

2011 Smart Structures/NDE

Technical Summaries

spie.org/ss

Conference Dates: 6-10 March 2011

Exhibition Dates: 8-9 March 2011

Town and Country Resort and Convention Center
San Diego, California, USA

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Conference 7975: Bioinspiration, Biomimetics, and Bioreplication

Monday-Wednesday 7-9 March 2011

Part of Proceedings of SPIE Vol. 7975 Bioinspiration, Biomimetics, and Bioreplication

7975-01, Session 1

Structural colors in nature as bio-inspiration for selective vapor sensing

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Sensing materials fabricated with nanometer-scale features enable previously unavailable opportunities for chemical and biological sensing. In vapor sensing, a well-accepted advantage of nanofabricated photonic sensing structures over organic dyes is the elimination of photobleaching problems. Unfortunately, the main limitation of existing nanofabricated photonic vapor sensing materials is their low response selectivity to analytes. Thus, their selectivity is typically enhanced with chemically selective moieties or layers.

We will discuss a quite different approach for selective response to diverse vapors by taking advantage of the hierarchical and highly ordered photonic nanostructure formed in the scales of butterfly wings. This iridescence is known to be a result of the combined effects of diffraction and interference of light. We have found that upon interaction with different vapors, such photonic structure produces remarkably diverse differential reflectance spectra. The significance of this finding is that the response selectivity of iridescent scales of butterfly wings dramatically outperforms existing nano-engineered photonic sensors. Approaches for the bio-inspired fabrication of photonic sensing structures will be also discussed.

This work has been supported in part by DARPA Contract 18W911NF-10-C-0069.

7975-02, Session 1

Bioinspired optical sensors for unmanned aerial systems

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Insects are dependent on the spatial and temporal distribution of light in the environment for navigation, collision avoidance and flight control. The principles of insect vision have been decoded over many decades by biological scientists. This paper reports on bioinspired implementations of these behaviours on unmanned aerial vehicles.

Optical flow techniques inspired by bee behaviour have been applied to the problems of an unmanned aircraft maintaining a constant height above ground. The technique for sensor fusion of optical flow with conventional barometric altitude sensing is presented. A problem faced by all air vehicles is the deviations off course caused by winds. By fusing optical flow, attitude and magnetometer information a highly effective solution was demonstrated.

A biomimetic instrument for measuring the polarization pattern of the sky was implemented. The usefulness of this auxiliary direction reference in demanding environments is explained. A biomimetic version of dragonfly ocelli (an optical system that coexists with the compound eye) was implemented as a stabilisation sensor. The behaviour of the aircraft under the control of this sensor is examined. In each case the flight test results are presented including video from flight trials where appropriate.

The behaviours demonstrate most of the core functionality found in the lower levels of the sensorimotor system of flying insects. Future work will develop the high level autonomy required from unmanned aerial systems in the future. Future high value opportunities for biomimetic optical sensor development will be discussed, using some inspirational examples of engineering by biology as exemplars.

7975-03, Session 1

A bioinspired methodology for odor recognition using chemical sensor arrays

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Through the use of diverse materials and specialized operational schemes, analytically rich data are obtained from chemical sensor arrays so that a broad range of analytes is sensed and differentiated. Extending these concepts into real-time recognition, however, is extremely difficult when the sensor is asked to characterize analytes upon which it has not been trained. Nevertheless, this is a problem that is solved by the olfactory system of even evolutionarily primitive animals. Here we demonstrate a biologically inspired hierarchical classification scheme for robust recognition of chemical analytes. Using this approach, analyte composition is refined in a progression from more general (e.g., whether the target is a hydrocarbon) to highly precise (e.g., whether the target is ethane or propane), using optimized data for each step. We validate this concept using a MEMS-based chemical microsensor array (16 sensing elements with eight different materials) that senses and categorizes 11 simple analytes at trace concentrations and identifies various alcohols and ketones as such even though they were not members of the training set. Recent expansion of this work towards recognition of analytes within complex mixtures or in the presence of chemical interferences will also be discussed.

7975-04, Session 1

Biomimetic gas sensors for large-scale drying of wood particles

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The Australian pyrophilic beetle *Merimna atrata* needs freshly heated wood to bring up its offspring and, consequently, shows a very high sensitivity to volatiles specific for wood-fires and heated wood. Volatile organic compounds released by wood particles heated at different temperatures were collected. Parallel trace analytical examination and antennal responses of the pyrophilic beetles to volatiles released by the wood reveal a highly differentiated detection system of these insects for early and late products of wood pyrolysis. This enabled a selection of marker compounds used by insects since several million years for the discrimination of different stages of pyrolysis in wood. In the industrial production of engineered wood such as particle boards, wooden particles are dried in large-scale high temperature dryers. Despite the resulting energy-efficiency of high temperature drying, high temperatures are avoided because of the increased risk of spontaneous combustion. In order to raise the drying temperature without risking a fire, it is important to increase the reliability of sensors providing warnings at situations of over-heating. Thus, perception filters and evaluation algorithms of pyrophilic insects can provide blue prints for biomimetic gas sensors for large-scale drying of wood particles. Especially tungsten oxide sensor elements exhibit a high sensitivity to the key substances combined with low cross sensitivity to water and carbon monoxide. In order to enhance sensitivity we synthesized ordered nanostructured WO₃ in a nanocasting process. The high sensitivity of the nanostructured material to hydroxylated compounds in combination to low cross-reactivity with water and carbon monoxide mimics highly efficient biological fire detection systems.

7975-05, Session 2

Biomimetic infrared sensors based on the infrared receptors of pyrophilous insects

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The larvae of the beetle *Melanophila acuminata* need freshly burnt wood for their development. Therefore, the beetles of the parental generation search for forest fires by a pair of thoracic infrared (IR) pit organs located below the wings. About 70 dome-shaped IR receptors are located in each pit organ. A single sensillum consists of a round outer cuticular shell and an inner microfluidic core. It is assumed that the absorbed infrared radiation increases the internal pressure especially inside the core which is measured by a mechanosensitiv neuron.

Transferring this biological principle of infrared detection into technology can result in a novel uncooled infrared sensor with high sensitivity. To demonstrate the functional principle we built a macroscopic sensor with a sealed inner chamber which can be filled with gas, fluids or mixtures of fluids and solid particles. Irradiation by a broadband IR emitter causes deflection of a bottom membrane which is measured by a capacitive sensor. Results help to verify the biological principle and to optimize the composition of the fluidic core of the technical sensor.

In the *Melanophila* sensillum a system of fine channels extend through the outer shell. We speculate that these channels may serve for the compensation of stochastic fluctuations of the ambient temperature. For designing a miniaturized technical sensor we derived a set of equations to calculate the time constant of the compensation channel and the pressure decrease in the fluid cavity in relation to all important parameters. This allows optimizing the layout of the temperature compensation.

7975-06, Session 2

Lateral line canal morphology and signal to noise ratio

A. T. Klein, H. Herzog, H. Bleckmann, Rheinische Friedrich-Wilhelms-Univ. Bonn (Germany)

With aid of the lateral line fish can detect minute water motions. The smallest functional unit of the lateral line is the neuromast, a sensory structure that occurs free standing on the skin and in fluid filled canals. In their natural habitat fish not only face biotic water motions but also abiotic fluctuations caused by various inanimate sources. Since the detection of meaningful signals is crucial for the survival of fish, one can assume that natural lateral line systems are optimized to separate signals from noise. This may be one of the reasons why the number and distribution of neuromasts as well as canal dimension, canal shape and canal branching patterns can differ substantially among fish species. We studied various types of artificial lateral line canals equipped with artificial neuromasts (sensors). We found that proper selected canal parameters significantly altered the response properties of artificial lateral lines and that certain canal types enhanced signal to noise ratios. For instance, certain canals were much better in displaying the presence of a vortex street caused by a cylinder exposed to laminar or turbulent flow. One advantage of these canal types is that the distance over which a cylinder can be detected is markedly increased. Supported by the DFG (GRK Bionic)

7975-07, Session 2

Bioinspired vision sensors with hyperacuity

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Musca domestica, the common house fly, possesses a powerful vision system that exhibits features such as fast, analog, parallel operation

and hyperacuity -- the ability to detect movement and objects at far better resolution than predicted by photoreceptor spacing. The Wyoming Information, Signal Processing, and Robotics Laboratory have investigated these features to develop an analog sensor inspired by the fly. Research efforts have been divided into electrophysiology; mathematical, optical and MATLAB based sensor modeling, physical sensor development, and applications. This paper will provide an in depth review of recent key results in each of these areas including development of a multiple, light adapting cartridge based sensor constructed on both a planar and co-planar surface using off-the-shelf components. Both a photodiode-based approach and a fiber based sensor will be discussed. Applications in long term building monitoring and autonomous robot navigation are also discussed.

7975-08, Session 2

Hair cell sensing with encapsulated interface bilayers

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Our research focuses on developing robust material platforms that use the functionality of assembled biological molecules to develop a wide variety of chemical and biochemical detectors, pharmaceutical screening assays, bio-inspired flow sensors, and energy conversion platforms. A central concept of our work is the formation of durable lipid bilayers that mimic the basic structure of a cell membrane. The addition of biomolecules such as proteins into a lipid bilayer results in the formation of a selectively-permeable membrane that can initiate biochemical reactions, transport species, and send signals in response to particular stimuli. In this fashion, processes that occur in cells can be replicated and designed into artificial material systems that feature networks of lipid bilayers. Unlike much of the early work devoted to the formation and study of suspended or supported lipid bilayers, we use the regulated attachment method (RAM) to connect lipid-encased aqueous volumes submersed in oil and contained within a durable polymeric substrate to form durable lipid bilayers. This technique uses an applied force on the substrate to open and close an aperture that separates adjacent aqueous volumes, providing a simple method for controlling the size of the bilayer. Most recently, we have demonstrated that bilayer formation via RAM can be conducted using either liquid aqueous phases or water-swollen hydrogels, which are formed via photo-polymerization and, unlike liquid aqueous phases, can be made in nearly any shape or size. This paper investigates how an interface bilayer formed lipid-encased hydrogels can be used to develop a bio-inspired hair cell sensor.

7975-11, Session 3

Mechanical behavior of autonomic gelatin and polyacrylamide gels

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Freedom from direct external control and stimuli is a feature not often found in synthetic materials. On the other hand, complex biological systems regularly display autonomic behavior. Examples include unconscious beating of the heart, synchrony of flashing fireflies, and undulatory motion in certain swimming organisms. Self-oscillating hydrogels driven by the Belousov-Zhabotinsky (BZ) reaction provide a unique foundation for the mimicry of these autonomic biological functions. Like biological tissue these materials can convert chemical signals into a mechanical response. Under appropriate conditions BZ gels exhibit sustained mechanical swelling-deswelling oscillations; and arrays of these gels have the potential to form networks of coupled oscillators with applications ranging from device locomotion to information processing. One of the key challenges to developing criteria for device design and assessing practical performance limits of

these materials is detailed knowledge of the mechanical characteristics of the BZ gels at various states of autonomic behavior. Recently we developed two, easily synthesized, BZ gel systems based on gelatin and polyacrylamide. The gelatin system uses a succinimidyl amine coupling reaction to covalently bond a ruthenium catalyst to the gel network which can be completed under biological conditions. Herein, the swelling-deswelling amplitude and mechanical forces produced during uniform oscillations are discussed for gelatin and polyacrylamide microgels of various sizes. These studies provide an experimental foundation to tune currently available theoretical models and to guide the design of autonomic devices.

7975-12, Session 3

The importance of water for the mechanical properties of insect cuticle

D. Klocke, H. Schmitz, Rheinische Friedrich-Wilhelms-Univ. Bonn (Germany)

Insect cuticle has a broad range of mechanical properties, depending on the function of a certain structure of the insect skeleton. As cuticle has to provide a very efficient and lightweight skeleton, it is a highly interesting composite-material and may serve as a natural model for biomimetic materials.

However, the water content of insect cuticle is of great importance for its material properties. Here, we present a new method to perform nano-indentation experiments in cuticle which is fully saturated with water. We dissected parts of the exoskeleton of *Locusta migratoria* and used a Berkovich-tip suitable for experiments in fluid to determine the elastic modulus (E_r) and hardness (H) of the cuticle. Cuticle sections were measured in air and then submerged and measured in water. As insect cuticle is an anisotropic material, we performed nano-indentation in the normal as well as in the transverse direction to the cuticle surface. We also tested different cuticle layers within each sample (exo-, meso- and endo-cuticle).

It turned out that a change of the water content has a significant impact on the material properties of the cuticle. For example, the E_r of submerged endo-cuticle turned out to be 75% lower than of dried endo-cuticle samples. Further, the proportion of material properties between different cuticle layers within a sample changes strongly after addition of water. If measured in air, E_r of endo-cuticle is significantly higher than of meso-cuticle. In contrast, E_r of endo-cuticle is significantly lower than of meso-cuticle if the sample is submerged in water.

7975-13, Session 3

Bio-inspired assembly of nanoplatelets for reinforced nanocomposites and gas-barrier coatings

P. Jiang, Univ. of Florida (United States)

The nacreous layer of mollusk shells is both strong and stiff. This is attributed to the unique three-dimensional (3D) assembly of platelet-like ceramic building blocks which are embedded in a polymer matrix. Layer-by-layer (LBL) assembly of clay nanoplates and polyelectrolytes has been developed to make polymer nanocomposites that mimic the natural structures and mechanical properties of nacles. However, the LBL approach is tedious in assembling thick coating. Here we report the rapid fabrication of large-area nacreous coatings by utilizing capillary, electrical, and shear forces. Hexagonal gibbsite nanoplates with ~200 nm diameter and ~10 nm thickness and graphene sheets with atomic-scale thickness can be assembled into ordered multilayers with controlled thickness ranging from submicrometer to hundreds of microns. The interstitials between the assembled nanoplatelets can be filled up by polymers and metals. The resulting nanocomposites exhibit unique combination of stiffness, strength, and toughness. A simple shear-lag model has also been developed to predict the mechanical properties of the ordered nanocomposites. The experimental results agree well with this model.

Besides application in reinforced materials, the unique combination of the ultra-low permeability of graphene sheets and the long diffusion length of chemicals and gases in the oriented graphene-polymer nanocomposites also enable high-performance gas-barrier coatings. We will also discuss this application in the talk.

7975-14, Session 3

Computational multi-scale constitutive model for wood cells and its application to the design of bio-inspired composites

E. I. Saavedra Flores, M. I. Friswell, E. A. de Souza Neto, Swansea Univ. (United Kingdom)

In an attempt to understand the highly irreversible processes existing in wood, our main objective in this paper is to investigate the non-linear mechanical response of wood cells by means of a finite element-based computational multi-scale approach. At the level of cell-wall, the material response is described by a Representative Volume Element (RVE) composed of three basic constituents: hemicellulose, lignin and cellulose. Furthermore, at a lower scale the cellulose fibre is represented as a periodic arrangement of crystalline and amorphous portions, whose overall constitutive behaviour is modelled as a single material defined at each Gauss-point by means of a second RVE. We anticipate that key features of the mechanical behaviour of wood cells are reproduced by the proposed model, such as fibre reorientation-induced stiffening under different microfibril angles. The predictive capability of the present multi-scale model is demonstrated by comparing the numerical results with published experimental data.

In addition, the structural and mechanical concepts involved in wood cells are exploited further in order to design new wood inspired composites. Based on our results obtained from the numerical modelling of wood cells, we suggest a bio-inspired strategy to increase the resistance to failure and to control the balance between stiffness and flexibility in prototypes of new composites. This strategy is suggested by the strong influence of the proportion of volume fractions of crystalline and amorphous celluloses on the overall mechanical behaviour of wood cells. This important concept can be adopted as a strategy in the future designs of biologically inspired materials.

7975-15, Session 3

Nonhomogeneity and anisotropy of membrane and finite element modelling of a beetle wing

T. Jin, N. Ha, N. Goo, H. C. Park, Konkuk Univ. (Korea, Republic of)

In the present study, a digital image correlation method has been applied to measure the elastic modulus of a beetle wing membrane. The specimen was attached to a designed fixture to induce a uniform displacement using a micromanipulator. We measured the applied load and the corresponding displacement by a load cell with a maximum capacity of 5 N and by an ARAMIS system based on the digital image correlation method respectively. The measured thickness of a beetle wing varied from point to point of the wing part and the elastic modulus was different according to the loading direction. Furthermore, a method of building a finite element model of beetle wing has been proposed based on the real beetle wing which was 50 mm long in spanwise direction and 20 mm long in chordwise direction. We scanned a real beetle wing with a scanner to get its two dimensional image. The scanned image was used to make a CAD data of membrane and vein's outer lines. Those lines were used to build a finite element model. The model was divided into 48 regions so that thickness variation of membranes and veins could be taken account. The effect of vein's cross section on the exactness of the finite element model was investigated. The finite element model simulated a bending test of a real beetle wing, and the analysis results are in agreement with the experimental result.

7975-16, Session 4

Structural color mixing through vertically stacked heterogeneous photonic bandgap structures using magnetically tunable and photochemically fixable photonic crystal

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Found in nature on butterfly wings or peacock feathers, structural color results from the interaction of light with sub-wavelength structures. Specific wavelengths of light cannot travel into such structures, which be seen as a color. Unlike chemical pigments or dyes, structural color shows iridescent and metallic color, additionally, structural color does not suffer from photo-bleaching as time passes. Due to its unique characteristics, the fabrication process to produce artificial structural color has been extensively studied, including colloidal crystallization, dielectric multilayer stacking, and direct lithography. Artificial structural color may have applications including optical filters, forgery protection, and new materials design.

