturing cost of the products made from VARTM process. In the present approach single mode optical fibers are used to monitor the resin flow, Fiber Bragg Grating (FBG) is used for cure monitoring and Extrinsic Fabry Parrot Sensor (EFPI) is used to measure the residual strain. In this approach cleaved single mode optical fibers are used to track resin flow. Reflectance value changes due to change in interface medium at SMF fiber end as resin reaches fiber end and the change in reflectance is captured using an Optical Time Domain Reflectometer (OTDR). Cure monitoring is done using FBG sensor. FBG sensor is sensitive to thermally induce strain and temperature. A temperature insensitive extrinsic Fabry Parrot Sensor (EFPI) was used to measure the thermally induce strain. This strain data is deduced from the FBG response and exact temperature profile of the curing cycle is obtained. This scheme is applied for the production of a stiffened plate using VARTM process. Experimental results demonstrated that using SMF and FBG process monitoring could be done for the production of large component using VARTM

6935-41, Session 9

Fluid-coupled slow wave for remote sensing

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Some applications require remote nondestructive evaluation (NDE) of plates, tubes and pipes separated from the transducer by two or more layers. In a previous paper [1] we reported a low attenuation waveguide for guided waves. Here we report on the results of calculations and finite element simulations for the case of two thin plates separated by a layer of fluid. The position detection of industrial lead screws has been demonstrated at distances in excess of one meter from a fixed transducer. The paper presents summaries of the calculations and simulations, a description of the experimental set-up and comparisons between theory and experiment as shown in guided wave dispersion diagrams. Also shown are calculated displacement amplitudes within the waveguide for different launch angles.

[1] K. Joseph, B. Tittmann, M. Pedrick, and M. Kropf, "Low attenuation waveguide for leaky surface waves," Proc. Of SPIE, vol. 6179, 61790E (2006).

6935-42, Session 9

Effect of transducer boundary conditions on the generated ultrasonic field

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Several investigators have modeled the ultrasonic fields in front of finite sized transducers. Most of these models are based on Huygens principle. Following Huygens-Fresnel superposition principle one can assume that the total field of a finite transducer is obtained by simply superimposing the contributions of a number of point sources uniformly distributed on the transducer face. If the point source solution, also known as the Green's function, is known then integrating that point source solution over the transducer face one can obtain the total field generated by a finite transducer. This integral is known as Rayleigh-Sommerfield integral. It is investigated here how good the Huygens principle and Rayleigh-Sommerfield integral based predictions are for different boundary/interface conditions at the transducer face-fluid interface such as 1) when only the normal component of the transducer velocity is assumed to be uniform on the transducer face and continuous across the fluid-solid interface, or 2) when all three components of velocity are assumed to be uniform on the transducer face and continuous across the interface, 3) when the pressure instead of velocity is assumed to be uniform on the transducer face and continuous across the interface. All these different boundary and interface conditions can be successfully modeled by the newly developed Distributed Point Source Method (DPSM) but not by the Rayleigh-Sommerfield integral representation. From the comparison of Rayleigh-Sommerfield integral results and the DPSM predictions it is studied what kind of discrepancies are observed between the Rayleigh-Sommerfield results and the actual pressure fields generated by a transducer under different boundary/interface conditions.

6935-43, Session 9

Finite element simulation of two points source method: its use for damage detection in concrete structures

J. Woo, W. Na, D. Woo, Pukyong National Univ. (South Korea)

For the development of nondestructive testing techniques associated with acoustic waves, finite element simulation has been often used to investigate the efficiency of a testing technique. For example, during the development of impact echo method, finite element method was used to simulate the impact echo responses of structures. Finite element models permitted investigators to study transient stress wave propagation in bounded solid with or without defects. However, the finite element simulation of elastic wave propagation with a relatively high frequency such as ultrasonic wave is quite challenged. In the finite element simulation, high frequency wave means the element size should be small enough to represent the wavelength. In other words, the solution time becomes incredibly large. Thus, other numerical methods such as boundary element method, semi-analytical finite element method, elasto-dynamic finite integration technique, and distributed point source method have been simultaneously developed. Recently, thanks to the development of computer hardware and software such as ABAQUS/Explicit, ANSYS LS-DYNA, FEMLAB, and MARC, large amount of numerical calculations of finite element models become possible.

This study is about developing a nondestructive technique using an acoustic wave with a relatively high frequency. This technique focuses on damage detection in concrete structures. For the development, this paper proposes two points source method for baseline-free damage detection. In finite element modeling process, two types of models are considered as follows: 2-D plane strain and 3-D solid models. In the case of the 3-D models, non-reflecting boundary conditions are introduced to simulate an infinite medium so that they will prevent artificial dilatational stress wave reflections generated at the boundaries from reentering the model and contamination the results. For all the models, two different types of damages (crack and deterioration) are introduced to see if the proposed method can detect the damages. From the finite element simulation, it is shown that two different types of damages are detected and their severities can be also identified. Besides, the proposed method has shown that it does not require any baseline signal to alarm the damage detection; hence, its efficiency is verified.

6935-44, Session 9

A differential method for the determination of the time-of-flight for ultrasound under pulsed wide-band excitation including chirped signals

K. S. Tarar, E. Twerdowski, R. Wannemacher, W. Grill, Univ. Leipzig (Germany)

A pulse compression method has been developed for applications involving the determination of variations of the time of flight in pulsed echo or transit experiments. The method is based on Fourier transformation and allows for an optimized compression of the signal to a bandwidth-limited approximation of the Dirac delta function. The respective transformation of time-shifted response signals allows for the successful separation of otherwise overlapping signals and detection of variation of the time of flight for the individual echo components with high resolution. The developed processing scheme corrects for dispersion and attenuation in the electronics, transmission lines, and transducers. Applications including examples for time-of-flight resolutions better than 1/1000 of the oscillation period at center frequency are demonstrated.

6935-45, Session 9

Theoretical modeling of acoustic emission waveforms from delamination sources in multilayered composite plates

S. Banerjee, St. Louis Univ.; A. K. Mal, Univ. of California/Los Angeles

The propagation characteristics of guided wave modes due to delamination initiation in multilayered thick composite plates are studied using a newly developed wavenumber integral method. The acoustic emission waveforms from the initiation of point and distributed delamination sources of both Mode-I and Mode-II type at various interfaces are calculated. The influence of the source depth on the extensional and flexural wave modes for various propagation angles is studied. For the delamination source at the mid plane, the results from the present calculation are compared with those from an approximate laminate theory with shear correction factor and "moment tensor" representation of the source. The results obtained by the two methods are shown to have excellent agreement in the low frequency ranges. It is found that the amplitude variations of these modes are strongly dependent on their propagation direction as well as the source depth location. Wavelet transformation is being employed on the signals in an effort to understand the energy content of various modes. The current theoretical results somewhat conforms to the experimental waveforms reported earlier and should be useful to identify the source location with some confidence.

6935-46, Session 10

A novel polymeric magnetostrictive fiber optic sensor system

W. Wang, Univ. of Washington

A novel polymeric magnetostrictive fiber-optic sensor is presented. The sensor uses a newly developed ferromagnetic polymer (WCS-NG1) as the magnetostrictive coating for magnetic field detection. A simple fiber-optic Mach-Zehnder interferometer is deployed; where magnetic field induced magnetostriction effect is detected based on the phase modulation measurement. The magnetostrictive effect has a number of advantages of sensor. It is relatively simple to fabricate on the optical fiber. Optical technique also provides high sensitivity in its measurant. Therefore, magnetostrictive effect is used for the fiber optics magnetometer. Comparison with Teflon or other conventional magnetostrictive sensors, this novel polymeric magnetostrictive fiber-optic sensor is much less complex relatively smaller in size, and optical technique also prevents RF interference that is common in typical electromagnetic type sensors. In this paper, characterization of the material and magnetic properties of the embedded polymer will be discussed. Preliminary results on the magnetic field and current sensing will be presented. A theoretical simple model, which gives predictions in agreement with experimental evidences in the range of linear behavior, will be presented.

6935-47, Session 10

Determination of the velocity of sound with high-resolution by ultrasonic imaging of wedge shaped objects in transmission with vector contrast

U. Amjad, Y. K. Verma, J. Ndop, W. Grill, Univ. Leipzig (Germany)

The determination of the velocity of sound in small objects often suffers from limited resolution concerning determination of both the path length and the time of flight. Detection of the sound transmitted through wedge-shaped objects allows for tracking of the phase of the transmitted signal as the thickness of the object increases continuously. Changes in the time of flight can be measured in this way with ultimate precision using a phase sensitive acoustic microscope (PSAM).

The thickness of the object does not influence the time of flight if a coupling fluid with sound velocity equal to that of the object is employed. Similarly, the error in determination of the thickness is reduced when coupling fluids with sound velocities close to that of the object are employed. This way the error in determination of the thickness of the sample, which can be substantial for microscopic objects, can be minimized by selection of suitable coupling fluids. The method is demonstrated for different objects and coupling fluids.

6935-48, Session 10

Enhanced image capabilities for industrial radiography applications using megavoltage x-ray sources and digital flat panels

J. E. Clayton, G. F. Virshup, Varian Medical Systems, Inc.

The use of flat panel imagers based on amorphous silicon technology for digital radiography has been accepted by the medical community as having advantages over film imaging for several applications. For industrial applications, the same advantages for panels exist. Digital radiography can give the user improved sensitivity, contrast resolution and high speed of data acquisition. Radiographic and tomographic images were taken in the 3 - 9 MeV energy range demonstrating the excellent imaging capabilities of the flat panel digital imagers in this high-energy range.

6935-49, Session 10

Fiberoptic viscosity sensor

W. Wang, Univ. of Washington

Fluid viscosity is an important property which can be used to extract information from a fluid. Method of measuring the fluid viscosity has not changed significantly over the past few decades. Previous viscometers, mostly mechanical devices, are often large and cumbersome to use. Besides, they are frequently confined to narrow viscosity ranges and specific fluid requirements. In recent years, acoustic wave devices employing piezoelectric crystal, electro-ceramic and piezoelectric-thin-film have received attention as fluid viscosity sensors due to their high sensitivity [1-3]. However, the drawback of these devices is that they are limited to measure the properties of the surrounding liquid rather than the bulk fluid. Until recently, an optical method using a forward light scattering pattern as an indirect measurement of fluid viscosity was developed by Wang et al [4-8]. The fluid viscosity was derived from a comparison between the measured vibration amplitude and the damping of a fluid.

In this paper, we will present an optical technique similar to the concept in our previous paper [4-8] by using a fix-free end fiber configuration as an optical transducer for viscosity measurement. This configuration is ideal for a portable viscometer due to its much more compact size than our previous viscosity sensor.

A new optical technique for measuring the vibration of the probe will be presented. Several fluids including water and glycerol will be tested. The concentration of glycerol are 6%, 12%, 24%, 36%, 52% and 60%. Previous result shows that the bandwidth will increase when the viscosity increase in fix-fix end fiber. Based on the preliminary result, we see a higher damping effect based on fix-free configuration. We will present our quantitative

findings and future application in the presentation.

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6935-50, Session 10

Stand-off detection of mixed radiation fields

G. C. Giakos, Univ. of Akron

Fundamental limitations of the existing detector technologies consist on the direct interaction with the emitted ionizing radiation. As a result, radiation sources of all types of ionizing radiation may be detected only at distances less than the mean free path (MFP) of the IR particle or photon. For example, alpha particles, beta particles or gamma ray photons with an initial energy of a few MeV will have a MFP in the atmosphere of the order of a few centimeters, a few tens of meters and a few hundred meters respectively, while in dense media their penetrating ability is sharply decreased. By taking advantage of the radioluminescence phenomenon, it is possible to detect ionizing radiation photons or particles at standoff distances well larger than their MFP.

Interestingly enough, radioluminescence occurs when molecules, atoms, ions of the medium are excited and/or ionized by the ionizing radiation, relax or recombine with a specific and unique light emission. Although the produced light in air is very weak because only a very small part of the ionizing radiation energy is transformed into light (10-5), the emitted radioluminescence has a specific spectrum and can be transmitted through air for considerable distances, typically several orders of magnitude greater than the MFP of the emitted nuclear radiation. In fact, the atmospheric alpha-RL optical spectrum consists of 316, 337, 358, 380 nm etc., 2-3 nm wide spectral bands, which belong to the 2+ system of molecular transitions of nitrogen. Each alpha particle creates approximately 30 UV photons in the atmosphere.

As a result, detection of the radioluminescence by passive optical techniques located far from the ionizing sources enables radioactive materials to be detected remotely.

The presented principles and methodology may have tremendous applications in the area of homeland security for remote detection and discrimination of radiation sources in the presence of mixed radiation fields.