To expand the potential of artificial structural color a useful new capability might be the use of color mixing to broaden the color expression range, as been employed by certain species of cephalopods. While color mixing of chemical dyes can be easily achieved simply by mixing multiple color dyes with different absorption bands, mixing of the structural colors with different photonic bandgaps is quite challenging since it requires sophisticated manipulation of nanoscale building blocks. Here, we present a new material system and instrumentation to overcome the limitations of previous approaches, and demonstrate rapid production of high-resolution patterns of multiple stacked structural colours. Photonic crystals with different bandgaps are formed on various substrates using a single magnetically active material and maskless lithography, within a few seconds.

7975-17, Session 4

The optics of spider orb webs

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Spider webs are known to produce colour displays in nature, both in reflection and transmission of sunlight, under certain illumination conditions. The cause of these colours has been the subject of speculation since the time of Newton. It has also been the topic of observational interpretation and some experiment which has proposed diffraction by the fine silks, scattering from rough/structured surfaces and thin film effects as the primary causes. We report systematic studies carried out using the silks of Australian orb web weaving spiders. Studies of both white light and laser light scattering/propagation by natural spider silks have definitively determined the primary cause of the colour displays is rainbows that can be understood by the application of geometric optics combined with new knowledge of the optical properties of the spider silks and proteins as optical materials. Additionally, a range of microscopies (optical, AFM, optical surface profiling) show the silks to be optically flat. Overall, spider silks emerge as fascinating optical materials with high dispersion, high birefringence and the potential for future research to show they have high nonlinear optical coefficients. Their importance as a bioinspiration in optics is only just beginning to be realised. Their special optical properties have been achieved by ~136 million years of evolution driven by the need for the web to evade detection by insect prey.

7975-18, Session 4

Prismatic bioinspired compound lenses for solar cells

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Efforts are being made continually to improve the efficiencies of silicon solar cells. To this end several strategies are employed, including the use of anti-reflection layers, texturing of the front surface of the silicon slab, mechanical solar tracking, and the use of concentrators. We suggest that a prismatic lens, whose shape is inspired by the apposition compound eyes of some dipterans, be mounted on the silicon slab to improve the solar harvesting capability. The bioinspired compound lens (BCL) has a fractal construction procedure in which the cross-section of the lens is a frustum of a infinitely long circular cylinder at the zeroth-stage, and is decorated with sections of smaller cylinders at higher stages of construction [1]. We analyzed BCLs made of silicon as they can be textured directly on the front surface of the silicon slab. Within a spatial regime where geometrical optics is valid [2] and considering the complex-valued nature of the refractive index of silicon, generalized reflection and refraction laws as well as generalized Fresnel coefficients [3] were used to evaluate the light-coupling efficiency of the BCL. For a given wavelength, numerical simulations allowed us to determine the values of morphological parameters optimizing the performance of the BCL. We found that first-stage BCLs perform better than untextured silicon and that the efficiency of first-stage BCLs cannot be enhanced by higher-order stages. A multifrequency analysis of first-stage BCLs taking into account the broadband nature of solar radiation and its amplitude at the sea level (AM1.5G spectrum) demonstrated that the light-coupling efficiency can be enhanced by as much as 40% with respect to that of the silicon slab alone. Thus, properly designed silicon BCLs can significantly improve the light-harvesting capabilities of silicon solar cells.

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7975-19, Session 4

Self-assembled biomimetic antireflection coatings for highly efficient photovoltaics

P. Jiang, Univ. of Florida (United States)

Millions of years before we began to generate functional nanostructures, biological systems were using nanometer-scale architectures to produce unique functionalities. Some nocturnal moths use hexagonal arrays of subwavelength nipples as antireflection coatings (ARCs) to reduce reflection from their compound eyes. Similar periodic arrays of pillars have also been observed on the wings of cicada to render superhydrophobic surfaces for self-cleaning functionality. Inspired by these natural nanostructures, we have developed a simple and scalable templating technique for fabricating self-cleaning, broadband ARCs on a large variety of technologically important substrates (e.g., crystalline Si, GaAs, GaSb, glass, and polymer). The technique is based on a spin-coating platform that combines the simplicity and cost benefits of bottom-up colloidal self-assembly with the scalability and compatibility of standard top-down microfabrication. The resulting subwavelength-structured ARCs exhibit superior broadband antireflection properties than traditional multilayer dielectric ARCs and are promising for applications ranging from highly efficient solar cells and photodetectors to flat-panel displays.

7975-20, Session 5

Take-off of a beetle-mimicking flapping-wing system

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The unsurpassed flight performance of insects has captured researcher's attention to draw creative ideals for insect-inspired flying robots or hovering capable flapping-wing micro air vehicles (FW-MAVs). Potential applications of these FW-MAVs are foreseen in many applications for space exploration, military intelligence as well as civil services. Possessing an exoskeleton which is different from that of birds, flying insects can simultaneously flap and rotation their wings at high frequency and amplitude for both flight and maneuver by changing their left and right wing kinematics. Most of these features are well understood and revealed by many researchers, and well documented in literatures related with insect flight. However, in engineering aspect, it is a challenging problem to implement these features into a compact flapping-wing model for real applications.

Recently, we have introduced a Scotch yoke-based and beetle-size flapping-wing system weighing about 6.5 g without battery attachment. Powered by an onboard battery (lithium battery, 3.7 V, 180 mAh), the flapping-wing system could create a large flapping angle of 145o at flapping frequency of 25 Hz, and produced an average vertical force of about 3 g. However, the flapping frequency is still lower than that of a real beetle (about 35 Hz to 40Hz), and the vertical force is still relatively small when compared with the flapper's weight. Thus, we expect that at higher applied voltage from an external power supply the flapping-wing system can flap at higher flapping frequency close to that of a real beetle, and produce a large enough force to lift its own weight.

In this paper, we summarize the design of a beetle-inspired flapping-wing system as an effort to fully mimic the beetle flight, *Allomyrina Dichotoma*, in near future. In the design, we use a combination of Scotch yoke and linkage mechanism to transform the rotary motion of motor into a large output flapping angle. Passive wing rotation is implemented into the flapping-wing system by means of flexible members. By using a high-speed camera, observation for the wing movement of the flapping-wing system powered at high voltage is conducted to measure the flapping frequency and determine the wing kinematics. For a reliably measurement of the force produced by the flapping-wing system, we use three different approaches, which are load cell test, wired-flight test and swing test, and compare with each other. The results of force measurement from the three approaches are in good agreement and confirm the flapping-wing system can produce a large enough force to lift its own weight. In addition to the force measurement, we vary the body angles of the flapping-wing system with and without elytra implementation to investigate its pitching moment. We search for a body angle at which the flapping-wing system generates a lowest pitching moment, and shows inherent pitching stability. Finally, we demonstrate a vertical take-off of the flapping-wing system.

7975-21, Session 5

Closed loop heading control in the Tobacco Hawkmoth, *Manduca sexta*

M. W. Shafer, Cornell Univ. (United States); R. Tiwari, The Boyce Thompson Institute for Plant Research (United States) and Cornell Univ. (United States); E. Garcia, Cornell Univ. (United States)

The study of the anatomy and neurogenic patterns of the tobacco hawkmoth, *Manduca sexta*, has progressed to a point that closed loop flight heading control is possible on the live, flying animals. Presented is a method for closed loop control that has been demonstrated on tethered subjects. Two groups of mesothoracic muscles are responsible for the gross motion of the wings in the tobacco hawkmoth. The dorsal longitudinal (DLM) and dorsal ventral (DVM) muscle groups are responsible for the downward and upward motion of the wings,

respectively. Previous research has shown that these muscles are stimulated similarly to mammalian cardiac muscle tissues and that the moths vary the phase of their activation in order to affect yaw in flight. Additionally, other groups have developed biocompatible stimulation probes for these moths that specifically target the DLM and DVM groups. With this knowledge, the question of close loop control arises. Both the possibility and basic strategies are addressed. The experimental setup only allowed for yaw motion of the active moths and the closed loop control system allowed for varying types of pulsed electrical stimulation. Using these tools, the effects of the DLM and DVM stimulation were measured to understand how to affect yaw rates of flying moths. Additionally, different control strategies were attempted in a search for one that would provide a gainable parameter for closed loop control. The research shows that closed loop heading control is possible on flying insects and presents initial and improved control strategies.

7975-22, Session 5

Two-dimensional localized flow control using distributed, biomimetic feather structures: a comparative study

C. J. Blower, A. M. Wickenheiser, The George Washington Univ. (United States)

This paper presents the design of a distributed, bio-mimetic flow control system and a characterization of its performance compared to a wing with traditional control surfaces. This design consists of a skeletal structure with a network of feather-like panels installed on the upper and lower surfaces, extending beyond the trailing edge. Each feather is able to deform into and out of the boundary layer, thus permitting local airflow manipulation. Furthermore, piezoelectric elements will be integrated into the feathers' displacement mechanism to act as sensors, actuators, and load-bearing members simultaneously and form a distributed control system over the wing. The gust load sensing is predominately performed near the leading edge of the airfoil, and the reaction forces are generated by the feathers located at the center and trailing edge of the wing. For this study, two airfoil sections are compared - a standard wing section with a trailing edge flap - and a feathered wing section. COMSOL Multiphysics is used to model the flow field and the fluid-structure interactions using Direct Numerical Simulation. This model is connected in-the-loop to Matlab for feedback control implementation and design optimization. The simulations allow initial feather optimization to be performed through analysis of the interaction between the airfoil and airflow; this includes the feather's size, shape, and location on the wing's upper and lower surfaces. For this study, linear quadratic regulators are chosen as the form of the control laws. Discrete and continuous gusts are simulated, and the disturbance rejection capabilities of the baseline and feathered wing cases are compared. Additionally, the steady-state aerodynamic performance of the two airfoils is analyzed. The design optimization results are also discussed with respect to maximizing the effectiveness of sensing disturbances as they strike the leading edge and counteracting them before they pass over the trailing edge. Furthermore, this paper discusses how these two-dimensional results can be extended to models of this distributed control architecture over the entire wing.

7975-23, Session 5

Estimation of force generated by a beetle-mimicking flapping-wing system by using the blade element theory

Q. Truong, Q. V. Nguyen, H. C. Park, D. Byun, N. S. Goo, Konkuk Univ. (Korea, Republic of)

In this paper, we present a BET model to estimate the aerodynamic forces produced by both a free flight beetle and a beetle-mimicking flapping system, which is mimicking the flapping motion of a real beetle. The BET model is validated with the model presented by Dickinson in [1]. The difference between the averages of the estimated forces (lift and

drag) and those in Ref. [1] is less than 5%. Later on, the BET model was also applied to estimate the force produced by a freely flying beetle. The wing kinematics used in the BET calculation of a real beetle was captured from high-speed cameras. The results showed that the estimated vertical force is close to the weight of the beetle. Finally, the model was applied to estimate the force produced by a beetle-mimicking flapping-wing system [11]. The force produced by the flapper was also measured via a load cell. The averages of the estimated force and the measured one were in good agreement. These results show that the unsteady lift and drag coefficients measured in [1] are still useful for the relatively higher Reynolds number cases, and the BET can be a good way to estimate the force produced by a flapping-wing system.

7975-24, Session 5

The barn owl wing: An inspiration for silent flight in the avian industry?

T. Bachmann, Technische Univ. Darmstadt (Germany); H. Wagner, G. Mühlenbruch, RWTH Aachen (Germany)

Barn owls are specialists in prey detection using acoustical information. The flight apparatus of this bird of prey is most efficiently adapted to the hunting behavior by reduction of flight noise. An understanding of the underlying mechanisms owls make use of could help minimize the noise disturbance in airport or wind power plant neighborhood.

Here, we characterize wings of barn owls in terms of an airfoil as a role model for studying silent flight. This characterization includes surface and edge specialization (serrations, fringes) evolved by the owl. Furthermore, we point towards possible adaptations of either noise suppression or air flow control that might be an inspiration for the construction of modern aircraft. Three-dimensional imaging techniques such as surface digitizing, computed tomography and confocal laser scanning microscopy was used to investigate the wings and feathers in high spatial resolution.

We could show that wings of barn owls are huge in relation to their body mass resulting in a very low wing loading which in turn enables a slow flight and an increased maneuverability.

Profiles of the wing are highly cambered and anteriorly thickened, especially at the proximal wing, leading to high lift production during flight. However, wind tunnel experiments showed that the air flow tends to separate at such wing configurations, especially at low-speed flight.

Barn owls compensated this problem by evolving surface and edge modifications that stabilize the air flow. A quantitatively three-dimensionally characterization of these structures is presented here.

7975-25, Session 6

Engineered biomimicry: polymeric replication of surface features found on insects

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The conformal-evaporated-film-by-rotation (CEFR) and modified-CEFR techniques have been developed to produce high-fidelity replicas of the surface features of biological specimen by thermally evaporating inorganic materials in high-vacuum conditions on to a biotemplate while rapidly rotating the sample-holder about two axes. We set out to produce a die that could be used to produce multiple replicas from a single biotemplate by combining the modified-CEFR technique with nickel electroforming. An approximately 250-nm-thick nanocrystalline nickel film was deposited on various surface structures of interest found in class Insecta, and the coated biotemplates then reinforced with a roughly 60- μm -thick structural layer. The structural layer was produced by nickel electroforming and gave the CEFR coating the structural integrity needed to be used for casting or stamping. The feature resolution of this die was then evaluated and polydimethylsiloxane (PDMS) castings made using the die.

7975-26, Session 6

BOWOOS: bionic optimized wood shells with sustainability

G. Pohl, Hochschule für Technik und Wirtschaft des Saarlandes (Germany)

In architecture, shell construction is used for the most efficient, large spatial structures. Until now the use of wood rather played a marginal role, implementing those examples of architecture, although this material offers manifold advantages, especially against the background of accelerating shortage of resources and increasing requirements concerning the energy balance.

Regarding the implementation of shells, nature offers a wide range of suggestions. The focus of the examinations is on the shells of marine plankton, especially of diatoms, whose richness in species promises the discovery of entirely new construction principles. The project is targeting at transferring advantageous features of these organisms on industrial produced, modular wood shell structures.

Currently a transfer of these structures in CAD - models is taking place, helping to perform stress analysis by computational methods. Micro as well as macro structures are the subject of diverse consideration allowing to draw the necessary conclusions for an architectural design. The insights of these tests are the basis for the development of physical models on different scales, which are used to verify the different approaches.

Another important aim which is promoted in the project is to enhance the competitiveness of timber construction. Downsizing of the prefabricated structural elements leads to considerable lower transportation costs as abnormal loads can be avoided as far as possible and means of transportation can be loaded with higher efficiency so that an important contribution to the sustainability in the field of architecture can also be made.

7975-27, Session 6

Modeling and optimization of IPMC actuator for autonomous jellyfish vehicle (AJV)

K. Joshi, Virginia Polytechnic Institute and State Univ. (United States); B. J. Akle, Lebanese American Univ. (Lebanon) and Virginia Polytechnic Institute and State Univ. (United States); D. J. Leo, S. Priya, Virginia Polytechnic Institute and State Univ. (United States)

Ionomeric Polymer Metal Composite (IPMC) actuators generate high flexural strains at small voltage amplitudes of 2-5V. IPMCs bend toward the anode when a potential drop is applied across its thickness. The actuation mechanism is due to the motion of ions inside it; which requires a form of hydration to dissociate and mobilize the charges. In our group IPMCs are developed either water based or Ionic Liquid based which is also known as the dry IPMCs. This combination of small voltage requirement with operation in both dry and underwater conditions makes the IPMCs a viable alternative for an Autonomous Jellyfish Vehicle (AJV). In this study, we estimate the mechanical properties of IPMC actuator having curved geometry using FEM model to match the experimental deformation. We combine the results from an electric model to estimate charge accumulated on electrode surface with piezoelectric model to estimate stress due to this charge accumulation. In the last step, the results are integrated with a structural model to simulate the actuator deformation. We have designed an AJV with embedded IPMC actuators using these properties to achieve the curvature of relaxed and contracted Jellyfish (*Aurelia Aurita*). Bio-mimetic deformation profile was achieved by using structural mechanics of beams with large deformation to get optimum AJV section stiffness (by adding passive membrane material appropriately), along with size and shape of the actuator. The propulsive efficiency and proficiency of swimming performance of the AJV is compared with that of natural jellyfish and AJV based on BISMALC technology.

7975-28, Session 6

Bio-inspired hovering and locomotion via wirelessly powered ionic polymer metal composites

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The study of hovering mechanics in biological systems such as birds, insects, and fish continues to draw considerable interest within the fluid dynamics and robotics communities, see for example [1]. Experimental platforms to study actively hovering bodies demand light weight, flexible, and low power consuming materials. Ionic polymer metal composites (IPMCs) are a promising smart material candidate for constructing active hovering surfaces. However, propulsive systems based on IPMCs attribute a large portion of their size and weight to their battery and onboard electronics [2].

In this paper, we demonstrate a proof-of-concept platform for IPMC wireless powering towards the synthesis of hovering centimeter-scale micro-swimmers. In particular, we design and employ a wireless powering system comprised of an external power source, resonant coupling system, and power electronics. We implement the resonant coupling system through four radio frequency magnetically coupled coils, see [3]. We design an ad hoc power electronics to demodulate the high frequency radio frequency wirelessly transmitted signals into a low frequency square wave suitable for IPMC powering and actuation. We illustrate the IPMC integration into the wireless powering system and compare local flow parameters in the vicinity of the vibrating wirelessly powered and wired IPMCs.

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7975-29, Session 7

TBD

M. Sarikaya, Univ. of Washington (United States)

Proteins enable biology to be viable through molecular interactions. Using biology as a guide at the molecular dimensions, we biocombinatorially select, bioinformatically enhance and genetically tailor solid binding peptides and utilize them as molecular building blocks in carrying out molecular and nanomaterials science and engineering. In this emerging field of molecular biomimetics, genetically engineered peptides for inorganic materials (GEPI) are used as bionanosynthesizers in biomaterialization, heterofunctional linkers to create thermodynamically stable interfaces between dissimilar materials, and as molecular assemblers for the targeted and directed assembly of nanomaterials towards addressable ordered architectures with genetically designed functions. Here, we will give an update of the utility of various kinds of GEPIs in nanoparticle formation for hybrid probe design and for bionanosensors, and in peptide-enabled nano-electronics and nanophotonics to demonstrate the new paradigm in technology and medicine. Primary funding is by NSF-MRSEC Program.

7975-30, Session 7

Physical and chemical influence from calcium phosphate coatings and its possible effect on enhanced bone engineering

D. W. Hutmacher, Queensland Univ. of Technology (Australia)

The aim of this talk is to summarize our present knowledge about calcium phosphate (CaP) coatings on scaffolds with respect to their topographical appearance at micrometer as well as nanometer level and also the reported influence on in vitro and in vivo bone tissue engineering.

7975-31, Session 7

Acceleration of osteogenesis by using barium titanate piezoelectric ceramic as an implant material

K. Furuya, Y. Morita, K. Tanaka, T. Katayama, E. Nakamachi, Doshisha Univ. (Japan)

Since osseointegration is important for fixation of implants that generally used for the repair of bone defects, previous studies tried to develop surface treatments and material structures to accelerate osteogenesis. As bone has piezoelectric properties, an electrical charge is generated on bone surfaces when a load is applied to it. It has been reported that this electric charge may enhance the activity of bone cells. Therefore, it is expected that activity of bone cells and bone formation can be accelerated by applying piezoelectric ceramics to implants. Since lead ions, included in ordinary piezoelectric ceramics, are harmful, a barium titanate (BTO) ceramic, which is a lead-free piezoelectric ceramic, was used in this study. Rat bone marrow cells seeded on surfaces of BTO ceramics were cultured in culture medium supplemented with dexamethasone, β -glycerophosphate and ascorbic acid while a dynamic load was applied to the BTO ceramics. After 10 days of cultivation, the cell layer and synthesized matrix on the BTO surfaces were scraped off, and then DNA content, alkaline phosphatase (ALP) activity and calcium content were measured, to evaluate osteogenic differentiation. ALP activity on the charged BTO surface was slightly higher than that on the non-charged BTO surface. The amount of calcium on the charged BTO surface was also higher than that on the non-charged BTO surface. These results showed that the electric charged BTO surface accelerated osteogenesis. It is believed that it is possible to achieve early fixation between implant and bone by using implants with piezoelectric ceramics.

7975-32, Session 7

Single channel conductance modeling of the peptide alamethicin in synthetically formed bilayers

M. A. Creasy, D. J. Leo, Virginia Polytechnic Institute and State Univ. (United States)

Bilayers are synthetically made cell membranes that are used to study cell membrane properties and make functional devices that incorporate inherent properties of the cell membranes. Lipids and proteins are two of the main components of a cell membrane. Lipids provide the structure of the membrane in the form of two leaflets or layers that are held together by the amphiphilic interaction between the lipids and water. Proteins are made from a combination of amino acids and the properties of these proteins are dependent on the amino acid sequence. Some proteins are antibiotics and can easily self insert into the membrane of a cell or into a synthetically formed bilayer. The peptide alamethicin is one such antibiotic that easily inserts into a bilayer and changes the conductance properties of the bilayer. Analytical models of the conductance change with respect to the potential and other variables across the bilayer follows the nonlinear conductance changes seen with the incorporation of the

peptide in a bilayer. The individual channels formed by the peptide have been studied and the peptide has several discrete conductance levels. These discrete levels have been shown to be dependent on the potential across the bilayer and several other variables including the lipid variety. The conductance level for a single channel can change with time in a probabilistic fashion. This paper will model these discrete conductance levels of the peptide alamethicin and the model of the single channel conductance will be used to model the cumulative effect of multiple channels within a bilayer.

7975-33, Session 7

Snake oil and venoms for medical research

H. D. Wolpert, Bio-Optics (United States)

The snake oil peddler was a stock character in Western movies depicting the traveling doctor in the early days of the West. He would sell "snake oil" medicine that claimed to cure everything from rheumatism, heart problems and the common cold. Some think that using the derivatives of snake venom for medical purposes is the modern version of snake oil but they are seriously miss-judging the research potentials of some of these toxins in medicines of the 2000's. Several venoms have shown the possibilities that could lead to anti-coagulants helpful in heart disease. The blood clotting protein from the taipan snake has been shown to rapidly stop excessive bleeding. Snake venom is not the only poison that is being researched for medical purposes. Venom from the South American dart frog, mollusks, lizards, some species of spiders and tarantulas, cephalopods, mammals, fish, intertidal marine animals and the honeybee are being investigated for potential medical benefits. While dangerous, medical researchers have derived compounds from these creatures that have been found to be useful in curing or inhibiting certain medical abnormalities. While not all clinical trials have worked out, many have, or have lead to other solutions for a disease or a certain medical condition. The field of drug discovery from the venoms and poisons of animals does, however, hold promise as the success rate grows thanks to better screening capabilities and with more cross over between disciplines.

7975-38, Poster Session

Inspection and analysis of the walls of fluid filled tubes by active electrolocation: a biomimetic approach

M. G. Gottwald, Rheinische Friedrich-Wilhelms-Univ. Bonn (Germany); H. Bousack, Forschungszentrum Jülich GmbH (Germany); K. Mayekar, Rheinische Friedrich-Wilhelms-Univ. Bonn (Germany); S. Biswas, Forschungszentrum Jülich GmbH (Germany); M. G. Metzen, G. von der Emde, Rheinische Friedrich-Wilhelms-Univ. Bonn (Germany)

During their nocturnal activity period, weakly electric fish employ a process called "active electrolocation" for navigation and object detection. They discharge an electric organ in their tail, which emits electrical current pulses, called electric organ discharges (EOD). Local EODs are sensed by arrays of electroreceptors in the fish's skin, which respond to modulations of the signal caused by nearby objects. Fish thus gain information about the size, shape, complex impedance and distance of objects.

Inspired by these remarkable capabilities, we have designed technical sensor systems which employ active electrolocation to detect and analyse the walls of small, fluid filled pipes. Our sensor systems emit pulsed electrical signals into the conducting medium and simultaneously sense local current densities with an array of electrodes. Sensors can be designed which (i) analyse the tube wall, (ii) detect and localize material faults, (iii) identify wall inclusions or objects blocking the tube (iv) and find leakages. Here, we present first experiments and FEM simulations on the optimal sensor arrangement for different types of sensor systems and different types of tubes. In addition, different methods for sensor read-out

and signal processing are compared.

Our biomimetic sensor systems promise to be relatively insensitive to environmental disturbances such as heat, pressure, turbidity or muddiness. They could be used in a wide range of tubes and pipes including water pipes, hydraulic systems, and biological systems. Medical applications include catheter based sensors which inspect blood vessels, urethras and similar ducts in the human body.

7975-39, Poster Session

Material properties of bird feathers

A. Schmitz, B. Honisch, H. Schmitz, H. Bleckmann, Rheinische Friedrich-Wilhelms-Univ. Bonn (Germany)

Birds differ in the morphology and in material properties of their primary feathers. This was investigated in different bird species using nanoindentation and scanning electron microscopy. We tested the centre of the fourth primary feather of different species amongst which we had the fastest known vertical flyer, the peregrine falcon (*Falco peregrinus*), and the fastest horizontal flyer, the white-throated needletail (*Hirundapus caudacutus*). With nanoindentation we measured the reduced E-modules and the hardness of the rachis of the primaries. If indented from above, the E-module of the feathers of *Falco peregrinus* was significantly higher (7 GPa) than in the snowy owl (*Bubo scandiacus*), the common kestrel (*Falco tinnunculus*), the swift (*Apus apus*), and in *Hirundapus caudacutus* (in all 4.2-5.8 GPa). Indentation from below lead to a higher E-module in *Falco peregrinus* (7.2 GPa) than in all other species (4.5-6.4 GPa). The hardness of all samples was about the same lying between 0.2 and 0.45 GPa, but was a little bit higher if feathers were indented from below. Using SEM we found that in *F. tinnunculus* the length of the hooklets (80 µm) is greater than in the other tested species (50-60 µm). This structure is responsible for the stability of the feather face and it seems that the feathers of *F. tinnunculus* are the most robust of the tested species. Other features, e.g. the length of the barbules, differ in size between the species, but there was no clear correlation between flight formation and the length of these structures.

7975-40, Poster Session

Elastic honeycomb-patterned microporous substrate to mechanically regulate cellular functions

T. Kawano, M. Sato, H. Yabu, Tohoku Univ. (Japan); M. Shimomura, Tohoku Univ. (Japan) and Japan Science and Technology Agency (Japan)

Cell functions are regulated by various mechanical property of extracellular matrix. In particular, elasticity of substrate surface around the cells plays an important role in cellular proliferation, differentiation, migration and signaling. The designing of the mechanical property of the extracellular matrix is one of the critical basis of development of functional biomaterials as scaffold for cell culture and tissue engineering. The mechanical designs of the biomaterial surfaces have not been established to manipulate cell behaviors and functions by the biomaterial. For the mechanical characterization and controlling of the interaction between the cells-biomaterials, we prepared the elastic honeycomb-patterned microporous surface that could be systematically controlled the elasticity of substrate surface. The honeycomb-patterned surface of poly(1,2-butadiene) with hexagonal micron sized pores could be tunable the surface elasticity by changing the photo-cross-linking degree, which are regulated by UV light irradiation. Surface elasticity distribution on the prepared surfaces was determined using microindentation test using AFM. Analyzing the cell morphology and focal adhesions of fibroblast on the honeycomb-patterned surface with high elasticity, the fibroblast were well spread and markedly organized large focal adhesions. In contrast, small focal adhesions of cells on surfaces with low elasticity were observed. These results suggested that cell shape and formation of focal adhesions responded to the elasticity of the honeycomb-patterned surface.

7975-41, Poster Session

The chameleon grip-frictional properties of subdigital setal pads in chameleons

M. Spinner, G. Westhoff, H. Bleckmann, Rheinische Friedrich-Wilhelms-Univ. Bonn (Germany); S. N. Gorb, Christian-Albrechts-Univ. zu Kiel (Germany)

Chameleons possess unique adaptations to their arboreal lifestyle, such as a laterally compressed body, downward projecting extremities, and a curved prehensile tail. In contrast to all other lizards chameleons possess adnated toes forming grasping feet to oppose torsional forces on narrow perches. In representatives of Chameleoniae the feet's ventral surface is covered by tapered or spatulate setae with an average length of 10 μm (subdigital pad) that also occur on the ventral side of the prehensile tail. The rest of the body features spines with an average length of 1 μm . Due to their occurrence on the contact surfaces of the animal (feet and tail) and their similarity to the gekkotan adhesive system, the chamaeleonid setae are assumed to enhance friction. However, that has never been shown.

In a comparative study we measured the frictional properties of the setal foot pads and spinulate dorsal epidermis of the veiled chameleon (*Chamaeleo calytratus*) on various substrata.

Subdigital setal pads of this species consist of 20 μm long setae with narrowed, fibrous tips. Our results show that the chamaeleonid setal foot pads are microstructural friction enhancing devices that support a firm grip for arboreal locomotion. Understanding the structure/function principles may be useful for designing friction optimized surfaces.

7975-42, Poster Session

Spitting cobras: fluid jets in nature as models for technical applications

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Spitting cobras defend themselves by shooting rapid jets of venom through their fangs towards the face of an offender. To generate such rapid jets, the venom delivery system of spitting cobras has some unique adaptations like prominent ridges on the venom channel surface. We examined the fluid acceleration mechanisms in three species of spitting cobras of the genus *Naja*. To investigate the liquid-flow through the venom channel we have built a three-dimensional 60:1 scale model: In a first step we determined the three-dimensional structure of the channel by using micro computer tomography. By using the micro-computer tomographic data we created a negative form out of wax. Finally, silicon was casted around the wax form and the wax was removed, resulting in a completely transparent model of the cobra's venom channel. The physical-chemical properties of the cobra venom were measured by micro rheometry and tensiometry and an artificial fluid with similar properties was generated. Particle image velocimetry (PIV) was performed to visualize the flow of the artificial liquid in the three-dimensional model. Experimental results show the influence of venom channel's surface structures on the liquid flow through the channel and on the structure of the liquid jet. The understanding of the biological mechanisms of venom ejection may help to enhance industrial processes such as water jet cutting, cleaning and injection in technical and medical sectors, e.g. liquid microjet dissection in microsurgery. Supported by the Deutsche Forschungsgemeinschaft (DFG).

7975-43, Poster Session

Measurement of flow velocity of fluids and gases

H. Herzog, A. T. Klein, H. Bleckmann, Rheinische Friedrich-Wilhelms-Univ. Bonn (Germany)

With the aid of the lateral line fish can detect minute water motions. The smallest functional unit of the lateral line is the neuromast, a sensory structure that occurs free standing on the skin and in fluid filled canals. Fish use lateral line information to estimate the velocity of bulk water flow. This ability may be important for rheotaxis and station holding. In many technical applications it is also essential to determine the flow velocity (or the volume flow) of liquids or gases. Conventional flow meters use different principles to measure flow rates. Nevertheless, nearly all conventional flow measurements are based on monitoring the dc-component of the flow. Since it is notoriously difficult to measure dc-signals, fish are not sensitive to this component but instead use a different mechanism: they are highly sensitive to the fluctuations superimposed on the flow. Most likely fish use the propagation speed of the flow fluctuations to estimate bulk flow velocity. Applying this principle to artificial lateral lines we were able to determine bulk flow velocity and thus volume flow with high precision in both water and air. Supported by the BMBF

7975-44, Poster Session

Biomimetics on gecko locomotion: a force measuring array to measure 3D reaction forces and the inspiration obtained from the measurements

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Measuring the interaction between each foot of animals and substrate is one of the most effective ways to understand the dynamics of legged locomotion. Here a newly developed facility-Force Measuring Array (FMA) -is introduced and applied to measure 3D reaction forces of gecko on vertical substrate but along different directions. The difference of forces measured by FMA and by formerly used force platform was compared and discussed.

The FMA consists of 16 three-dimensional sensors with resolution to micro-Newton. Meanwhile the locomotion behavior of gecko freely moving on FMA was recorded by high speed camera. The reaction forces acting on individual foot of gecko measured by the FMA and correlated with locomotion behavior provided enough information to reveal the mechanical and dynamic secrets of gecko locomotion. Moreover, dynamic forces were also measured by a force platform and correlated with locomotion behavior. The results show that FMA is the right way to obtain true reaction force acting on individual foot of geckos.

The reaction force measurement and locomotion behaviour observation show that gecko increased speed by increasing stride frequency. The foot of gecko generate adhesive and shear forces to balance the gravity and overturning the moment of the gravity. The feet above the mass centre of gecko play a more important role than those beneath the mass-centre in supporting, driving and even keeping stable.

The research provide a effective tool to reveal the secret of legged locomotion and the results obtained would greatly inspire the design of gecko-mimicking robot.

7975-45, Poster Session

Semiautomatic calibration and alignment of a low-cost, nine-sensor inertial magnetic measurement sensor

A. Mizutani, Odonatrix Pty Ltd. (Australia); K. Rosser, J. S. Chahl, Defence Science and Technology Organisation (Australia)

As UAVs, handheld devices and sensor networks become ubiquitous, cost and accuracy will be increasingly traded. Price of solid state sensors decrease with time, however, any process that might involve human intervention is likely to increase in cost. We have developed techniques for calibration of UAV autopilot sensors that consider this problem.

The technique performs a nonlinear optimisation through all variables associated with zeroth and first order effects on accuracy of the sensors. The optimisation is constrained by the known properties of the magnetic and gravitational fields. The input data is generated by randomly rotating the embedded device. The variables found include offset and bias for gyroscopes, accelerometers and magnetometers, as well as soft iron terms for magnetic sensors. It will be shown that as sensors become smaller, the challenges presented by magnetic field distortions become significant. A unique process for aligning magnetic and acceleration sensor axes is presented that exploits the variation of measured field directions by the sensors. A similar method is applied to the equally important problem of thermal calibration. The methods assume that no reference of rate, position or temperature exists other than magnetic North and gravity.

A miniature autopilot is presented as an example of the pressing need for automation of calibration. The deployment concepts and cost sensitivity of potential users is considered. Examples of calibration are presented including data from the calibrated instrument suite in flight.

7975-46, Poster Session

Vertically displaced optical flow sensors to control the landing of a UAV

J. S. Chahl, Defence Science and Technology Organisation (Australia); A. Mizutani, Odonatrix Pty Ltd. (Australia); K. Rosser, Defence Science and Technology Organisation (Australia)

We report on the design and testing of an optical device to aid landing of Unmanned Aerial Systems. A number of sensors were tested including ultrasonic ranging, active infrared ranging and optical flow. The sensor study aims to eliminate the need for GPS or external precision approach radar during autonomous landing. Under the conditions tested, an unsealed runway in daylight, optical flow provided the most reliable signal.