6935-51, Session 11

Acoustic emission monitoring of FRP reinforced concrete

S. Degala, K. Ramanathan, P. Rizzo, K. A. Harries, Univ. of Pittsburgh

Debonding of externally bonded carbon fiber reinforced polymer (CFRP) materials used for repair of reinforced elements is commonly observed and is often the critical limit state for such systems. This paper presents an

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acoustic emission (AE) study performed during laboratory tests of concrete slab specimens strengthened with CFRP strips. Several specimens having different bf/s ratio (ratio of CFRP width-to-CFRP spacing) were monitored. An AE paradigm to monitor damage initiation, progression, and location in the test specimens is demonstrated. An algorithm to classify the cracks in concrete, the disbond of the CFRP strips from the soffit of the slab, and the eventual failure (debonding or concrete shear) is also presented. The proposed general approach can be applied to large scale CFRP-concrete systems. The results presented here are part of a broader study, conducted at the University of Pittsburgh, aiming at characterizing the structural response and the debonding behavior of reinforced concrete strengthened with CFRP.

6935-52, Session 11

Wireless ultrasonic guided-wave tomography for corrosion monitoring in pipes

J. P. Koduru, L. J. Breon, J. L. Rose, The Pennsylvania State Univ.

Structural Integrity of predetermined critical zones in a structure is of growing interest in the non-destructive testing (NDT) community. Quite often the presence of defects does not imply the end of life of the underlying structure and it could be economical to continue using the structure until the severity of damage reaches a point where it can no longer be used. For structures like pipelines and aircraft in which a failure can be catastrophic, it is extremely important to continuously monitor any defects on the structure. Leave in place sensors provide a convenient way to embed the sensors permanently on the structure to periodically monitor and establish its integrity. Large structures like pipelines need extensive cabling to connect individual monitoring units to a central data collection unit, increasing the complexity and cost of permanent monitoring systems on the structures. Taking advantage of the recent advances in wireless technology enables the deployment of several sensor units to monitor different sections of the structure and communicate information to a central data collection infrastructure. In this paper we present a wireless corrosion monitoring system which uses 8 sensors to generate ultrasonic guided waves in the structure. With ultrasonic guided waves it is possible to locate and size defect regions using algorithms for tomographic reconstruction. This work uses the Reconstruction Algorithm for Probabilistic Inspection of Damage (RAPID) technique to reconstruct the image and size the defects in the region enclosed by the sensors. The wireless unit encompasses an actuator generating a spike pulse and a data acquisition unit to condition the acquired signals. The data acquired by the system from the structure is processed to identify any changes in the structure in comparison to the state of the structure when the system was installed. A digital signal processor (DSP) is used as the controller to manage all the activities of the sensor unit. A low power radio unit is used for wireless communications in the 2.4 Ghz ISM (industrial, scientific and medical) band. The wireless unit collects waveforms from the structure and communicates them to the base station as requested. Batteries are used as the primary source of power and ways to minimize the power consumption of the system were investigated. The system was used for thickness measurements of the pipe wall between two piezoelectric disc sensors with center frequency of 350 KHz mounted on the structure with a separation, providing an economical online thickness monitoring possibility. The wireless unit was tested on a pipe with a simulated corrosion at different wall thickness and the system readily found multiple defects. It was observed that the wireless communications performed well over a range of 20m in an indoor environment with just over 5% packet failure rate.

6935-53, Session 11

Hybrid vibration-impedance approaches for damage detection in plate-girder bridges

D. Hong, H. Do, J. Kim, W. Na, H. Cho, Pukyong National Univ. (South Korea)

In this paper, a hybrid vibration-impedance approaches is newly proposed to detect the occurrence of damage, the location of damage, and extent of damage in steel plate-girder bridges. Firstly, theoretical backgrounds of the hybrid structural health monitoring are described. The hybrid scheme mainly consists of three sequential phases: 1) to alarm the occurrence

of damage in global manner, 2) to classify the alarmed damage into subsystems of the structure, and 3) to estimate the classified damage in detail using methods suitable for the subsystems. Damage types of interest include flexural stiffness-loss in girder, degradation in deck, and perturbation in supports. In the first phase, the global occurrence of damage is alarmed by monitoring changes in acceleration features. In the second phase, the alarmed damage is classified into subsystems by recognizing patterns of vibration and impedance features. In the final phase, the location and the extent of damage are estimated by using modal strain energy-based damage index methods. The feasibility of the proposed system is evaluated on a laboratory-scaled steel plate-girder bridge model for which hybrid vibration-impedance signatures were measured for several damage scenarios.

6935-54, Session 11

Measurement of modal amplitudes of guided waves in rails

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Guided wave inspection and monitoring of structures is being researched for various industrial applications. One important application is that of rail condition monitoring where long lengths of rail can be monitored from permanently attached transducer locations. During the development of such a system it is advantageous to be able to measure the amplitude of the individual modes of propagation. Such measurements can be used in the field to determine which modes will propagate over large distances and in the lab during development of transducers to target a particular mode. The problem is to extract the amplitudes of the individual modes that contribute to a measured time domain signal.

This paper addresses the problem of extracting modal amplitudes from measured time domain signals performed at a limited set of points on the waveguide. The method developed uses the wave propagation characteristics of the waveguide predicted by numerical modelling to extract the modal amplitudes from experimental measurements. The wavenumbers and corresponding mode shapes, of the propagating modes, are computed as functions of frequency from a waveguide finite element model (semi-analytical finite element model). The frequency response at a set of measurement locations is described by a superposition (with unknown amplitude coefficients) of the frequency response of the modes that propagate in the frequency range of interest. Experimental time domain responses are measured and transformed to frequency responses. The amplitude of each mode is estimated using the pseudo-inverse to provide a minimum norm least-squares estimate.

The technique is demonstrated on a rail excited by a piezoelectric patch transducer. A laser vibrometer was used to measure displacements at 5 points around the rail circumference at three distances from the transducer giving a total of 15 measurements. Six propagating modes were extracted from these measurements. The extracted modes were then used to predict the response at different points along the waveguide and these predictions were verified by further measurements. Good agreement was obtained, demonstrating that the modes of propagation were accurately estimated. The technique requires that the distance between the measurement points be known but does not require that the distance from the transducer be known. This feature and the fact that only a few measurements are required make the method suitable for measuring the propagation of individual modes over long distances in the field.