Optical flow calculates a measure of observed angular movement of the image seen by the sensor but is incapable of providing a range measurement directly. Optical flow measures can be converted to range if speed of the sensor perpendicular to the image plane is known. Our approach eliminates this requirement by using two optical flow sensors displaced vertically to calculate range. Range is computed from the ratio of the response of the two sensors knowing the vertical difference between their positions. The solution provides a measure of ground speed in the process which can not be provided using laser, ultrasonic or infrared rangefinders.

The initial implementation was tested on an instrumented UAV with promising results. More compact and easily integrated designs of the sensor that utilise refractive and reflective optics to emulate the vertical displacement are introduced with preliminary results. Preliminary results from implementing the sensor on hovering platforms are also presented. We argue that this technique is comparable to vision techniques such as stereo in this application and more versatile.

7975-47, Poster Session

Atomistic mechano-chemical modeling of kinesins

S. Patriche, Univ. 'Dunărea de Jos' of Galați (Romania); S. Matsushita, Kyoto Univ. (Japan); M. Banu, Univ. 'Dunărea de Jos' of Galați (Romania); B. I. Epureanu, Univ. of Michigan (United States); T. Adachi, Kyoto Univ. (Japan)

This work is concerned with the dynamics of motor proteins. In particular, we discuss the development of computational analysis tools for predicting the dynamics of molecular motors such as certain types of kinesin. The ability to model and predict how these biomolecular machines work forms the critical link to biotechnological device development, including lab-on-a-chip applications and many others. The focus of his research is on the identification and modeling of nonlinear dynamic phenomena caused by coupled thermal, chemical, and mechanical fields. A mechanistic model of kinesin has been developed recently at University of Michigan. This model accounts for transient dynamics and uses parameters which have to be identified from experimental data and/or from first principles. In this work, accurate atomistic simulations using a monomeric human kinesin structure (PDB ID: 1MKJ, 2.70 Angstroms resolution) and a dimeric rat kinesin structure (PDB ID: 3KIN, 3.10 Angstroms resolution) are used instead of experimental data to obtain key nano-scale properties of the motor protein. The approach allows an accurate bridging between nano-scale processes occurring over pico seconds and micron- or millimeter-scale processes occurring over seconds. The partial financial support of the National Science Foundation and RIKEN-IPA Contract, POSDRU SOP HRD-EFICIENT 61445, Program and PNII IDEAS 1758-2009 is gratefully acknowledged.

7975-48, Poster Session

Biomimicry of the adhesive organs of stick insects (Carausius morosus)

M. Bennemann, RWTH Aachen (Germany); I. Scholz, Rheinische Friedrich-Wilhelms-Univ. Bonn (Germany); W. Baumgartner, RWTH Aachen (Germany)

Adhesive organs enable insects to cling to various substrates even during rapid locomotion. In this process a very fast but reliable change of adhesion and detachment is realised. To reveal the detailed underlying mechanisms of this impressive performance we analysed the ultrastructure, the physical properties, the adhesion force and the detachment process of the smooth adhesive organs of the stick insect *Carausius morosus*. Those organs are composed of several layers decreasing in stiffness towards the outer surface. The layered setup represents a superior design to conform and adhere to substrates with roughness at different length scales. Atomic force microscopy (AFM) contact mode imaging revealed that the cuticula of the arolium is mechanically anisotropic. This anisotropy could presumably be explained by the fibrous inner structures of the arolium. Confocal laser scanning microscopy (CLSM) Scanning electronic microscopy (SEM) and Transmission electronic microscopy (TEM) were used to reveal the fibrous inner structure of the adhesion organ. All determined data were transferred on a Finite Element model to analyse the functions of those fibres. We assume that the fibres are responsible for the elasticity and the tensile strength of the adhesion organ. Furthermore the fibres could improve the moulding of the substrate or play an important role in detachment. Based on the data achieved from the Finite Element model we develop a technique to fabricate a fibre reinforced artificial adhesion organ, which develops high adhesion forces to substrates of different roughness and which can easily be detached if desired.

7975-49, Poster Session

Sandfish inspired engineering

K. Staudt, F. Saxe, A. Weth, W. Baumgartner, RWTH Aachen (Germany)

The sandfish (Scincidae: *Scincus scincus*) is a lizard, which has the remarkable ability to move in desert sand in a swimming-like fashion with a velocity from up to 30 cm/s. This is facilitated through several morphological adaptations like a shovel formed snout, strong limbs with fringed digits and protected nostrils. The most outstanding adaptation to its subterranean life however, is the epidermis that shows low friction behaviour and extensive abrasion resistance against sand, outperforming not only the skin of related species but also artificial surfaces like teflon and even steel. We investigated the topography, the composition and the mechanical properties of sandfish scales. Remarkably, atomic force microscopy shows an almost complete absence of attractive forces between the scale surface and a silicon tip, suggesting that this is responsible for the unusual tribological properties. Biochemical analysis of the moulted exuviae revealed glycosylated keratins with a high amount of sulphur but no hard inorganic material, such as silicates or lime. The unusual glycosylation of the keratins was found to be absolutely necessary for the described phenomenon. The scales were dissolved and reconstituted on a polymer surface resulting in properties similar to the original scale. Thus, we provide a pathway towards exploitation of the reconstituted scale material for future engineering applications. In present studies we examine the keratin gene to find out type and abundance of glycosylation sites and further analysis will be performed to analyse the glycans, attached on the keratin protein.

7975-34, Session 8

Control valve with the ability to 'dangle'

M. A. Meller, R. Tiwari, E. Garcia, Cornell Univ. (United States)

The twitchy, robot-like behavior of hydraulic cylinders is an issue of traditional hydraulics that is consistently overlooked. This behavior can be attributed to the design of the control valve. Most double-acting hydraulic cylinders are controlled via a 4/3 spool valve, which allows for the movement of the cylinder in both directions, as well as holding its current position. These control valves lack the ability to "dangle," or rather, the ability to permit the hydraulic cylinder to freely sway passively in response to external forces.

Including the ability to "dangle" within a control valve is of particular interest for a number of reasons. It allows for a much more natural actuation of the hydraulic cylinder, making it further compatible with bio-inspired platforms, such as driving the legs of an exoskeleton for human augmentation, or for morphing a perching UAV for munitions.

"Dangling" not only presents a more fluid behavior of the system, but also offers an opportunity for considerable efficiency improvement. This is possible because the momentum of the actuator, gravity, among other external loads, can be utilized to move the actuator instead of solely relying on an active input.

A novel control valve integrating all the features of a traditional 4/3 spool valve with the concept of "dangle" has been successfully prototyped and reported herein. Further improvements and testing of this valve are underway. A parametric analysis modeling of the system with the novel control valve that incorporates depressurization of the system, scaling of the system down to the meso-scale, and predicting the resulting effects is reported in the paper as well.

7975-35, Session 8

Biomimetic super-hydrophobic surfaces for use in enhanced dropwise condensation

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There have been many attempts to enhance heat transfer during the condensation (vapor to liquid) process since condensation is a critical heat transfer mechanism in many industrial processes. One conventional method of enhancing condensation heat transfer is to specially treat the condensing heat exchanger-surface to adequately promote so-called "dropwise" condensation. Coating with hydrophobic materials is often employed for surface treatment. This coating on the condensing heat transfer surface effectively shifts the condensation mode from filmwise (the conventional heat transfer mode) to dropwise, resulting in much higher condensation heat transfer. In this method the thickness of coatings is a key parameter to govern the heat transfer rate. Thin coating benefits the heat transfer but can lead to weakening hydrophobicity and failure to have an acceptable life span. However, thick coating reduces or eliminates the merit of the dropwise condensation phenomenon because the coating introduces additional thermal resistance. Herein, we report an innovative biomimetic concept in connection with a surface treatment that solves the aforementioned issues. Instead of using conventional dense coatings on the condensing surface, the concept of randomly arranged or structurally oriented nano or submicro-scale fins and/or porous surfaces similar to nature-invented hydrophobic surfaces allowing molecular clustering for effective steam condensation, is theoretically presented, mathematically analyzed, and experimentally verified.

7975-37, Session 8

Tunable ultrahydrophobic/philic multiple roughness for heat transfer applications

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In recent years, "surface wettability" has been considered for use in self-cleaning, inkjet printing, lab-on-chip and heat transfer. Especially, surface wettability phenomenon has been a hot issue for phase change heat transfer applications, because it is known to be an important parameter to evaporation, boiling and condensation heat transfer coefficients. Up to now, with the aid of high-end techniques such as nanoelectromechanical system (NEMS) and microelectromechanical system (MEMS), its research area expands the interest from microscale into nanoscale structured surfaces. However, those techniques are rather expensive and time-consuming to create the practical nanoscale-structures.

In this study, we propose a technique to create tunable ultrahydrophobic/philic multiple roughness made of the self-assembled copper oxide nanostructures. Using a building-up process, the simple, cost-effective and bulk fabrication requiring a short fabrication time can be achieved relative to NEMS and MEMS. Through the present experiments, we can control the surface wettability by introducing morphological adaptivity. Thus, the multiple roughness turned out to be significant to affect the surface wettability. In this study, the evaporation characteristics of a sessile liquid drop on different surface wettability conditions discussed in detail.

Conference 7976: Electroactive Polymer Actuators and Devices (EAPAD) XIII

Monday-Thursday 7-10 March 2011

Part of Proceedings of SPIE Vol. 7976 Electroactive Polymer Actuators and Devices (EAPAD) 2011

7976-01, Session 1

Walking with springs

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At the Human and Machine Integration Laboratory at Arizona State University, we are developing a new generation of powered prosthetic devices based on lightweight, energy storing springs that will allow for more functional gait. Current ankle-foot prosthetic devices are passive, un-tunable, and function well in only one task. We believe that a powered spring-based robotic ankle will allow one prosthetic device to be used in different scenarios such as walking, running, and donning a heavy pack. Our bionic systems mimic the power, energy, motion, and weight of the human ankle. More importantly, the tuned spring minimizes the peak motor requirements allowing for a much lighter device. We use a robotic-tendon to store and release energy properly during the gait cycle. We have demonstrated walking, jogging, jumping, walking up and down slopes, and ascending and descending stairs.

7976-02, Session 1

Dielectric elastomers: from the beginning of modern science to applications in actuators and energy harvesters

S. G. Bauer, Johannes Kepler Univ. Linz (Austria)

The observation of electrostatical deformations of dielectrics dates back to the beginning of modern science. The transduction principle of dielectric elastomer actuators (DEA) was anticipated by Volta in 1776 and visualized by Röntgen in 1880 [1]. A reproduction of Röntgen's experiment with modern materials showed that charge control prevents electromechanical instabilities in DEAs [2]. After their reinvention by Pelrine and co-workers in a landmark Science paper [3], DEAs are studied in a wide range of applications, from robotics, biomimetics, optics, to acoustics. Use of DEAs for mechanical energy scavenging to pump up electrical charges to higher potentials is the latest frontier of research in DEAs. Here DEA based designs promise very high specific energies for the conversion of mechanical into electrical energy [4]. Examples from past and recent research, ranging from very early observations of electrostatical deformations of dielectrics, to elastomer actuation and energy harvesting are used to highlight the potential of DEAs.

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7976-03, Session 1

Directions for development of the field of electroactive polymer (EAP)

Y. Bar-Cohen, Jet Propulsion Lab. (United States)

In last few years, the field of EAP has been developing at an accelerated rate and it increasingly getting closer to the point of finding them used in commercial products. Significant development has been reported in the understanding of their drive mechanisms and the parameters that control their electro-activation behavior. Further, efforts are being made to develop fabrication techniques that can maximize their actuation capability and operation durability. In parallel, effective processing techniques are being developed for their mass production, as well as the reliable characterization of their response. The recent efforts to develop energy harvesting techniques, haptic interfacing (including refreshable braille displays), and toys are increasing the likelihood of finding niches for these materials. In this paper, a review of the current state of the art and potential directions for the future development of the field of EAP will be described and discussed.

7976-04, Session 2

From boots to buoys: promises and challenges of dielectric elastomer energy harvesting

R. D. Kornbluh, R. Pelrine, H. Prahlah, A. Wong-Foy, B. McCoy, S. Kim, J. Eckerle, SRI International (United States)

Dielectric elastomers offer the promise of energy harvesting with essentially no moving parts. Power can be produced simply by stretching and contracting a relatively low-cost rubbery material. This simplicity, combined with demonstrated high energy density and high efficiency, suggests that dielectric elastomers are promising for a wide range of energy harvesting applications. Indeed dielectric elastomers have been demonstrated to harvest energy from human walking, ocean waves, flowing water, blowing wind and pushing buttons. While the technology is promising, there are challenges that must be addressed if dielectric elastomers are to be a successful and economically viable energy harvesting technology. These challenges include developing materials and packaging that sustains long lifetime over a range of environmental conditions, design of the devices that stretch the elastomer material, as well as system issues such as practical and efficient energy harvesting circuits. Progress has been made in many of these areas. We have demonstrated energy harvesting transducers that have survived over 5 million cycles. We have also shown the ability of dielectric elastomer material to survive for months underwater while undergoing voltage cycling. We have shown circuits capable of 78% energy harvesting efficiency. While the possibility of long lifetime has been demonstrated at the watt level, reliably scaling up to the power levels required for providing renewable energy to the power grid or for local use will likely require further development from the material through to the systems level.

7976-05, Session 2

Acrylic IPNs for dielectric elastomer generators

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Dielectric elastomer energy harvesters are an emerging technology that promise high power density, low cost, scalability, and the capability of fitting niche markets that have yet to be exploited. Thus far, materials issues that limit their overall performance have hampered the full potential of these devices. In order to supplant existing technologies, even in niche markets, dielectric elastomer generators must increase their energy density and reliability. We explore the use of acrylic interpenetrating polymer network elastomers using 3M's VHB 4905 as the host material. We test the effects of additive content on the material properties of the elastomer films and compare their energy harvesting capabilities with prestrained VHB 4905 films.

7976-06, Session 2

Characterization of effects of energy harvesting on the dynamic response of dielectric elastomers

H. L. Lai, C. Tan, Y. Xu, Wayne State Univ. (United States)

Recent energy harvesting research has developed dielectric elastomer energy harvesting devices for use in low frequency applications including waves, wind and human motion. While DE has shown promise for harvesting energy during the walking stride, there have not been any investigations into the effects of DE energy harvesting on the performance of the wearer's stride. Investigations using motors rather than smart materials as electro-mechanical coupling mechanism have improved upon previous attempts at harnessing walking motion by strategically removing energy only when it creates beneficial or mutualistic effects. Several mutualistic knee joint harvesting devices have been developed using motors to store energy only during the swing phase of the stride, when it aids in normal motion, rather than encumbering.

In order for an energy harvester to be useful in applications such as walking, the changes in the dynamic response of the device must be well understood. This paper investigates the structural damping effects of DE energy harvesting in order to develop a mutualistic technique for harvesting excess energy while improving the overall performance. Results relate frequency, strain and bias voltage to energy harvesting efficiency and dynamic response using both static and dynamic mechanical tests. The outcome of this investigation has the potential to be used as a strategy for the development of rehabilitative device for patients with muscle deterioration or transfemoral amputation.

7976-07, Session 2

Energy harvesting from flutter instabilities of heavy flags in water through ionic polymer metal composites

A. Giacomello, M. Porfiri, Polytechnic Institute of NYU (United States)

Ionic polymer metal composites (IPMCs) are a novel class of smart materials that show favourable characteristics as sensors, actuators, and energy harvesters [1]. The capabilities of IPMCs as energy harvesters in aqueous environments have been discussed in [2]. In this paper, we study the energy harvesting capabilities of an IPMC whose vibration is caused by the flutter instability of a host flag in water. The flag is designed for maximal weight and minimal stiffness as in [3] to allow for flutter instabilities at moderately low speeds.

We model the structure as a Kirchhoff-Love plate undergoing cylindrical deformation. The effect of fluid-induced drag on the flutter boundary is also accounted for. We consider the fluid to be Eulerian and two-dimensional, and we model the fluid-structure interface as a bound vortex, see [3]. The critical flutter speed is determined using linear stability analysis. The IPMC is described by using the reduced order model presented in [2].

Experiments in a water channel are conducted to elucidate the conditions for the onset of flutter and to assess the IPMC energy harvesting capabilities as a function of the shunting resistive load and the flow speed. Optimal positioning of the IPMC strip for maximal energy harvesting is performed through image analysis.

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7976-08, Session 4

Maximal energy that can be converted by a dielectric elastomer generator

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Dielectric elastomers are being developed as generators to harvest energy from renewable sources, such as human movements and ocean waves. We model a generator as a system of two degrees of freedom, represented on either the stress-stretch plane or the voltage-charge plane. A point in such a plane represents a state of the generator, a curve represents a path of operation, a contour represents a cycle of operation, and the area enclosed by the contour represents the energy of conversion per cycle. Each mechanism of failure is represented by a curve in the plane. The curves of all the known mechanics of failure enclose the region of allowable states. The area of this region defines the maximum energy of conversion. This study includes the following mechanisms of failure: material rupture, loss of tension, electrical breakdown, and electromechanical instability. It is found that natural rubber outperforms VHB elastomer as a generator at strains less than 15%. Furthermore, by varying material parameters, energy of conversion can be increased above 1.0 J/g. This is a joint work with Soo Jin Adrian Koh, Christoph Keplinger, Tiefeng Li, and Siegfried Bauer

7976-09, Session 4

Conducting polymers, carbon nanotubes, and other low voltage ion based actuators as mechanical energy harvesters

J. D. W. Madden, The Univ. of British Columbia (Canada); T. Mirfakhrai, Stanford Univ. (United States); T. Shoa, The Univ. of British Columbia (Canada)

Conducting polymers, carbon nanotube yarns, and ionic polymer metal composite-based actuators rely on the reversible voltage driven insertion of ions and solvent for their operation. The application of a compressive load leads to the expulsion of ions and entrained solvent. This expulsion changes the equilibrium potential of the actuator, and can lead to substantial passage of charge. Thus far these devices have attracted interest as sensors, but not as generators. A reason there has been little interest on the generation side is that voltages produced are at the millivolt level, making them a challenge to scale up. Electromechanical coupling is also low. Key to improving generator output is increasing operating stress levels and/or increasing the strain produced per ion that is inserted. Significant progress has been made in these characteristics of the past several years. Current performance is presented, and the ultimate potential (relying on some advances in materials engineering) is given.

7976-10, Session 4

Realizing the potential of dielectric elastomer generator systems

T. G. McKay, B. M. O'Brien, The Univ. of Auckland (New Zealand); E. P. Calius, Industrial Research Ltd. (New Zealand); I. A. Anderson, The Univ. of Auckland (New Zealand)

The global demand for renewable energy is growing, and ocean waves and wind are renewable energy sources that can provide large amounts of power. A class of variable capacitor power generators called Dielectric Elastomer Generators (DEG), show considerable promise for harvesting this energy because they can be directly coupled to large broadband motions without gearing while maintaining a high energy density, have few moving parts, and are highly flexible.

At the system level DEG cannot currently realize their full potential for flexibility, simplicity and low mass because they require rigid and bulky external circuitry. This is because a typical generation cycle requires high voltage charge to be supplied or drained from the DEG as it is mechanically deformed.

Recently we presented the Integrated Self-Priming DEG system that minimized external circuitry. This was done by using the inherent capacitance of DEG to store excess energy. An energy density of 12.6mJ/g was experimentally demonstrated, which compares favorably with similarly sized electromagnetic and electrostatic power generators. The system consisted of two DEG deformed 180° out of phase. The DEG were electrically configured to form a pair of charge pumps. When the DEG were cyclically deformed, additional energy and voltage fluctuations were provided, allowing the charge pumps to produce energy and convert it to a higher charge form. In this paper we present an Integrated Self-Priming DEG system that contains just one charge pump, reducing its complexity. To demonstrate its ability to harvest from large, broadband, rectilinear motions, a hand driven system is presented.

7976-11, Session 4

Regulation of self-priming dielectric elastomer generators

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Dielectric Elastomer Generator(s) (DEG) show great potential as a source of renewable energy with important advantages over established generator technologies. Examples include a better ability to operate with varying frequencies than wind turbines, and a higher energy density than solar cells.

By relaxing a stretched, charged DEG, elastic potential energy is transferred to the charges by increasing the voltage. Using a self-priming circuit, cyclic stretching of the material can build up the voltage and charge over time. Little research has been done to find ways of extracting this energy and converting it into a form useful for devices. Conventional methods of regulation are unsuitable due to the high voltage low charge form of energy, and the requirement for an initial charge at the beginning of each cycle.

We present a regulation circuit suitable for DEG. The regulator extracts energy from the DEG in a controlled manner such that the DEG remains charged at all times. This energy is converted into a low voltage form which is fully regulated. Such a regulator opens up DEG for use in self-powered devices, as well as large scale energy harvesting from wind and ocean waves.

7976-12, Session 4

Battery modeling for energy harvesting system

R. Tiwari, E. Garcia, Cornell Univ. (United States)

Recent advancements in wireless technology and portable devices have led researcher to explore new realm of energy sources. Much of the energy harvesting work has focused on tapping into individual energy sources like vibration, solar, wind and thermal. Due to low power generation capability of common energy harvesting systems an energy storage device is needed for accumulation of energy. Batteries are commonly used for energy storage in energy harvesting systems due to high energy density. An equivalent circuit model of rechargeable batteries for vibration energy harvesting system is reported in this paper. The model is used for studying the effect of various parameters (like internal resistance, charge discharge efficiency, impedance and state of charge) on vibration energy harvesters. The model is a modified Thevenin circuit model. The model also incorporates impedance parameters of the battery derived using potentiostat.

7976-13, Session 5

Electromechanical charge pumps based on dielectric elastomer membranes: maximal energy of conversion for energy harvesting applications

C. Keplinger, Johannes Kepler Univ. Linz (Austria) and Harvard Univ. (United States); R. Baumgartner, Johannes Kepler Univ. Linz (Austria); T. Li, Harvard School of Engineering and Applied Sciences (United States); M. Kaltenbrunner, R. Schwödiauer, Johannes Kepler Univ. Linz (Austria); Z. Suo, Harvard Univ. (United States); S. G. Bauer, Johannes Kepler Univ. Linz (Austria)

Dielectric elastomer generators promise exceptionally high values of specific energy that can be electromechanically converted. In addition they are based on cheap and robust materials making them economically interesting candidates for energy harvesting applications on large and small scales.

Here we present an experimental demonstration of an electromechanical charge pump operating between two charge reservoirs at different electrical potentials. The mechanical energy is supplied with compressed air, resulting in an inflation of an elastomer membrane to a balloon shape. The charge pump is operated close to the limits of material failure in order to assess the maximal specific energy of conversion for the elastomer used, in our case the common 3M VHB 4910 acrylic elastomer tape. These limits include the dielectric breakdown strength limiting the maximum useable electrical field, the stretch of rupture limiting the deformation and the borderline of the electromechanical pull-in instability. The harvesting results are compared to a thermodynamic model of the system and different operating frequencies are reviewed with respect to electric losses to determine the ideal operating conditions in future devices.

The experimental results accompanied by the theoretical analysis may be used as a benchmark for the aptitude of the VHB elastomer tape in specific energy harvesting applications. Our fully computer controlled, laboratory scale generator set-up may be readily used to test other elastomers with favorable properties, like elastomers with a large dielectric constant or elastomers with an exceptionally high dielectric strength, etc.

7976-14, Session 5

Inflation of dielectric elastomer membranes for energy harvesting: prestretch, rupture, dielectric breakdown, and the electromechanical instability

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Since dielectric elastomers are considered as promising candidates for energy harvesting applications, efforts are increasing to assess the maximal amount of energy that can be generated with a specific material. Recently theoretical works identified dielectric breakdown, rupture and the electromechanical instability as mechanisms limiting the amount of energy that can be electromechanically converted. Nevertheless only sparse experimental data on these material limits is available.

Here we present a fully computer controlled laboratory scale generator setup, where compressed air is used to inflate a dielectric elastomer membrane, a favorable geometry for biaxial deformation, which is achieved at the top region of the balloon shaped membrane. All necessary mechanical and electrical parameters are in situ monitored during inflation of the membrane with different applied voltages. This allows the construction of limiting lines in work conjugate plots confining an area of safe operation states that define the maximal specific energy that can be harvested. Different amounts of pre-stretch of the elastomer membrane before inflation are used to examine possible operating conditions of practical devices. In this work we used the common 3M VHB 4910 polyacrylic elastomer tape but our method and setup can be readily used to extract the material limits of all kinds of dielectric elastomers which could be interesting for energy harvesting applications.

7976-15, Session 5

Dielectric elastomer materials for actuators and energy harvesting

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The future success of dielectric elastomer materials in actuator technology as well as in energy harvesting critically depends on the material parameters, e.g. breakdown field, dielectric constant, and elastic modulus. They have a direct impact on the driving voltage which should be as low as possible. By increasing the dielectric constant of a material, this voltage can be decreased. The increase of dielectric constant, however, is often associated with an unwanted decrease in the breakdown field. In this presentation, dielectric elastomer materials with increased dielectric constant and high breakdown fields are presented.

7976-16, Session 5

Evaluation and optimization of energy harvesting cycles using dielectric elastomers

C. Graf, J. Maas, Ostwestfalen-Lippe Univ. of Applied Sciences (Germany)

Electro Active Polymers can be used as generators to convert mechanical strain energy into electrical energy by charge transfer using the polymer's capacitive behavior. The relative energy gain basically depends on the capacity change induced by the mechanical strain, while

the amount of the energy gain requires a certain initial quantity of charges provided by the electrical power supply.

Based on the results of a theoretical study for energy harvesting cycles with constant charges, voltage and electric field strength, the energy gain depends only on the applied mechanical stretch. When also the electrical losses due to the polymer resistivity and electrode conductivity are considered, decreasing the energy gain. While the polymer losses depend on the applied voltage, the conductivity of the electrode causes current-dependent losses during charge transfer, especially at the time of charging and discharging. The validity of the derived models for energy gain and occurring losses are proven by experimental investigations.

Based on these results, the mentioned energy harvesting cycles are combined to establish an energy-optimal cycle, in order to maximize the overall energy gain under consideration of limitations by the power electronics.

Under dynamical aspects, the conductivity of the electrode causes another problem. Due to the resistance of the electrode, the flow of charges causes a significant delay of the electric field propagation on the DE surface, reducing the effective voltage and thus the energy gain. These effects are investigated by measurements, to derive design rules for a required electrode conductivity and connection placement.

7976-17, Session 5

Scaleable design of DEAP for energy harvesting utilizing PolyPower

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Design and manufacture of EAP based devices used for energy harvesting is a challenging multidiscipline task. Research has predominately focused on small scale proof of concept designs and human powered size devices. Methods for scaling from the proof of concept size into large scale EAP devices are addressed. EAP material properties for energy harvesting applications are established. Results of the mechanical and electrical characterization of large scale EAP energy harvesting devices are presented. Manufacturing and quality controls concepts used by PolyPower for large scale energy harvesting are presented.

7976-18, Session 6

Molecular level materials design for improvements of actuation properties of dielectric elastomer actuators

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Dielectric elastomer actuators are soft electro-mechanical transducers with possible uses in robotic, orthopaedic and automotive applications. The active material must be soft and have a high ability to store electrical energy. Hence, three properties of the elastic medium in a dielectric elastomer actuator affect the actuation properties directly: dielectric constant, electric breakdown strength, and mechanical stiffness. The dielectric constant of a given elastomer can be improved by mixing it with other components with a higher dielectric constant, which can be classified as insulating or conducting.

Insulating particles such as TiO₂ nanoparticles can raise the dielectric constant, but may also lead to stiffening of the composite, such that the overall actuation is lowered. It is shown here how a chemical coating of the TiO₂ nanoparticles leads to verifiable improvements.

Conducting material can also lead to improvements, as has been shown in several cases. Simple percolation, relying on the random distribution of conducting nanoparticles, commonly leads to drastic lowering of the breakdown strength. On the other hand, conducting

polymer can also be employed, as has been demonstrated. We show here how an approach based on a specific chemical reaction between the conducting polymer and the elastomer network molecules solves the problem of premature breakdown which is otherwise typically found. This approach leads to strong improvements in actuation, but due to its inherent stiffness, the maximum actuation strains observed are limited to a few %. We demonstrate how the maximum actuation strain and the actuation coefficient (strain for electrical field) can be strongly improved by blending with similar elastomers of much lower stiffness. As such, it is demonstrated that the use of conducting polymer for enhancement of dielectric elastomer actuators is feasible and viable.

7976-19, Session 6

Conducting IPNs based electrochemical actuators: from chemistry towards devices

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In recent years, numerous studies on electroactive polymer actuators have been reported. One promising technology is the elaboration of electronic conducting polymers based actuators with Interpenetrating Polymer Network (IPN) architecture. Their advantageous properties as low working voltage, light weight and high lifetime (several million cycles) make them very attractive for various applications including robotics. In our laboratory we recently synthesized new conducting IPN actuators based on high molecular mass elastomer, poly(ethylene oxide) derivative and poly(3,4-ethylenedioxythiophene). The design of the IPN greatly improves the actuator performances such as mechanical resistance, output force, and speed response.

The first example is the development of a microactuator for a flapping wing microrobot mimicking insect. The goal is to replace an heavy electromagnetic actuation by a conducting IPN actuator with large bending deformation and a vibration frequency around 100 Hz. Because high-speed actuation devices can be obtained only with high ionic conductivity, new IPN matrix has been designed based on PEO and a high molecular mass elastomer, Nitrile Butadiene Rubber (NBR). We have determined the spectral response of IPN actuators using a laser beam equipped device. The second application is the IPN actuator integration in a biomimetic vision system. In this example, high frequency actuators are not required but strong mechanical properties, high ionic conductivity, high output forces and the ability to be position controlled are the key parameters. The results concerning the IPN actuators synthesis are described as well as a first biomimetic vision demonstrator able to follow and to focus on objects.

7976-20, Session 6

Electro-mechanical modeling of dielectric elastomer transducers with micro-structured electrodes

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Recently micro-structured solid electrodes were applied to dielectric elastomers. Compared with common powder or liquid electrodes the electrical conductivity of the electrodes is enhanced while the compliance necessary for large active deformations is retained. Potential applications range from energy harvesting to structural damping and actuation. Since the compliant conducting electrodes can be attached to the passive dielectric materials in an industrial process, cheap and easy to build dielectric elastomer materials with reproducible properties became available. This enhanced the common interest in the technology

and many more applications will be developed. While some of these applications aim for maximum actuation performance others require a superior reliability at moderate performance. For both strategies design and optimization of the active parts are essential. This work provides results of an extensive experimental characterization of the passive and active response of a novel PolyPower membrane. We further developed a 3D nonlinear viscoelastic model suitable for finite element modeling and verified key assumptions of the modeling approach with multiaxial stress tests. The model is shown to provide good predictions of both blocking force as well as active deformation of an actuator system. Observed deviations are shown to be due to assumptions of the distribution of the electrical field as well as the anisotropic mechanical behavior of the micro-structured electrode.

7976-21, Session 6

Electroactive semi-interpenetrating polymer networks architecture with tunable IR reflectivity

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Owing to the choice of the components, interpenetrating polymers networks (IPN)s allow to build up materials with controlled properties [1]. On the other hand, electronic conducting polymers (ECP) are of great interest as active component notably in electrochromic devices [2]. In order to elaborate new simple devices, we have interpenetrated poly(3,4-ethylenedioxythiophene) (PEDOT) in a polyethyleneoxide network (PEO) thin film leading to a device which can be both monoblock and self-supported [3-4]. Swollen in an electrolyte and after applying a low voltage, this semi-interpenetrating polymer network (semi-IPN) exhibits electrochromic properties similar to a multilayer device both in transmittance in the visible [3] and in reflectance in the IR [4] arising from the switching between the redox states of the PEDOT.

We will first describe the elaboration of PEO/PEDOT semi-IPN. Then, we will show from spectro-electrochemical study that this device displays tuneable optical reflectance change in the IR depending on the applied voltage. This study demonstrates that such a simple device does not need any reflective surface as in multilayered devices, what proofs that the PEDOT acts both as a current collector and as active reflective material. We will present also the switching time and the life time of the device during cyclability at various temperatures. Owing to the degradation observed, we will finally show that the PEO matrix can be advantageously replaced by a new flexible IPN associating PEO network and nitrile butadiene rubber (NBR) network. Reflectivity change of this last system will be described.

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7976-22, Session 6

DEA material enhancement with dipole grafted PDMS networks

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Silicone elastomers (PDMS) are highly suitable for application in the field of dielectric elastomer actuators (DEA) due to their unique material

properties (e.g. low glass temperature, thermal stability, large capability of chemical tailoring). The elastomer forming PDMS employed for this study consists of chains with vinyl termination and is cross linked via hydrosilylation to a cross linking molecule in the presence of platinum catalyst. Here, dipole molecules (N-methyl-4-nitro-N-prop-2-enylaniline) were specifically synthesized such that they could chemically graft to the silicone network. The grafting was carried out via the vinyl termination of the dipole to the PDMS network in a one step film formation process. The most prominent advantage of this approach is the achievement of a homogeneous distribution of dipoles in the PDMS matrix and a suppression of phase separation due to the grafting to the junction points of the rubber network. Several films with dipole contents ranging from 0%wt up to 9.1%wt were prepared. The films were investigated to determine their mechanical (tensile testing), dielectric (dielectric relaxation spectroscopy) and electrical (electrical breakdown) properties, which are determining for the performance as DEA.

7976-23, Session 6

Carbon aerogel based electrode material for EAP actuators

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There are several EAP materials available. One type of these materials, ionic polymer-metal composites (IPMC-s) contain of ionic polymer, metal and a liquid of electrolyte. There are also EAP materials that could be called Carbon-Polymer Composite (CPC) actuators. They are made from non-ionic polymer in composition with nanoporous structured carbon and electrolyte. It is generally understood that the large interfacial surface area of electrodes gives rise to better actuation performance; therefore, designing EAPs with high specific surface area electrodes is of interest. In this work we report an actuator material, that consist of carbon aerogel, 1-ethyl-3-methylimidazolium tetrafluoroborate (EMIBF4) and poly(vinylidene-co-hexafluoropropylene) (PVdF(HFP)). Actuators were made by using layer-by-layer casting method and it works as a bending actuator. Carbon aerogel is synthesized from 5-methylresorcinol, which is a waste product in oil-shale industry. It makes the material "environmentally green". Carbon aerogels have a very low density and considerable specific surface area. The assembled three layer actuators require low voltage to operate and work steadily in open air due to non-volatile electrolyte. The electromechanical and electrical characteristics of prepared actuators were examined and compared to our previously reported actuators based on the carbide-derived carbon and activated carbon electrodes. The differences in actuation performance were analyzed in the context of pore characteristics and degree of graphitization of carbons. The gas sorption measurements were performed to characterize pore size distribution.