6935-55, Session 11

Damage detection in concrete and cementitious composites

H. Wu, Wayne State Univ.

Traditionally ultrasonic testing is used to estimate the extent of damage in a concrete structure. However Pulse-velocity and amplitude attenuation methods are not very reliable, and are difficult to reveal early damage of concrete. In a previous study, a new active modulation approach, Nonlinear Active Wave Modulation Spectroscopy, was developed and found promising for early detection of damage in concrete. In this procedure, a probe wave is passed through the system in a fashion similar to regular acoustic methods for inspection. Simultaneously, a second, low-

frequency modulating wave is applied to the system to effectively change the size and stiffness of flaws microscopically and cyclically, thereby causing the frequency modulation to change cyclically as well. It has been also shown that it is advantageous to apply the Hilbert-Huang transform to decompose nonlinear non-stationary time-domain responses of plain concrete. Such procedure leads to improving the damage detection sensitivity of this modulation method in concrete. In this paper, further investigation on mortar and fiber reinforced concrete will be presented and discussed.

6935-56, Session 11

Introduction of structural health and safety monitoring warning system for Shenzhen-Hongkong western corridor Shenzhen Bay Bridge

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Though the brief introduction of the completed structural health and safety monitoring warning systems for Shenzhen-Hongkong western corridor Shenzhen bay highway bridge (SZBHMS), the self-developed system frame, hardware and software scheme of this practical research project are systematically discussed in this paper. The data acquisition and transmission hardware and the basic software based on the NI (National Instruments) Company virtual instruments technology were selected in this system, which adopted GPS time service receiver technology and so on. The objectives are to establish the structural safety monitoring and status evaluation system to monitor the structural responses and working conditions in real time and to analyse the structural working status using information obtained from the measured data. It will be also provided the scientific decision-making bases for the bridge management and maintenance. Potential technical approaches to the structural safety warning systems, status identification and evaluation method are presented. The result indicated that the performance of the system has achieved the desired objectives, ensure the long-term high reliability, real time concurrence and advanced technology of SZBHMS. The innovate achievement which is the first time to implement in domestic, provide the reference for long-span bridge structural health and safety monitoring warning systems design.

6935-57, Session 11

Local health monitoring of Sifangtai Bridge using fiber Bragg grating sensors

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As one of the most important fiber optic sensor, significant amount of interest in Fiber Bragg Grating (FBG) sensing techniques has been generated in a variety of fields. Since the photosensitivity of Germania doped fiber was discovered by Hill (1978), and transverse holographic method using UV illumination was invented by Meltz(1989), Fiber Bragg Grating received extensive attentions from research organizations around the world. FBG, as a novel type of sensor, was initially applied to military fields such as aviation. Lots of measurands such as stress, vibration, pressure, magnetic field can be measured by FBG sensor through the two basic measurands, strain and temperature. Because of distinct advantages (EMI immunity, high sensitivity, multiplexing capabilities, durability etc) over traditional sensors, FBG sensor is regarded as one of the most promising candidates for applications in structure health monitoring.

Sifangtai Bridge located in Harbin city is one of the biggest cable stayed bridges in northeastern part of China, whose whole length and main span length are 696 meters and 336 meters, respectively. Because of the cold weather in winter and big environment temperature shift during one year's time, the bridge structure will face much worse environment condition than those in southern part. Deterioration of the bridge structure in serving period will be inevitable. In order to ensure the bridge safety, one health monitoring system is required to detect the structural failure. In this paper, one large FBG sensor sensing network for bridge local health monitoring was studied, designed and implemented to Harbin Sifangtai Bridge. According to the hot point principle and finite element analysis

results, FBG sensors installation scheme was made to monitor the local strain and the temperature of key elements, respectively. 60 FBG sensors had been installed in monitoring points along the height of I-shape girders distributed in three main monitoring sections along the bridge. Monitoring results in load testing period was obtained, the static and dynamic results show that FBG sensors can monitoring the local strain precisely, and the local strain response is in the safe range under test vehicle load. Monitoring results in service period was obtained, 9 months after load test. Results show that maximum local strain responses in three main monitoring sections are in the safe range, under the dynamic vehicle load. Comparison of the monitoring results from FBG sensor sensing network are used to unveil the local health condition of Sifangtai Bridge reflected by local strain response. The analysis shows that Sifangtai Bridge's key structural elements are under good health condition.

6935-58, Session 12

Quantification of damage detection sensitivity given optimized excitations in a structural health monitoring application

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We have recently demonstrated that a system of ordinary differential equations may be modified with an evolutionary algorithm such that a time series produced by the system will improve damage detection sensitivity when used to excite a structure. In this work we extend the concept of excitation optimization from a computational spring-mass model to an experimental platform. Damage is simulated in the experimental spring-mass system as an increase in mass and state-space features such as prediction error are used to determine the minimum amount of mass addition required for detection given a particular excitation. Various inputs are used to activate the structure and the minimum detection sensitivity is noted for each excitation. In particular, the best excitation discovered by the evolutionary optimization procedure is used to excite the system as well as excitations discovered during the optimization procedure that are less "fit" than best discovered input. Multi-tone and phase-randomized excitations with frequency spectra that match the best discovered excitation are also applied to the structure to demonstrate that deterministic phase relationships are important and that frequency considerations alone are not responsible for improved damage detection. Chaotic excitations are also tested. Ultimately, we demonstrate that the best discovered excitation provides the best damage detection sensitivity while simultaneously rejecting noise-induced false positives. System identification techniques are used to closely match the model required for the optimization to the experimental system.

6935-59, Session 12

Optimized guided-wave excitations for health monitoring of a bolted joint

T. R. Fasel, C. C. Olson, M. D. Todd, Univ. of California/San Diego

Recent research has shown that chaotic structural excitation and state space reconstruction may be used beneficially in structural health monitoring (SHM) processes. This relationship has been exploited for use in detection of bolt preload reduction by using a chaotic waveform with ultrasonic frequency content with a state-space prediction error algorithm. The signal is actively applied to a structure using a bonded macro fiber composite (MFC) patch. The response generated by the mechanical interaction of the MFC patch with the structure is then measured by other affixed MFC patches. In this study the suitability of particular chaotic waveforms will be investigated through the use of evolutionary algorithms. These algorithms will attempt to find the optimum excitation for maximum damage state discernability.

Many currently employed vibration-based SHM methods use low frequency broadband excitation as input to an examined structure. While these methods have been shown to be capable of detecting small levels of damage in particular situations they are largely unable to identify the precise location(s) of damage within a structure because only global dynamical behavior is excited. High frequency (ultrasonic) guided waves have therefore been posited as a solution to the problem of damage localization. The use of high frequency chaotic interrogation combined with MFC active sensing allows the location of incipient damage in the

structure to be easily identified because of the small length and time scales of these ultrasonic excitations.