This actuator shows high strain, low relaxation and low power consumption and it is good for slow-response applications compared to other CPC actuators.

7976-24, Session 6

Lifetime of dielectric elastomer stack actuators

P. Lotz, M. Matysek, H. F. Schlaak, Technische Univ. Darmstadt (Germany)

Dielectric elastomer stack actuators (DESA) are well suited for the use in mobile devices, fluidic applications and small electromechanical systems. Despite many improvements during the last years the long term behaviour of dielectric elastomer actuators in general is not known or has not been published.

The first goal of the study we are presenting in this paper is to characterize the overall lifetime under laboratory conditions and to identify potential factors influencing lifetime. For this we have designed a

test setup to examine 16 actuators at once. The actuators are subdivided into 4 groups each with a separate power supply and driving signal. To monitor the performance of the actuators driving voltage and current are measured continuously and additionally, the amplitude of the deformations of each actuator is measured sequentially.

From our first results we conclude that lifetime of these actuators is mainly influenced by the contact material between feeding line and multilayer electrodes. So far, actuators themselves are not affected by long term actuation. We have tested several materials (e.g. graphite powder, silver grease, conductive paint,...) With the best contact material actuators can be driven for more than 500 hours at 200 Hz with an electrical field strength of 20 V/ μ m. This results in more than 300 million cycles. Actually, there are further actuators driven at 10 Hz for more than 900 hours and still working. We will present definite results in the full paper with various parameters of the actuator geometry, driving conditions and dielectric material.

Furthermore, we examine the influence of temperature and humidity on actuators' lifetime. Identical actuators are placed in a climatic chamber. Results will also be presented in the full paper.

7976-25, Session 6

Self-sensing properties of carbon-polymer composite (CPC) actuators

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CPC (carbon-polymer composite) is a type of low voltage electromechanically active material, which is often built using two layers of electrodes containing nanoporous carbon separated by a thin ion-permeable polymer film; ionic liquid is used as electrolyte. In cantilever configuration, while voltage (up to 3 V) is applied to these electrodes, the CPC sheet undergoes bending. In comparison to ionic polymer-metal composites (IPMC), CPC actuators exhibit higher force and practically no back-relaxation, but as a trade-off the speed of actuation (bending) is reduced.

To date, virtually no research into sensing properties of these materials has been conducted. The current paper aims to implement distributed model of IPMCs on CPC actuators. In order to determine the position (curvature) of the CPC actuator, change of surface resistance in the process of bending is measured. Within the scope of this paper, it is also investigated whether the acquired signals are feasible for the use as a feedback to the actuator's driving mechanism and thus creating a self-sensing CPC device. Experimental data on how surface resistance varies during the actuator's work-cycle is presented and analyzed.

7976-89, Poster Session

Inkjet printing of electroactive polymer actuators on polymer substrates

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Electroactive polymers (EAP) are promising materials for application as actuators in different fields. This presentation reports inkjet printing as a versatile tool for manufacturing EAP actuators. Drop-on-demand inkjet printing can be used for additive deposition of functional materials onto substrates. Cantilever bending actuators with lateral dimensions in the mm range are described here. A commercially available solution of

electroactive polymers (solvent 190, Solvay Solexis S.p.A.) is dispensed onto metalized polycarbonate substrates using inkjet printing. These polymers exhibit piezoelectric behavior. Multiple layers are printed resulting in a film thickness of 5-10 μm . After printing, the polymer layers are annealed thermally at 130 $^{\circ}\text{C}$. Top electrodes are deposited onto the EAP layer by inkjet printing a silver nanoparticle ink (Cabot CCI-300, Cabot Corp.). The as-printed silver layers are sintered using argon plasma - a recently developed technique that is compatible with low T_g polymer foils. Typically, silver nanoparticles require sintering temperatures $>200^{\circ}\text{C}$, which is obviously not compatible with polymer foils. [J. Reinhold, C. E. Hendriks, R. Eckardt, J. M. Kranenburg, J. Perelaer, R. R. Baumann, U. S. Schubert, J. Mater. Chem. 2009, 19, 3384] After printing the EAP layers are poled. When applying an electric field over the polymer layer, piezoelectric strain in the EAP leads to a bending deflection of the structures. With driving voltages of 250 V the actuators generate displacements of 20-25 μm and blocking forces of 5-10 mN. Resonance frequencies are approximately 200-300 Hz. Possible applications of these actuators include lab-on-chip devices and positioning tasks in microoptical systems.

7976-90, Poster Session

Electroactive polymer devices for active vibration damping

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Depending on the amount of converted energy, dielectric elastomer generators (DEG) can be used as controllable damping devices. Since this damping can be realized only during relaxation, the following mechanical setup is used for a continuously adjustable damping. Two single circular DEGs are clamped on the upside and downside of a rigid pipe and are mechanically mounted in series with a piston inside the rigid pipe. Since the two DEGs are equally built, the stiffness of the damper is constant. In case of a mechanical excitation of the piston through the vibrating surface, one of the DEGs is stretched, while the other contracts and vice versa respectively and one of the two DEGs can always be used to convert mechanical into electrical energy. Through this, an adjustable damping, which can be controlled with the amount of initial power transferred to the DEG, is achieved. If the DEGs are also operated in the actuator mode, it is possible to achieve a full active damping.

To realize a vibration isolation with this kind of active damper, proven control concepts like skyhook-damping can be used, where a velocity dependent damping coefficient is calculated. In case the DEGs operate only or at least most of the time in the generator mode, the harvested energy can be used for the electrical supply of the controller, the power electronics and additional sensors aiming an energy autarky vibration control system.

7976-91, Poster Session

Dielectric elastomer actuators with enhanced permittivity and strain

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For the successful commercialization of dielectric elastomer actuators, improved elastomer and electrode materials are required. The presently used elastomer materials are not the result of specific developments for this purpose, but have been derived from other applications. Therefore, new materials with improved properties adapted to the special requirements for dielectric elastomer actuators are necessary.

It is well known, that the permittivity of the elastomer plays a decisive role for the actuation strain, since it directly influences the achievable Maxwell pressure between the electrodes and the corresponding strain of actuation. Several approaches to enhance the permittivity of the elastomer have been tested so far, but the advantage of the permittivity

enhancement was usually canceled by the change of other properties like the increase of the Young's modulus of the elastomer, which lowers the actuation strain.

In this work, dielectric elastomer actuators with films of silicone elastomer filled with barium titanate particles were prepared and investigated. The concentration of high dielectric particles in the elastomer matrix must be as high as possible, because the curve of the permittivity versus the particle concentration starts with a small slope at low concentrations and becomes steeper with increasing concentrations. With a concentration of 20 vol.% barium titanate particles, the relative permittivity of the silicone elastomer has been increased from 3 to 7.3 by about 140 %. Simultaneously, the Young's modulus of the silicone elastomer was kept nearly constant at about 100 kPa.

Simple film actuators were manufactured with the unmodified silicone elastomer and the corresponding material modified with barium titanate particles. The elastomer films were coated with electrodes of graphite particles in a silicone matrix. Stretch strain measurements on these dielectric elastomer actuators with variable electric field strength were performed using a laser triangulator. The modification of the material results in a strong increase of the actuation strain versus the electric field, which corresponds to the measured enhancement of the permittivity. The strain of the modified material is approximately doubled with respect to the pure silicone elastomer.

Moreover, first multilayer actuators from this modified silicone elastomer were prepared using a repeated spin-coating process. Actuation measurements of the film thickness versus the electric field strength confirmed the results, which were independently received from the stretch actuation experiments. It is concluded, that strong enhancements of the actuation strain of dielectric elastomer actuators can be achieved by the modification of silicone elastomer with barium titanate particles in high concentration.

7976-92, Poster Session

Photopatternable electrical conductive MWCNT-SU-8 nanocomposite for MEMS/MST

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An electrically conductive SU-8 has been formulated and can be used to build micro-components for MEMS, microfluidics and packaging applications. SU-8 is an insulating near -UV negative tone photoresist. In order to enhance the electrical conductivity of SU-8, Multi-walled Carbon nanotube with an average diameter of 1-2nm and length of 15 micron were dispersed by MEK assisted ultrasonic agitation.

The resulting nanocomposite was successfully patterned. Evolution of electrical conductivity of SU-8 as a function of weight percentage has been studied. It is observed that the conductivity increases slowly up to 3.1 wt% weight concentration. However, after this point the conductivity increases rapidly. This behavior of conductivity variation can be explained in terms of the percolation theory. At lower concentrations of MWCNT, percolation paths are not set up by the nanoparticle network. As the concentration of nanoparticles in the composite increases, the percolation paths via conducting nanoparticles are set up. At this stage, the nanoparticles control the conductivity of the nanocomposite matrix.

7976-93, Poster Session

PWM drive of IPMC actuators with the consideration of the capacitive impedance

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In many robotic applications using IPMCs (Ionic Polymer Metal Composites), batteries are required for autonomous locomotion. Sometimes, short duration of the batteries may become a problem especially in the use of linear amplifiers. The reason of this problem

is owing to the high capacitive current of IPMCs and the energy consumption in amplifiers.

In this paper, we consider driving an IPMC actuator with a PWM (Pulse Width Modulation) amplifier, in order to shed light on the characteristics of PWM driving of IPMCs. A PWM amplifier, also called switching amplifier, transforms input signal into output signal which consists of high-frequency square waves. In general, it is said that efficiencies of PWM amplifiers are higher than those of linear amplifiers. However, a high current flows across the IPMC in the use of a PWM amplifier, because the impedance of the IPMC is small in the high frequency and the PWM voltage has high frequency component. Therefore, it is supposed to become the power consumption high even in the use of PWM amplifiers. We solve this problem by putting an appropriate filter circuit between a PWM amplifier and an IPMC. We show that the filter circuit greatly reduces the current across the IPMC in the use of the PWM amplifier. In this paper, we discuss a selection of suitable filter circuits and investigate the frequency characteristic. The simulation and the experiment results demonstrate the effectiveness of the proposed method.

7976-94, Poster Session

Active suspension with multilayer dielectric elastomer actuator

R. Karsten, P. Lotz, H. F. Schlaak, Technische Univ. Darmstadt (Germany)

This paper is about a new application of dielectric elastomer actuators (DEA) for active suspension. The research on active damping methods is essential because the passive elements such as springs and rubbers or viscous fluids can not eliminate vibrations of low frequencies. Currently, piezoceramic actuators are primarily used for active vibration control. One of the key disadvantages of this type of actuators is the low deformation, which is especially required for low frequencies. Multilayer dielectric elastomer stack actuators combine properties of active and passive bearings. This kind of actuators may be well applied in active vibration control in the low frequency range (0 - 200 Hz). As an additional feature these actuators show the characteristics of passive bearings at high frequencies. One possible application of DEA is the protection of lightweight sensible equipment from vibrations like optic components.

Typically, three kinds of control methods are used for an active vibration control. These are the skyhook damper, the feedforward and feedback controller. In this paper we describe a dynamic model of an actuator. As the model of DEA shows a non linear behaviour, it is linearized in operating point. The parameters of operating point such as layer thickness, stiffness and damping constant are depending on the mass of equipment and offset voltage. DEAs with 25 mm diameter show resonance frequency about 75 Hz. Therefore vibration extinction up to 50 Hz is possible. Finally, different control algorithms for DEA have been designed.

In the full paper a dynamic linearized model of DEA, control algorithm and measuring results will be presented.

7976-95, Poster Session

Low voltage driven electroactive polymer actuator with integrated piezoelectric transformer based driver without magnetic components

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Today's ElectroActive Polymer (EAP) actuators utilize high voltage in the range of kilo volts to fully stress the actuator. The requirement of high voltage is a drawback for the general use in the industry due to safety concerns and high voltage regulations.

In order to avoid the high voltage interface to EAP actuators, a low voltage solution is developed by integrating the driver electronic into a 110mm tall cylindrical push EAP actuator. To decrease the size of the

driver a Piezoelectric Transformer (PT) based solution without inductors is presented. In prior art an inductor is shown to be necessary in series with the PT to achieve soft switching and efficient operation. However the inductor is eliminated in this half-bridge topology by use of a novel PT design without compromising the efficiency. The PT is essentially an improved Rosen type PT, which is optimized for inductor-less soft switching. Furthermore the PT is optimized for a 4W output at a half-bridge voltage of 24V with a maximum EAP voltage of 2.5kV. The topology is simulated and verified through measurements on a working prototype. Output voltages above 2.5kV are demonstrated with a flexible input range of 15 - 30 volts. The steady state consumption is kept low by careful design of the high voltage stage to decrease the leakage current drawn from the EAP.

As a result a 95x13x7mm driver is integrated in a 110x32mm actuator, forming a low voltage interface EAP with a 7N blocking force and a non-load stroke of 1.1mm.

7976-96, Poster Session

Ion distribution in ionic electroactive polymer actuators and device design

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Ionic electroactive polymer (i-EAP) actuators with large strain and low operation voltage are extremely attractive for applications such as MEMS and smart materials and systems. In-depth understanding of the ion transport and storage under electrical stimulus is crucial for optimizing the actuator performance. In this study, we perform direct measurements of the ion distribution in charged and frozen actuators by using Secondary Ion Mass Spectrometry (SIMS). High temperature actuators that consist Aquivion ionomer membrane and high melting temperature ionic liquid 1-butyl-2,3-dimethylimidazolium chloride ([BMMI+][Cl-]) serve in this study. Electrical impedance, I-V characteristics, and potential step charging of the actuator are characterized at 25°C and 100°C. The conductivity of the actuator is 0.3mS/cm at 100°C and 2.9μS/cm at 25°C, respectively. The electrochemical window of the device is 3V and a 2mm tip displacement is observed under 2.5V 0.2Hz at 100°C. A semi-quantitative depth profile of the relative ion concentration in charged and frozen actuators is measured by SIMS and an ion concentration map through the sample thickness is plotted by fitting with the potential step charging data. The result shows that, unlike semiconductors, ions do not deplete from the electrodes with same signs. Due to a strong cluster effect between the ions, [Cl-] and [BMMI+] accumulate near both cathode and anode. Furthermore, the profile indicates that the ion size difference causes the [BMMI+] space charge layers (~5μm) much thicker than those of [Cl-] (~0.5μm). Based on these findings, we have designed i-EAP and IPCNC actuators with much improved responses.

7976-97, Poster Session

Fast and multi-level LC-SLM using AFLC

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Liquid -Crystal-Spatial-Light-Modulator (LC-SLM) has been developed because of its main characteristics, i.e. low power consumption or its convenience. Recently, owing the development of the technology, the characteristics of quick response or high density of panels are the main demands in the field of optical communications or optical information processing.

A lot of LC-SLM (nematic or ferroelectric ones) being in the market, they can't be satisfied by high frame frequency and by multi-level phase control at the same time.

We propose the faster and multi-level deriving method by using the anti-ferroelectric-liquid crystal. The characteristics of our apparatus are mentioned below.

Under our measurements, the driving voltage is less than 3V and on-time or off-time response is less than 200 μ s each (quick response).

The amounts of phase shift are more than $.2\pi(\lambda=550\text{nm}$, cell thickness=2.2 μm) and its phase shift can be determined continuously (multi-level phase control). Contrast ratio is more than 300.

More phase shift quantities can be got if we used thicker cell.

This can be used both under the amplitude or phase modulations driving and the frame frequency is up to 5KHz.

7976-98, Poster Session

Electromechanical fatigue in IPMC under dynamic energy harvesting conditions

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Ionic polymer-metal composites (IPMCs) are an interesting subset of smart, multi-functional materials that represent promising energy conversion technologies. Being electromechanically coupled, IPMCs can function as dynamic actuators and sensors, transducers for energy conversion and harvesting, as well as artificial muscles for medical and industrial applications. Like all natural materials, even IPMCs undergo fatigue under dynamic load conditions. Here, we investigate the electromechanical fatigue induced in the IPMCs due to application of cyclic mechanical bending deformation under hydrodynamic energy harvesting conditions. Considering the viscoelastic nature of the IPMC, we employ an analytical modeling approach which indicates that the electromechanical fatigue primarily depends on the cyclic stresses induced on the membrane. It is to be noted that the polymer-metal composites undergo cyclic softening throughout the fatigue life without attaining a saturated state of charge migration. However, it results in (1) degradation in electromechanical performance; (2) nucleation and growth of microscopic cracks in the metal electrodes; (3) delamination of metal electrodes at the polymer-electrode interface. As a step towards addressing these issues, we employ a phenomenological approach experimentally involving relaxation of the IPMC membrane. It is observed that the electromechanical performance improves significantly. This is due to reorientation of the backbone polymer chains which eventually lead to better charge transport. Furthermore, we use carbon nanotubes (CNT) as electrodes for IPMC and compare the fatigue life of IPMC with silver electrode. Excellent improvement of 25% increase in peak-peak voltage over the fatigue life is observed for CNT-IPMC. This improved fatigue life coupled with enhanced electromechanical performance represents a promising step towards addressing the issue of longevity of IPMCs under dynamic energy harvesting conditions.

7976-99, Poster Session

EAP based neonatal lung simulator

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Each year 10 million newborns require some type of breathing assistance to transition from a fluid filled environment to an air filled environment (Wiswell, 2003). In such cases breathing assistance is usually given using a standard 'bag ventilator'. However it is very difficult to maintain the recommended pressure and tidal volume and given that a newborn's lung is extremely sensitive this can lead to ventilator induced lung injury (VILI).

To reduce the likelihood of VILI a neonatal lung simulator is being developed based on dielectric elastomeric actuators (DEAs). It is proposed that the simulator can be used in training of medical staff as well as in a research and development environment. DEAs are particularly suited for this application due to their natural like response as well as their self-sensing ability. By actively controlling the DEA the pressure and volume inside the artificial lung can be controlled giving rise to active compliance control. Additionally the capacitance of the DEA can be used as a live measurement of volume eliminating integration errors associated

with flow sensors. As DEAs have a reasonably good dynamic response, a multitude of lung conditions can be modelled.

Using the FEA package ABAQUS the characteristics of the lung simulator are modelled and the effect of changing the size of the DEA, varying the prestretch and the effect of various configurations are observed. The current results are promising and show that mimicking a lung with DEAs is possible. The apparent advantages over mechanical solutions are smooth operation and compact integrated actuation and sensing abilities.

Wiswell, T.E. (2003) Neonatal Resuscitation. *Respiratory Care*, 48 (3),288-295.

7976-100, Poster Session

Open-loop control of IPMC actuators under varying temperatures

R. Dong, X. Tan, Michigan State Univ. (United States)

It is often difficult or costly to implement sensory feedback for ionic polymer-metal composite (IPMC) actuators in many of their envisioned biomedical and robotic applications, because of size and complexity concerns. It is thus of interest to develop open-loop control strategies for these actuators. Such strategies, however, are susceptible to change of IPMC dynamics under varying environmental conditions, a predominant example being the temperature.

In this paper we present a novel approach to open-loop control of IPMC actuators in the presence of ambient temperature changes. First, a method is proposed for modeling the temperature-dependent actuation dynamics. The empirical frequency response of an IPMC actuator, submerged in a water bath with controlled temperature, is obtained for a set of temperatures. For each temperature, a transfer function of a given structure, with numerator and denominator polynomials having same degree, is found to fit the measured data. A temperature-dependent transfer function model is then derived by curve-fitting each parameter as a simple polynomial function of the temperature.

Open-loop control is then realized by inverting the model at any given temperature. The approach thus assumes temperature measurement, which is easy to realize. However, the obtained model for IPMC actuators is of non-minimum phase and cannot be inverted directly. A stable but non-causal algorithm is adopted to implement the inversion. Furthermore, a finite-preview algorithm is examined to enable near real-time tracking of desired outputs. Experimental results show that the proposed approach is effective in ensuring consistent performance of IPMC actuators under varying temperatures.

7976-101, Poster Session

Influence of different fabrication techniques on IPMCs electrode morphologies and mechano-electrical properties

Z. Zhu, H. Chen, L. Chang, B. Li, Y. Wang, Xi'an Jiaotong Univ. (China)

IPMCs are a new kind of smart materials that have great potential application in bio-mimetic machine, bio-medicine and aerospace. Recently theoretical researches pointed out that the electrode (especially the electrode/ionomer interface) was the key to understand their mechano-electrical behavior, but there is little experimental report on the electrode morphologies and the forming mechanisms. In this paper, IPMC samples were fabricated by different techniques, then their surface and cross-section morphologies were observed by SEM and their mechano-electric properties were measured to study the influence of the techniques on the electrode.

Through the comparison of various roughing ways, it shows that the roughing veins of the membrane control the electrode surface structure in macro, and roughing can greatly promote the particles permeation into the membrane in the cross-section, but it also makes the electrode

rough and loose on the outside, which can increase the electrode resistivity and reduce the deformation. Different electrode reducing ways decide the size of the electrode particles in micro. The electrode reduced by immersing-reduction grows not only toward the membrane but also toward the outer surface, which is obvious after a few times reduction. The electrode reduced by chemical plating grows toward the outer surface, and it can make the penetrated electrode particles denser. Then the electrode forming mechanisms are proposed to explain these phenomena. The performance experiments further show that the deformation of the IPMCs reduced by immersing-reduction is far smaller than that of those reduced by chemical plating. It is found that the chemical constituents of the electrode are important to the mechano-electric properties besides the microstructure.

7976-102, Poster Session

Small strains measurement, calibration, and solution for self temperature compensation in CFRP sensors

H. Huang, Z. Wu, Ibaraki Univ. (Japan); C. Yang, Southeast Univ. (China)

This paper describes a new method to measure small strains by carbon fiber-reinforced polymer (CFRP) sensors suitable for the long-term structural health monitoring (SHM). The CFRP sensors are composed of carbon tows. The carbon tow is a common used structural material due to its excellent mechanical properties and resistance to corrosion. Recently the electrical conductivity of the carbon tow is studied, and it is realized that the carbon tow is a kind of a self-sensing structural material. The CFRP is designed as a long-gauge strain sensor. The effect of sensor size on the active region of the CFRP sensor is studied in order to enhance the sensitivity in small strains. The experimental results indicate that the CFRP sensor with long gauge-length shows better sensitivity than the short one. However, the CFRP sensor with 500 mm gauge-length can identify the strain change with 20 microstrain. In addition, the continuously monitoring results of cyclic tensile tests indicated that, the temperature effect influences the measuring accuracy of the CFRP sensor. The experimental results show that the CFRP sensor is a kind of negative temperature coefficient sensor in the normal temperature, a temperature compensation circuit in view of this conclusion is developed. The verification tests of CFRP sensors on RC beam and pull-out test are discussed.

7976-104, Poster Session

New elastomeric silicone based networks applicable as electro active systems

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The critical components for practical dielectric elastomer (DE) actuator design are the dielectric materials, DE formulation and DE processing (single or folded sheet, multilayer, etc.).

The aim of the present study was the formulation and the improvement of new intelligent silicone based dielectric elastomers applicable as muscle-like actuators.

An alternative network formulation method was adopted in order to obtain a different type of elastomeric systems - the so-called bimodal networks - using a vinyl-terminated polydimethyl siloxane (PDMS), a crosslinker (3 or 4-functional), and a platinum-catalyzed hydrosilylation reaction between the two reactants. The crosslinking condensation reaction was realized by mixing different amounts of short PDMS chains and long PDMS chains with the stoichiometric amount of tetrakis(dimethyl siloxy)-silane and curing them with 0.5 wt% platinum cyclovinylmethyl-siloxane complex catalyst in ambient conditions for 24 hours. The networks were synthesized using a two-step procedure. The final bimodal network has a different chain-length distribution than a traditional bidisperse mixture. The short chains organize themselves in

clusters between the long chains and this leads to unexpectedly good properties due both to the low extensibility of the short chains that attach strongly the long chains and to the extensibility of the last ones that retards the rupture process.

The curing time and linear viscoelastic properties were registered using a controlled stress rheometer in oscillation procedure. Furthermore, the filament stretch rheometer was used to characterize the mechanical elongation properties of the elastomeric networks by applying large amplitude oscillatory elongation measurements³ and planar elongation techniques.

7976-107, Poster Session

Induced interaction of NH₄NO₃ with poly(P-phenylene vinylene) by mean of zeolite Y

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Chemical sensor technologies play an important role in development and improvement of public health and environment through applications in many areas. Conducting polymers are unique among the sensing materials known to us at present. They have many advantages over conventional metal sensors. Poly(p-phenylenevinylene) (PPV) can serve as the active material in sensor devices because PPV possesses good optical and electrical properties, and it can be synthesized by a relative simple technique. Zeolite is chosen to be introduced into a polymer matrix in order to increase sensitivity toward ammonium nitrate gas. This work will focus on the effect of Si/Al ratio and cation type on the gas conductivity sensitivity.

7976-108, Poster Session

Elliptical modelling of symmetric hysteresis in a dielectric elastomer actuator

P. Tian, R. W. Jones, Mads Clausen Institute (Denmark)

Hysteresis poses a significant challenge for the modelling and control of smart material-based actuators. A range of phenomenological model-types have found widespread acceptance for modelling hysteresis; for example the Bouc-Wen model and operator-based approaches such as the Preisach Model, and the Prandtl-Ishlinskii model.

This work investigates an alternative approach to modelling symmetric hysteresis, namely using an elliptical model. Elliptical equation models come in many forms with the two most popular being the conic sector form and the geometric form. Both of these provide lower parameter representations of symmetric hysteresis than the Preisach and Prandtl-Ishlinskii operator-based approaches while elliptical models also allow a more straightforward implementation of the inverse hysteresis model for compensation purposes than both the Preisach and Bouc-Wen models.

The dielectric elastomer actuator considered in this work is a rolled tubular actuator commercially produced by Danfoss Polypower A/S. The actuator actually demonstrates asymmetric hysteresis behaviour due to the inherent nonlinear voltage-strain characteristic of the dielectric elastomer material. A gain scheduling term is introduced to compensate for the nonlinear voltage-strain behaviour of the actuator thereby producing a symmetric hysteresis characteristic for the actuator.

Elliptical-based model fits will be carried out on experimental data produced by applying periodic input voltages at a number of different frequencies to the tubular actuator. Both the conic sector and geometric form of ellipse models will be considered.

7976-109, Poster Session

Disturbance observer-based compensation of hysteresis in a dielectric elastomer actuator

R. W. Jones, Mads Clausen Institute (Denmark); M. Tham, Newcastle Univ. (United Kingdom)

Disturbance observers are a popular and effective linear model-based method for improving the disturbance rejection performance of controlled mechatronic systems. Disturbance observers have also been shown to make members of a certain class of non-linear systems behave linearly. In the literature it has been shown that disturbance observers can mitigate the effect of dead zone and also can suppress limit cycles in a system with backlash.

In this contribution a disturbance observer (DO) will be added to a feedback controlled dielectric elastomer actuator to provide dynamic hysteresis compensation. Dielectric elastomer actuators are also characterised by a nonlinear steady-state voltage-strain characteristic as well as creep. Two control schemes will be investigated. In the first scheme a conventional feedback controller is implemented followed by the DO. The linear model used in the DO will approximate the nonlinear dynamics of the actuator over the operating range. In the second control scheme, a gain schedule element, which provides linearization of the nonlinear steady-state voltage-strain characteristics, will be integrated into the first control scheme. In this case the linear model used in the DO should provide a more accurate representation of the actuator over the operating region. The results from both control schemes will be compared to assess (a) the ability of the DO to compensate for dynamic hysteresis and (b) the possible deterioration when the gain schedule is not included in the control scheme.

7976-110, Poster Session

Biomimetic small scale variable focal length lens unit using electro-active polymer actuators

B. Kim, H. Y. Kwon, K. J. An, Y. K. Lee, J. Nam, H. R. Choi, H. Moon, J. C. Koo, Sungkyunkwan Univ. (Korea, Republic of)

Having a combination of a gel-like soft lens, ligaments, and the Ciliary muscles, the human eyes are effectively working for various focal lengths without a complicated group of lens. The simple and compact but effective optical system should deserve numerous attentions from various technical field especially portable information technology device industry. Noting the limited physical space of those devices, demanding shock durability, and massive volume productivity, the present paper proposes a biomimetic optical lens unit that is organized with a circular silicone lens and an annular dielectric polymer actuator. Unlike the traditional optical lens mechanism that normally acquires a focus by changing its focal distance with moving lens or focal plane, the proposed optical system changes its lens thickness using an annular connected polymer actuator in order to get image focuses. The proposed biomimetic lens system ensures high shock durability, compact physical dimensions, fast actuations, simple manufacturing process, and low production cost.

7976-111, Poster Session

Reduced graphene oxide electrodes for artificial muscles

C. M. Koo, K. Min, J. Y. Jung, Korea Institute of Science and Technology (Korea, Republic of)

Reduced graphene oxides (RGOs) thin films were fabricated in order to apply for the compliant electrodes of artificial muscles. The RGO was chemically prepared by chemical oxidation of natural graphite via Hummers method and following reduction using hydrazine. The RGO

electrodes were coated on both sides of poly (styrene-*b*-ethylbutylene-*b*-styrene) (SEBS) triblock copolymer gel by using spray coater. The resulting SEBS dielectric elastomers with RGO electrodes had larger electromechanical strain response than those with conventional carbon paste electrodes. It might be caused by higher conductivity and higher flexibility of RGO than those of conventional electrodes.

7976-112, Poster Session

Electromechanical properties of P(VDF-TrFE)/CNT and P(VDF-TrFE)/Gr composites

C. M. Koo, S. M. Hong, Y. D. Park, J. H. Lee, Korea Institute of Science and Technology (Korea, Republic of)

Electromechanical properties of poly (vinylidene fluoride) (P(VDF-TrFE)) /carbon nanotube (CNT) composites and P(VDF-TrFE)/graphene (Gr) have been investigated. The electromechanical thickness strain of both composites increased with the filler content. P(VDF-TrFE)/Gr showed the larger strain than P(VDF-TrFE)/CNT at the same filler content. Such actuation properties of the composites with conductive fillers are discussed in the view point of dielectric constant, mechanical property, filler dispersion state and ground current.

7976-113, Poster Session

Electromechanical strain responses of SEBS/CB and SEBS/SWCNT composites

S. S. Hwang, M. H. Kim, S. M. Hong, C. M. Koo, Korea Institute of Science and Technology (Korea, Republic of)

Electromechanical strain responses of poly (styrene-*b*-ethylbutylene-*b*-styrene) (SEBS) /carbon black (CB) composites and SEBS/single wall carbon nanotube (SWCNT) composites have been investigated. The electromechanical thickness strain of both composites increased with the filler content. SEBS/SWCNT showed the larger strain than SEBS/CB at the same filler content. Such actuation properties of the composites with conductive fillers are discussed in the view point of dielectric constant, mechanical property, filler dispersion state and ground current.

7976-114, Poster Session

Constitutive behaviors of thermo-responsive shape memory polymer

B. Zhou, Harbin Engineering Univ. (China)

In this paper, Dynamic mechanical analysis (DMA) tests are conducted on the styrene-based shape memory polymer (SMP) to investigate its state transition behaviors. Tensile tests at various constant temperatures are carried out to reveal the stress-strain-temperature relationship of the styrene-based SMP. A thermo-mechanical constitutive model is developed to describe the stress-strain-temperature relationship of the styrene-based SMP. Numerical calculations illustrate the proposed model well describes the thermo-mechanical cycle of shape memory of styrene-based SMP, such as deformation at high temperature, shape fixity, unloading at low temperature and shape recovery.

7976-115, Poster Session

Investigation on mechanical behaviors of shape memory alloy beam

B. Zhou, Harbin Engineering Univ. (China)

DSC test is carried out to determine the phase transformation temperatures of a NiTi SMA, which include martensitic starting

temperature, martensitic finishing temperature, austenitic starting temperature and austenitic finishing temperature. The mechanical behaviors of shape memory alloy (SMA) beam are investigated by using Zhou's shear constitutive equation of SMA and the theorem of bending beam in mechanics of materials. A critical bending moment equation is developed to describe the relationship between the martensitic phase transformation critical bending moment of SMA beam and temperature.

7976-117, Poster Session

Methacrylate-based triblock copolymer for elastomeric electroactive material

K. Baek, Korea Institute of Science and Technology (Korea, Republic of)

Series of ABA triblock copolymers of methyl methacrylate (MMA) and dodecyl methacrylate (DMA) [poly(MMA-b-DMA-b-MMA)] were synthesized by sequential atom transfer radical polymerization (ATRP) to examine actuation properties as a novel electroactive material. Obtained well-defined triblock copolymers with various molecular weights of the block segments ($PDI \leq 1.2$) showed different morphologies from BCC to lamellar structures, which strongly affect the actuation behaviors. These relatively polar methacrylate elastomers showed the higher k values and the superior actuation properties in comparison to corresponding SEBS elastomers.

7976-118, Poster Session

Silvered dielectric elastomer actuator with high actuation strain

S. H. Low, G. Lau, Nanyang Technological Univ. (Singapore)

Conductive grease and powder are commonly applied as compliant electrodes for dielectric elastomer actuators (DEAs). Unfortunately, they can be rubbed off easily, and DEAs based on them cannot self-heal from localized electrical breakdowns. Metallic thin films are cleaner and more resilient alternatives for electrodes. They are currently widely used in metalized plastic capacitors, which are known for their self-healing capability. However, they are not widely used in DEAs due to limitations in strain. In this paper, we demonstrate that a metalized DEA is capable of areal strains of up to 21%. The inexpensive and simple method of electrodeless silver deposition has been used to create the electrodes for the single-layer DEA. The dielectric film of 100 micron thick was lightly prestrained at 10% in both planar directions. Upon activation, the silvered DEA demonstrated a diameter strain of up to 10% at an activation voltage of 5 kV. This is equivalent to a 21% areal strain and a 17% reduction in thickness during activation. The self-healing properties of the silver electrodes have also been observed. Localised breakdowns of the dielectric film self-healed, thereby averting electrical breakdown and allowing actuation to continue, even at higher applied voltages. In order to ascertain that the silver electrodes will be able to retain its continuity, even at greater in-plane actuated strains, mechanical strain tests were carried out. The silver electrodes were found to be able to withstand a uni-axial mechanical strain of 50%, showing the feasibility of such electrodes for use in DEAs.