However, while standard SHM methods for guided waves such as time-of-arrival, attenuation and reflectivity have proven useful for simple geometries (plates, rails, bonded joints, etc.) they cannot be easily applied to complicated geometries or bolted joints because of mode conversion and wave interference effects due to the complex boundary conditions. These methods can only be used to interrogate simple geometries and therefore would be exceedingly difficult to apply to any complicated joint configurations or large-scale structures. Recently, methods that employ chaotic excitations and attractor-based prediction error algorithms have demonstrated the capacity to detect bolt preload loss in various test bed structures. These algorithms are based on complex nonlinear time series analysis but can be characterized as a simple pattern recognition problem. Most importantly this method is valid for complex structural geometries.

This upconverted chaotic wave method has already been shown to be able to detect bolt preload loss and location in a multiple-joint frame structure. However, the waveform used in these experiments has never been examined for suitability to the particular application. The typical method in which the waveform to be upconverted is created is by digitally simulating an appropriate nonlinear system in the chaotic regime offline and using system output as the 'raw' input to upconvert for the present application. In this work the parameters of such an ordinary differential equation system are manipulated by an evolutionary algorithm in order to change the dynamic properties of the waveform created by integration of the system. Each generated waveform is then upconverted and applied to the structure in the damaged and undamaged state. The fitness of each solution is measured by how well the damaged state can be differentiated from the baseline and evolutionary pressure forces the creation of a waveform with improved detection capability.

6935-60, Session 12

Experimental validation of a soft identification algorithm for a MDOF frame structure

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Structural identification and damage detection have become an increasingly important research topic for health monitoring, performance assessment and safety evaluation of infrastructures. In the last two decades, most of the mathematical-model-based structural parameters identification algorithms using eigenvalues or mode shapes have been proposed. The ability of artificial neural networks to approximate arbitrary continuous function and its parallel computation character provide an efficient soft computing strategy for inverse analysis. In recent years, neural networks-based identification method for multi-degree-of freedom structures using vibration measurements without any mode shapes and frequency extraction have been proposed and validated with numerical simulation. The methodology is introduced firstly in this paper. An acceleration-based neural network for acceleration forecasting and a parametric evaluation neural network for parametric identification are constructed to facilitate the whole identification process. Based on the two trained neural networks using acceleration time histories, the inter-storey stiffness and damping coefficients of the object structure are identified using an evaluation index called root mean square of prediction difference vector. The accuracy, sensibility and efficacy of the proposed methodology for spatially complete and incomplete acceleration measurements is examined by experimental study with a multi-degree-of-freedom shear structure that is excited by base excitation on a shaking table. Results show that the proposed methodology is robust and may be an applicable method in practice for structural model updating and damage detection when structural dynamic responses measurements are available.

6935-61, Session 13

Integrated structural health monitoring for composites using proper orthogonal decomposition-based model filter

R. Jha, C. B. Shane, Clarkson Univ.

The use of composite materials has many benefits for aerospace structures,

including weight savings, smoother aerodynamic shape, reduction in the number of joints, improved fatigue life, and a higher resistance to corrosion. However, one potential drawback of composite materials is their susceptibility to impact damage and delaminations. Delamination cracks can be initiated by loading/impact as well as manufacturing defects and the crack lengths can reach critical lengths before the damage can be detected visually. An integrated structural health monitoring (ISHM) system is urgently needed to mitigate the potential risks from delaminations and other damages. We have previously studied damage detection methodologies based on linear time series analysis methods, Hilbert-Huang Transform, and Fourier spectral analysis. A drawback of using the time and frequency domain statistics is that while the methods are able to provide an indication that damage is present, they are often unable to provide any further information on the damage state without a good model or experimental data. Physics based models are often hard to come by since the systems being modeled are usually very complex and difficult to model accurately.

Active health monitoring systems collect vibration, strain, or acousto-ultrasonic data from a structure and provide an indication of its health after processing that data. It has been proposed that filtering the current sensor data (for 'unknown' structure) using a data-driven model can be used instead of a physics based model. We extract a reduced order model from structural responses using Proper Orthogonal Decomposition (POD) to serve as a model filter. The POD technique allows a high-dimensional process to be described by low-dimensional models and thereby a large amount of multidimensional data can be processed and analyzed easily. This aspect of POD makes it very attractive in terms of modeling a complex dynamical system. The POD filter will allow the health monitoring system to focus on changes caused by damage alone since structural responses due to changing operational/environmental conditions can be filtered out. This study investigates the use of the POD methodology for damage detection of composite plates. The POD based filter method will be applied to both numerical and experimental data. Numerical data will be generated using FEA in order to develop and refine the method. Experimental data will be used to validate the methodology and demonstrate its effectiveness in the presence of 'real world conditions', such as noise. The composite plates will be made with a carbon/epoxy material and will be excited with both global (shaker) and local (PZT patch) excitations. The plates will be damaged by introducing a delamination during fabrication as well as by impact. The response of the plate will be determined using a Scanning Laser Vibrometer and integrated piezo sensors. Preliminary work has been accomplished through finite element analysis of a carbon/epoxy composite structure using ANSYS. The results show that the POD method is very sensitive to damages. The level of damage will be decreased to reach the sensitivity limit of the method. More damage locations will be tested to fully understand its capability for correctly identifying damage locations. The final paper will fully describe mathematical basis of the POD based ISHM methodology and present simulation and experimental results.

6935-62, Session 13

Multiscale modeling of wave propagation in composite materials with defects

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The unique properties of composite materials have given way to many developments within aerospace engineering. These properties also present special challenges for detecting damage within composite materials. Acoustic based sensor networks are designed to detect damage by passing a wave through the structure via an actuator and comparing it with a received signal. In the case of fiber reinforced composites, the signal is attenuated irregularly due to the anisotropy of the material, and is also scattered considerably due to the fibers, plies, and boundaries that it interacts with. In the present work, a hybrid numerical model will be developed to describe the received signal due to its interaction with damage, material boundaries, and scattering surfaces within the material. The model will link the macro and micro scale scattering effects through FEA-MAC which has been developed at NASA Glenn Research Center. This application links the Finite Element Analysis utility of ABAQUS with a Micromechanics Analysis Code (MAC). The proposed research aims to add utility to the application in the form of wave propagation, while

investigating specific wave propagation problems related to damage detection. Types of damage modeled will include delaminations and fiber breakage. Initially, modeling and experimentation will be performed on uniaxial composite plates, and will be extended to more complex lay-ups. Correlation between the model and experiments will be evaluated on several test cases.

ACKNOWLEDGEMENTS

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6935-63, Session 13

Passive damage detection in composite laminates with integrated sensing networks

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The initiation and propagation of damage in composite laminates generate detectable Acoustic Emission (AE). The real-time AE monitoring has been extensively used for in-service damage detection in composite structures. In the present work, experimental and numerical studies are used to characterize the acoustic wave propagation in thin glass/epoxy composite plates. Experimentally measured and simulated emission signals are used to identify and locate the source of the acoustic wave. Signal processing algorithms and a passive damage diagnosis system based on AE techniques are proposed for continuously monitoring and assessing the health of composite laminate structures. The local sensing and distributed processing features of the considered sensor system result in a decreased demand for bandwidth and require lower computational power at the embedded nodes.

6935-64, Session 13

Structural damage detection and estimation by amplitude-frequency modulation analysis

P. F. Pai, Univ. of Missouri/Columbia

Presented here is an amplitude-frequency modulation method (AFMM) for extracting damage-induced nonlinear characteristics and intermittent transient responses by processing stationary/transient responses using the empirical mode decomposition, Hilbert-Huang transform (HHT), and nonlinear dynamic characteristics derived from perturbation analysis. A sliding-window fitting (SWF) method is derived to show the physical implication of the proposed method and other methods for transforming time-domain data into frequency-domain data. Similar to the wavelet transform the SWF uses windowed regular harmonics and function orthogonality to extract time-localized regular and/or distorted harmonics, and then the amplitude-frequency modulations of the harmonics are used to identify system nonlinearities. On the other hand the HHT uses the apparent time scales revealed by the signal's local maxima and minima and cubic splines of the extrema to sequentially sift components of different time scales, starting from high-frequency to low-frequency ones. Because HHT does not use predetermined basis functions and function orthogonality for component extraction, it provides more accurate instant amplitudes and frequencies of extracted components for accurate estimation of system characteristics and nonlinearities. Moreover, because the first component extracted from HHT contains all original discontinuities, its time-varying amplitude and frequency are excellent indicators for pinpointing times and locations of impulsive external loads and damages that cause intermittent responses. However, the discontinuity-induced Gibbs' phenomenon makes HHT analysis inaccurate around the two data ends. On the other hand, the SWF analysis is not affected by Gibbs' phenomenon, but it cannot extract accurate time-varying frequencies and amplitudes because of the use of pre-determined basis functions, function orthogonality, and windowed curve fitting for component extraction. Numerical results show that the proposed AFMM can provide accurate estimations of softening and hardening effects, different orders of nonlinearity, linear and nonlinear system parameters, and time instants of intermittent transient responses for damage detection and estimation.

6935-65, Session 13

A Dempster-Shafer evidence theory-based approach for on-line structural health monitoring

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On structural health monitoring, the uncertainty caused by the measurement noise and modeling error involved in an analytical model can impede reliability of damage identification. As a tool to deal with the uncertainty, the traditional probability theory has been used commonly in structural health monitoring, such as the Bayes theory. As an extension to traditional probability theory, the Dempster-Shafer (D-S) evidence theory uses belief and plausibility functions to quantify evidence and uncertainty. The structural damage detection methods based on the D-S evidence theory are researched in recent year. In this paper, a D-S evidence theory based approach for on-line structural health monitoring is presented. Firstly, the Bayesian method is employed to calculate the damage probability of substructures using the multi-sensors data sets measured from the monitoring structure. The damage basic probability assessments used for D-S evidence theory are got by weighing the damage probability considering the calculate accuracy of Bayesian method. Then, D-S evidence theory is employed to update the damage basic probability assessments when new test data became available. To reduce the computational cost when this method is used in complex structures, the preliminarily damage range is located by modal strain energy method. With considering cases of the measurement noise, shortage of high-order mode shapes and rarefaction of measure points, numerical studies on a 14-bay planar rigid frame structure are carried out. The results indicate that better diagnosis can be obtained by continually updating the damage basic probability assessments using multiple data sets than just by using each test data separately.

6935-66, Session 14

Comparative evaluation of ultrasonic lenses and electric point contacts for acoustic flux imaging in piezoelectric single crystals

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Piezoelectric point contact excitation and detection has been successfully employed for phase-sensitive ultrasound wavefront imaging (holography) in anisotropic piezoelectric single crystals using scanning acoustic transmission microscopy. The experimental data can be used, for example, for determination of the elastic constants of the material. Here we compare this approach with imaging using conventional ultrasonic lenses. The large bandwidth and the absence of internal lens echoes in the Coulomb excitation and detection scheme permit continuous unperturbed monitoring of multiple echoes in plane-parallel samples and the detailed investigation of mode conversion processes of longitudinal and transverse waves. Due to differences in the coupling, excitation of ultrasound by an acoustic lens or an electric point contact, respectively, result in noticeably different phonon focusing patterns. This is illustrated in the case of lithium niobate single crystals.

6935-67, Session 14

On normal modes of vibrations of the fiber partially immersed in fluid

W. Wang, Univ. of Washington

Optical techniques for viscosity measurement were not extensively explored until the recent development of an optical method utilizing a forward light scattering pattern as an indirect measurement of fluid viscosity by Wang et al. [1, 2]. Later [3], this concept was refined by replacing the fragile tapered micro-pipette cantilever with a more durable and mechanically stable fixed-end optical fiber partially immersed in a sample fluid. The light from the laser is incident normal to the optical fiber and results in a light scattering pattern. A linear relationship between the displacement of the fiber and the corresponding change in the observed

scattering intensity allows one to measure the small (<1.0 mm) vibration amplitude of the fiber. The viscosity of the fluid is deduced from the frequency response of the vibrating fiber, which is set in periodic motion by a piezoelectric transducer. It should be noted here that in contrast to the well-known normal modes of the fully immersed fiber vibrations the ones for the partially immersed fiber depend essentially on the density of the fluid and its height. The deep understanding of this issue is of critical importance for the correct interpretation of experimental data and of the fundamental interest as well.

In this paper the physical and mathematical model of the forced vibration of a partially immersed fiber is formulated. Based on an analytical solution of the model, natural frequencies of the partially fiber vibration have been found; they are eigenvalues of the transcendental equation. An "effective" speed of the wave propagation over the fiber has been introduced; this allows one to find out the physical meaning of normal modes of the partially immersed fiber vibration. Theoretical predictions agree precisely with experimental data.

6935-68, Session 14

Evaluation of coupled piezoelectric and electromagnetic technique versus stand alone techniques

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Vibration energy harvesting is an attractive technique for potential powering of wireless sensors. Even though much effort has been done, the power densities of these devices require a challenging hike in order to be employed in commercial applications. Piezoelectric and electromagnetic energy harvesting techniques are the most sought after, since the mechanical to electrical energy conversion ratio is attractive. Most of the devices built are based on a single energy harvesting technique, whose power output is solely dependent on the properties of the materials used. Apart from materials, damping is another critical parameter to efficiently harvest energy. In order for the energy harvesting device to have maximum power output, it is necessary to match the electrical part of the damping to the mechanical part. Even though it is evident from the theoretical model that the damping can be controlled by the applied load resistance, it is limited by the source impedance for which it needs to be matched for efficient power output.

In this work a coupled piezoelectric and electromagnetic energy harvesting device is evaluated for its efficiency and compared with the stand alone optimized techniques. A piezoelectric cantilever beam with an NdFeB magnet as its tip mass having a resonance frequency of 19 Hz is used, with a coil winding placed vertically aligned with the magnet such that, the magnetic tip would pass through the coil. The total power output from the coupled technique is monitored along with the damping. The length of the coil is altered to vary the associated damping, and it is determined that the experimental damping results matched with the theoretical values. The overall power output from both techniques is found to be higher than the individual optimized power outputs, suggesting that a coupled energy harvesting device would be an effective mechanism to efficiently harvest energy from vibrations.

6935-69, Session 14

Photonic sensor for nondestructive testing applications

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This paper presents the development of an optical waveguide-based sensor for measurements of strain, stress, temperature, and ultrasonic waves. The sensor design, fabrication, and instrumentation technique offers a number of advantages including sensor compactness, lightweight, low-cost, and multiplexing capability for damage detection and corrosion monitoring of advanced structures and components. Using a robust lock-in laser-based demodulation technique, simultaneous measurements of strain, temperature, and acoustic fields can be performed with high precision, high resolution, and high sensitivity. The sensor device containing an array of optical waveguide Bragg gratings can be surface mounted on monitoring structures for non-destructive testing applications including high resolution strain and acousto-ultrasonics detection.

6935-70, Session 14

Effects of solvent vapor pressure and spin-coating speed on morphology of thin polymer blend films

A. Kamanyi, Jr., Univ. Leipzig (Germany); W. Ngwa, Univ. of Central Florida; W. Grill, Univ. Leipzig (Germany)

Thin films of polystyrene (PS)/polymethyl methacrylate (PMMA) blends were made by casting from solutions with solvents of varying vapour pressure. Solvents used were chloroform, toluene and dichlorobenzene. Spin coating was carried out at varying speeds yielding films of different thicknesses. Atomic force microscopy (AFM) and phase-sensitive acoustic microscopy (PSAM) were used to investigate the effects of spin speed and solvent vapour pressure on morphology. The domains formed due to lateral phase separation proved to be strongly influenced by vapour pressure with completely different surface structures for the three solvents. The films cast from high vapour pressure solutions displayed an increased surface roughness. Surface morphology is explained by the relative solubilities in the different solvents, surface affinity, spin speed and solvent evaporation rate.

6935-71, Session 15

High-energy (MeV) x-ray imaging with a mercuric iodide imager

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A 13 cm x 13 cm size mercuric iodide (Hgl2) imager was tested the first time for high (MeV) energy X-ray imaging with a 6 MeV Betatron and a 4 MeV Linac x-ray sources. The 127 μ m pixel size imager gave excellent resolution, MTF of 45% at the Nyquist frequency, similar to that of measured at diagnostic (keV) energies. The sensitivity of the imager was measured using a 1mm thick Cu and a 0.5 mm thick Ta buildup plates placed on the top electrode of the Hgl2 layer and without any buildup plate. We got the highest signal using no buildup plate.

The imager can also capture fluoroscopic images up to 15 fr/sec at full resolution mode and up to 30 fr/s when binning the pixels 2 x 2. With this imager, we showed that small steel objects are clearly visible behind a 1/8" thick steel plate.

The experiments with high energy x-rays demonstrate that Hgl2 imagers could be used not only for the diagnostic energy range but also for the MeV energy range, moreover the same imager can be used for dual energy (keV and MeV) imaging for medical, NDE and homeland security applications.

6935-72, Session 15

Determination of mechanical properties with vector-contrast scanning acoustic

A. M. Esam, A. Kamanyi, Jr., M. von Buttler, R. Wannemacher, K. Hillman, W. Grill, Univ. Leipzig (Germany)

Microscopic objects including living cells on a planar substrate are commonly observed in bio-medical applications of scanning acoustic microscopy. Beside of the observation of lateral structures, the determination of mechanical properties such as density, sound velocity and attenuation is desired, from which elastic properties can be derived. This can be achieved with the aid of phase and magnitude contrast that can be represented in a polar plot. For homogeneous and sufficiently planar objects the contrast in amplitude and phase is a function of

the properties of the substrate and the coupling fluid, which both can easily be determined, and of the mechanical properties of the sample under observation. For observation in reflection and variable thickness of the sample the signal will depend on the actual thickness. This signature of the object can be fitted based on a conventional ray model for the propagation of sound including refraction and reflection. We introduce here observation with two different coupling fluids and demonstrate the effect of refinements of the employed model. Results are demonstrated and discussed for relevant bio-medical applications. Other well established methods are compared to the present scheme, which has not been widely used so far and is capable to reach resolution at and below 1% in applications involving imaging at 1.2 GHz in aqueous coupling fluids.

6935-73, Session 15

Identification of aortic-to-upper limb cardiovascular dynamics for aortic blood pressure recovery

J. Hahn, H. H. Asada, Massachusetts Institute of Technology; A. T. Reisner, Massachusetts General Hospital

This paper presents a novel method to identify the dynamics of an aortic-to-upper limb cardiovascular system based on the upper limb (e.g. brachial or radial) blood pressure measurement. The method, which is built upon the application of the pseudo-multi-channel (or over-sampling) blind system identification methodology to a gray-box model of the aortic-to-upper limb cardiovascular dynamics consisting of a time delay and two polynomial coefficients, is able to characterize the upper limb cardiovascular dynamics and recover the aortic blood pressure signal fed to it. It is shown that for a given time delay the system identification problem reduces to a linear least-squares problem, which can be solved to characterize the upper limb cardiovascular dynamics and recover the unknown input signal. The optimal time delay can be determined as the value of time delay which offers the input signal that is morphologically closest to the aortic blood pressure signal based on a priori knowledge on its waveform morphology. The experimental results based on 83 data segments obtained from a swine subject show that the cardiovascular dynamics can be accurately identified and the aortic blood pressure signal can be stably recovered solely from the upper limb blood pressure measurement under diverse physiologic conditions. Combined with non-invasive upper limb blood pressure measurement techniques such as arterial tonometry, this method is expected to be immediately extended to non-invasive central cardiovascular health monitoring applications.

6935-74, Session 15

Combined phase-sensitive acoustic microscopy and electric monitoring of rat heart muscle living cells

E. Twerdowski, M. von Buttler, R. Kurz, R. Wannemacher, A. Robitzki, W. Grill, Univ. Leipzig (Germany)

Phase-sensitive acoustic microscopy (PSAM) permits ultra-sensitive monitoring of the thickness of samples. The thickness resolution is not determined by the Abbe limit in this case. The method can be applied to non-invasive in-situ monitoring of living biological cells. Here measurements of periodic movements of rat heart muscle living cells by PSAM are compared to simultaneous registration of corresponding electric signals. The cells are simultaneously imaged by confocal laser scanning microscopy. The influence of chemical stimulants on the movements is investigated.

6935-75, Session 15

Advanced shape tracking to improve flexible endoscopic diagnostics

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Flexible endoscopes are used in a number of medical diagnostic procedures. For example, colonoscopy is the current gold standard for colorectal cancer screening, and inflammatory bowel disease diagnosis. Visual inspection of the colon is often performed in conjunction with tissue biopsy, and/or fluorescent tattoos to localize areas for further interventional procedures (surgery). However, one of the main challenges in performing colonoscopy is the near-blind navigation of the endoscope in the patient's colon, since the operator (clinician or researcher) can only "see" through the distal tip of the endoscope. There is a real need for better navigation aid to allow for better control of the endoscope which will translate to potentially fewer problems (e.g., looping of the colon) and more efficient examinations. A new shape tracking technology is being investigated to provide the operators with a real-time 3D image of the colonoscope on an augmented reality display. The key enabling technology for this is a fiber-optic shape tracker that utilizes a fiber, which has differentiable, fluorescent dyes located at specific positions along the fiber. Laser-light illumination through the fiber results in varying degrees of fluorescence depending

on the local curvature (i.e., more curvature results in more leakage and hence more fluorescence). A spectrometer collects the emitted spectra and further analysis allows for reconstruction of the 3D shape of the fiber-scope coupling, rendered in an augmented reality display. This technology can be applied to other applications where flexible boroscopes are used for visual inspection (e.g., complex industrial machines and homeland security). The technology would allow for better navigation and provide specific 3D location data for the operators.

This paper presents the initial results of developing the fiber optic tracking system with illuminator, fluorescent dyes, and spectrometer. A single multi-mode fiber with silica-core/silica-cladding and dark buffer was modified such that a small quantity of a fluorescent dye was embedded in a 200 μm hole in the cladding. Multiple unique dyes can be so embedded at pre-determined intervals along one axis of the fiber (on the same radial angle) to specify the length and location of the dye. That is, each hole is coated with a unique dye identifiable by its fluorescence with a specific peak spectrum. As the dyes respond to the amount of excitation light as a function of fiber bend, the effect of changing curvature on the emission spectra can be analyzed systematically for a number of different curved shapes.

The dye selection process, embedding techniques, and testing for photostability are described. Preliminary results indicate that there are a number of organic dyes that can fluoresce in the fiber with small holes and are stable under illumination for at least 10 minutes. Continuing studies are focused on measuring changing fluorescence with fiber bending. These initial results are limited to one plane while future studies will incorporate 3D curvatures as research continues.

6935-76, Session 15

High-speed ultrasound monitoring in the field of sports biomechanics

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Ultrasonic methods have been developed in order to observe variations of the performance of muscles under training. The monitoring scheme is suitable to determine muscle movement and is based on the measurement of the transit time of longitudinal ultrasound propagating through the muscles. Variations of the length of the muscle lead to variations of the lateral extension since the volume of the muscle is conserved. The corresponding variations of the observed time of flight result dominantly from the variation of the path length. This allows the time-resolved detection of the movement of the muscles in the path of the ultrasonic beam. In this way not only the degree of contraction or relaxation, but also the speed of these processes can be quantitatively monitored. The muscle thickness has been determined with a resolution of ± 0.02 mm corresponding to about $\pm 0.2\%$ of the thickness of the relaxed muscle. This resolution is already in the range of unavoidable uncertainties caused by the surface structure of the individual muscles. Similarly, the already obtained resolution in time corresponds to a fraction $1/750$ of the time of the fastest known human muscle movement of 7.5 ms, observed for the full contraction of the eye lid muscle. The time of flight is measured along a line between two coaxially adjusted acoustic transducers positioned on the skin on opposite sides of the monitored muscle. The transducers can be placed at any desired position but should be positioned such, that no bones or intestines are obstructing the path between them. The time of flight from which all other data is derived is observed with the aid of a computer-controlled arbitrary function generator (D/A-converter) and a synchronized transient recorder (A/D-converter). Even in the demonstrated developmental state the equipment is already rather compact (lap-top size) and can be battery operated. The implemented scheme is suitable for a future reduction to pocket size equipment and can also be adopted for radio-transmission of the monitored signals.

6935-77, Session 15

An offset multilayered optic sensor for shear and pressure measurement

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We have developed a multi-layered optical bend loss sensor that can

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be accommodated for shear and pressure measurement of an extended area.

The sensor is made of two layers of crisscross fiberoptic sensor array separated by an elastomeric layer. Each sensing layer has 8 fibers molded into a thin polydimethylsiloxane (PDMS) substrate to form a 4 by 4 mesh array or 16 intersection sensing points. The space between the adjacent fiber is 0.5cm. Measuring changes of light intensity transmitted through the fiber provides information about the force induced changes of the fiber's radius of curvature. Pressure is measured based on the force induced light loss from the two affected crossing fibers divided by each sensing area. Shear was measured based on the relative position changes on these pressure points between the two fiber mesh layers. The additional elastomeric layer provides mobility in the lateral direction to improve the shear sensing. In our last report, we replaced the elastomeric layer with gel. The results show that maximum transmission attenuation due to bending remains high. In this case, a 30% attenuation was observed at the top layer and 3% at the bottom layer. Shear induced loading point shift between top and bottom layer was also observed from the experiment. In this paper, we will present a new layout with implementation of an offset between the top and bottom sensing layer to further improve the shear sensitivity and sensor's spatial resolution. We will report our preliminary study on the new multi-layered sensor including results from the normal and shear load measurement. We will also discuss the auto calibration algorithm, results of the multiple pressing points and patterns with and without shear using the improved design.

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