7976-119, Poster Session

Ionic polymer-metal composite enabled robotic manta ray

Z. Chen, T. I. Um, H. Bart-Smith, Univ. of Virginia (United States)

The manta ray (*Manta birostris*) provides the inspiration for an electro-active polymer actuated robotic fish. This batoid ray demonstrates excellent swimming capabilities; generating highly efficient thrust via flapping of dorsally flattened pectoral fins. In this paper, we present an underwater robot that mimics the swimming behavior of the manta

ray. An assembly-based fabrication method is developed to create the artificial pectoral fins, which are capable of generating oscillatory with a large twisting angle between leading and trailing edges. Ionic polymer-metal composite (IPMC) actuators are used as artificial muscles in the fin. Each fin consists of four IPMC strips bonded with a soft Polydimethylsiloxane (PDMS) membrane. By controlling each individual IPMC strips, we are able to generate complex flapping motions.

The fin is characterized in terms of tip deflection, tip blocking force, twist angle, and power consumption. The characterization shows that the tip deflection, maximum twist angle, and tip force can reach up to 20%, 150, and 0.5 gram, respectively, but the power consumption of two fins is below 2 W. Based on the characteristics of the artificial pectoral fin, a small size and free-swimming robotic manta ray is developed. The robot consists of two artificial pectoral fins, a rigid body, and an on-board control unit with a lithium ion rechargeable battery. The robot is 18 cm wide, 8 cm long, 2.5 cm high and the overall weight is 55 grams. Experimental results show that the robot swam at a speed of up to 0.1 body length per second (bl/s).

7976-121, Poster Session

Harnessing electromechanical instabilities in polymers at multiple length scales

X. Zhao, Duke Univ. (United States)

Subject to a voltage, a layer of a dielectric polymer reduces thickness and expands area, so the same voltage will induce an even higher electric field. The positive feedback may cause the polymer to thin down drastically, resulting in an electrical breakdown. This electromechanical instability has long been recognized in the electrical power industry as a failure mode for polymer insulators.

However, since the electromechanical instability is generally followed by an electrical breakdown of the polymer, it is very difficult to directly observe its initiation and propagation. Here we report a simple method to observe whole evolution process of the electromechanical instability in polymer films with thickness ranging from millimeters to nanometers in real time. Experimental results indicate that the instability involve transitions of the polymer between homogeneous and multiple inhomogeneous deformation states. The experimental results are consistent with our theoretical predictions. Further, we show that the instability can be harnessed with promising applications in many areas including high-breakdown-field organic capacitors, electrostatic lithography, dynamic pattern formations, and fabrication of semi-permeable membranes.

7976-122, Poster Session

Experimental analysis of biasing elements for dielectric electro-active polymers

M. Hodgins, A. York, S. S. Seelecke, North Carolina State Univ. (United States)

When a high electric field is applied across a dielectric electro-active polymer change in strain is induced in the film decreasing the thickness and increasing the area. This change in strain can be used to generate linear actuation if the DEAP is subject to a suitable bias force. The type of biasing element used will directly affect the performance of the mechanism. Based on the application, the performance metrics of the mechanism, such as displacement stroke and force stroke, can be optimized by changing the biasing element.

This paper presents an experimental investigation of 3 types of biasing elements. A linear spring, a non-linear spring and a constant force input are separately tested as the biasing element of a circular/diaphragm DEAP. Tests are systematically performed at various DEAP pre-deflections, biasing stiffness and electrical loading rates. The stroke performance of each test is examined and analyzed. Finally, suggestions are given as to the best matching biasing element for pumping and valve applications.

7976-123, Poster Session

Dynamic window daylighting systems: electropolymeric technology for dynamic solar responsive building envelopes

E. Kriemeyer, A. Dyson, Rensselaer Polytechnic Institute (United States)

Human health and energy problems associated with the lack of control of natural light in contemporary buildings have further necessitated research into dynamic windows for energy efficient buildings. Existing dynamic window technologies have made moderate progress towards greater energy performance for curtain wall systems but remain limited in their performative response to dynamic solar conditions and variable user requirements for thermal and visual comfort. Recent developments in electropolymeric display technology provide opportunities to transfer technology to glazing systems that can achieve high levels of geometric and spectral selectivity through the building envelope in order to meet the lighting, thermal and user requirements of occupied spaces. Experimental simulations that investigate human factors and dynamic architectural effects as necessary controls and metrics into the experimental testing of electropolymeric glazing technology are presented.

7976-26, Session 7a

Miniaturized EAPs with compliant electrodes fabricated by ion implantation

H. R. Shea, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

Miniaturizing dielectric electroactive polymer (EAP) actuators will lead to highly integrated flexible actuator systems on a chip, combining dozens to thousands of actuators and sensors on a few square cm.

We present μm to mm scale EAP devices, batch fabricated on the chip to wafer scale, based on ion-implanted electrodes. Low-energy (2-10 keV) implantation of gold ions into a silicone elastomer leads to compliant stretchable electrodes consisting of a buried 20 nm thick layer of gold nanoparticles. These electrodes: 1) conduct at strains up to 175%, 2) are patternable on the μm scale, 3) add little stiffness to the silicone, 4) have good conductivity allowing for fast actuation, and 5) excellent adhesion since implanted.

The EAP devices consist of 20 to 30 μm thick silicone membranes with μm to mm-scale ion-implanted electrodes on both sides, bonded to a glass substrate with powder-blasted through-holes. Depending on electrode shape and membrane size, several actuation modes are possible. Characterization of 3mm diameter bi-directional buckling mode actuators, mm-scale tunable lens arrays, 2-axis beam steering mirrors, as well as arrays of 72 cell-size (100x100 μm^2) actuators to apply mechanical strain to single cells shall be reported. Speeds of up to several kHz are observed.

7976-27, Session 7a

Model study on the parameter dependence of an electro-mechanical breakdown model for insulating elastomeric films

M. Kollosche, H. Stoyanov, H. Ragusch, S. Best, G. Kofod, Univ. Potsdam (Germany)

Electrical breakdown due to electro-mechanical instability is the main intrinsic failure mechanism of dielectric elastomer actuators (DEA). The same mechanism may also be responsible for failure in soft insulating materials for other high voltage applications. Typically, the influence of mechanical properties on this breakdown phenomenon is investigated indirectly by variation of the temperature. This approach allows for the use of a single material for a full experiment, however, it may also

influence important secondary influences such as the conductivity and leakage current. Here, the variation in mechanical properties is achieved at constant temperature by blending of thermoplastic elastomers with identical chemical composition.

We report on the validation of a stress-balance model that describes electrical breakdown in dependence of the material properties of elastomeric films. This model includes hyper-elastic material behavior and a proper description of the experimental boundary condition. Specifically, the effects of material stiffness and boundary load are investigated. A continuous change of mechanical properties is possible by direct mass-blending of chemically identical tri-block thermoplastic elastomers with different stiffness's. Due to the identical chemistry, the dielectric properties were identical between the components. This approach enables breakdown measurements for a broad range of mechanical properties. The model is found to fit well for the investigated material stiffness and loads, which correspond to typical values for actuators, but tends to become less accurate at the highest loads and for stiffer materials.

7976-29, Session 7b

Multilayer dielectric elastomer actuators with ion implanted electrodes

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We present the design, fabrication process and characterization of multilayer miniaturized polydimethylsiloxane (PDMS)-based dielectric elastomer diaphragm actuators. The compliant electrodes are obtained by low-energy gold ion implantation. To increase force, decrease the required voltage, and avoid dielectric breakdown, we present here a technique to fabricate multilayer devices with embedded electrodes of complex shapes. By implanting electrodes on a partially cured PDMS film, then casting on it the next layer of PDMS, it is possible to have the compliant electrodes "molded" inside PDMS. Using custom shadow masks allows defining electrodes of any shape or size, we report sizes down to 0.1 mm. The minimal distance between independent electrodes inside the PDMS is limited solely by its breakdown voltage and can be also as small as 0.1 mm. After creating electrodes on the outward faces of the film we get a flat tight package of actuators. Using this approach, we have fabricated miniature compact devices consisting of several independent dielectric elastomer actuators on a single PDMS film. Applying different voltages to the separate actuators allows to achieve complicated movements of the whole device, e.g. act as a 3-DOF parallel manipulator. The thicknesses of the layers may be equal or different, depending on the needs. By applying different voltages to the separate layers, it is possible to force it buckling to the predefined direction. We report on a 3 mm diameter 2-axis beam steering device combining three actuators and on buckling mode actuators which can be buckled both up and down thanks to the multilayer fabrication.

7976-30, Session 7b

Multi-walled carbon nanotube (MWCNT) filled silicone as compliant electrodes for dielectric elastomer actuator

G. Lau, X. H. Neo, S. L. Chua, Nanyang Technological Univ. (Singapore)

A stacked dielectric elastomer actuator (DEA) consists of multiple constituent layers of dielectrics and compliant electrodes. It is capable to take a tensile load if only the stack has good inter-layer bonding. Unfortunately, the inter-layer bonding or cement is poor using the common material for compliant electrodes, such as grease and powder. In this paper, we experiment the use of multi-walled carbon nanotube (MWCNT) filled poly-dimethyl-siloxane (PDMS) as compliant electrodes and elastic cements for multi-layered DEA. Filling PDMS (Ecoflex) with MWCNT by 5% weight percentage makes the mixture moderately

conductive. The experiment shows that the filled and cured PDMS remain slightly conductive when uni-axially stretched up to a strain of 150%. The filled PDMS is at least twice stiffer than the unfilled PDMS. The enhanced stiffness of electrode is good for cementing dielectric layers against tensile stress. When is applied on a silicone dielectric layer to make a DEA, the MWCNT-filled PDMS limits the actuation strain. Preliminary experiments show that a 33% biaxially pre-stretched DEA using the MWCNT-filled PDMS electrode delivers a maximum areal strain up to 18% at an electric field strength of 93 MV/m. In comparison, the DEA using conductive grease electrode (the filled but uncured PDMS) could produce about twice the areal strain up to 44% at the same field strength. Further experiments with other pre-stretch ratio show that the DEAs with MWCNT-PDMS electrodes exhibit higher breakdown field strength than the DEAs with grease electrodes. This suggests that MWCNT-filled PDMS acts reliably as the compliant electrodes and cements for multi-layer DEA.

7976-77, Session 7b

Transparent active skin

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In the previous reports, we proposed the active skin as a new innovative tactile interface. The active skin is configured with a flexible polymer substrate embedded with multiple tactile cells, where a tactile sensor and tactile stimulator are integrated into single tactile cell. A tactile cell, composed of a tactile sensor and a tactile stimulator, is controlled independently. This paper presents a transparent active skin which is based on transparent electrodes with graphene. To make transparent electrode, we have used graphene which has optical and electrical properties as transparent conductors. Since transparent active skin is soft and stretchable, it can be utilized as an innovative tactile interface for a wide variety of application. The fabrication method of the transparent electrode on the dielectric elastomer is proposed and its feasibility is demonstrated experimentally.

7976-31, Session 8a

Superposition principle for analyzing the memory effect of conducting polymers

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Among various materials for soft actuators, conducting polymers are one of the most promising materials for artificial muscles. However, conducting polymers exhibit memory effect and their electrochemical and mechanical responses depend upon the electrochemical history, making practical application difficult. Here, we investigate the influence of the waiting time t_w at a holding potential E_w on the electrochemical responses of poly(3,4-ethylenedioxythiophene) (PEDOT) in relation to the conformational relaxation by means of cyclic voltammetry. The electrochemical responses allow us analyzing the conformational relaxation kinetics of PEDOT. The aging and rejuvenation processes are studied. By using the superposition principle, we are able to analyze the conformational relaxation processes from the electrochemical responses. Besides, the effect of electrochemical aging on the electrical properties is explained from the viewpoint of rearrangement of polymer chains, the electrochemical results are rationalized in terms of a master curve. Since the mechanical properties of the electrochemical actuators are related to the electrochemical responses then the better understanding of the electrical properties is very helpful for optimizing the electrochemical actuators based on conducting polymers.

7976-32, Session 8a

Dielectric elastomer actuators with granular coupling

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So-called 'hydrostatically coupled' dielectric elastomer actuators (HC-DEAs) have recently been shown to offer new opportunities for actuation devices made of electrically responsive elastomeric insulators. HC-DEAs include an incompressible fluid that mechanically couples a dielectric elastomer based active part to a passive part interfaced to the load, so as to enable hydrostatic transmission. Drawing inspiration from that concept, this paper presents a new kind of actuators, analogous to HC-DEAs, except for the fact that the fluid is replaced by fine powder. The related technology, here referred to as 'granularly coupled' DEAs (GC-DEAs), relies entirely on solid-state materials. This permits to avoid drawbacks (such as handling and leakage) inherent to usage of fluids, especially those in liquid phase. The paper presents functionality and actuation performance of bubble-like GC-DEAs, in direct comparison with HC-DEAs. For this purpose, prototype actuators made of two pre-stretched membranes of acrylic elastomer, coupled via talcum powder (for GC-DEA) or silicone grease (for HC-DEA), were manufactured and comparatively tested. As compared to HC-DEAs, GC-DEAs showed a higher maximum stress, the same maximum relative displacement, the same bandwidth and a higher resonance frequency. The paper presents characterization results and discusses advantages and drawbacks of GC-DEAs, in comparison with HC-DEAs.

7976-33, Session 8b

Learning and training effects in conducting polymer artificial muscles

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Natural muscle strengthens by training or repeat exercise. Electrochemomechanical deformation (ECMD) of conducting polymers also shows training or learning effect. Namely, the stroke of ECMD (strain) along the length direction increases by repeating electrochemical oxidation and reduction. The training effect is due to (1) increase in the electrochemically active area, which results in increase of redox charges, (2) anisotropic deformation by high tensile loads, which results from creeping, i.e. conformation change of polymer backbone. The increased stroke of ECMD is observed by removal of tensile loads, resulting from the relaxation of anisotropic deformation (uni-axially stretched polymer backbone). The elongated film by creeping, which is induced by electrochemical cycle under the application of high tensile loads, can be retained at the oxidized state. The retention results from the fact that anions inserted during electrochemical oxidation play the role of cross linker (ionic cross link) between polycations of conducting polymer. The retained shape can be returned to the original shape by removal of tensile stress and several electrochemical cycles (recover of creeping). The returning force is associated with the thermal relaxation of the anisotropic deformation. The film is stiffer at the oxidized state than that of reduced state by approximately two times, which is evidenced by the strain-stress curves or Young's moduli. During the electrochemical cycle dynamical flow of ions makes the film soft and easy to creep under high tensile stress.

7976-34, Session 8b

Altering the structure of conjugated polymers and the impact on electrodynamic performance

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Even though the main features of the actuation mechanism of conjugated polymers have been established, there is still insufficient understanding to design materials with particular behaviours, such as increased strain, speed or strength. Such understanding is considered to be critical, as is the need for obtaining actuator metrics for the more commonly studied systems.

Electroactive polymers such as polypyrroles actuate due to ion movements during redox switching. This ion transport depends, amongst other things, on the degree of cross-linking in the polymer. Despite this, little research has been undertaken to date on the affect that cross-linking has on the actuation of conjugated polymers.

Although, theoretical studies indicate that the temperature employed during synthesis is likely to be a factor that can control cross-linking, this has not been proven experimentally and little else is known about other factors. As a consequence, a synthetic strategy for controlling the cross-linking density of conjugate polymers is not evident in the literature. Understanding is hampered by the lack of a direct method for determining the cross-linking density of these particularly intractable polymers.

We have devised and implemented novel synthetic strategies aimed at altering the cross-linking density of electropolymerized conjugated polymers. The actuating performance of these materials has been assessed using a new type of apparatus capable of making non-contact dynamic measurements. The findings of the work to date will be presented and discussed. The relative merits of the synthetic approaches will be considered and future directions suggested.

7976-35, Session 9a

Refreshable tactile displays based on bistable electroactive polymer (BSEP)

X. Niu, B. Salazar, P. Brochu, Q. Pei, Univ. of California, Los Angeles (United States)

Refreshable tactile displays can significantly improve the education of blind children and the quality of life of people with severe vision impairment. A number of actuator technologies have been investigated. Bistable Electroactive Polymer (BSEP) appears to be well suited for this application. The BSEP exhibits a bistable electrically actuated strain as large as 335%. We will present improved refreshable tactile display devices fabricated on thin plastic sheets. Stacked BSEP films were employed to meet the requirements in raised dot height and supporting force. The bistability actuation reduces the power consumption and simplifies the device operation.

7976-36, Session 9a

PVDF actuators for Braille displays: design, fabrication process, and testing

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As of today, visually impaired people have little access to computer and digital technologies. Most commercially available Braille displays are expensive and have limited functionality. Size restrictions prohibit the device from printing more than one line at a time. This paper addresses the challenge of producing miniature and reliable rolled actuators that provide the required 0.6 mm pin displacement and 0.5 N blocking force for multi-line Braille displays. We describe a new design and fabrication process of core-free Electro Active Polymer (EAP) actuators using 5 micron thick PolyVinylidene Fluoride (PVDF) film as the means of actuation. Displacement measurements of over 3 percent have been achieved using only 100 volts per micron of film thickness. Electrodes made of thin aluminum or conductive polymer solution were deposited on the film to activate the polymer chains. The electroded film layers were then wound to form a 2 mm diameter by 3 cm long hollow tubular actuator. When applying voltage in the radial direction of the tube, the electrodes compress the film in the cross-sectional plane while extending

in the length direction. An automated machine was developed to perform the manufacturing steps reliably. The machine's software is pre-calibrated to handle and process the few micron thick film to produce the devices. The actuators were experimentally tested for displacement and blocking force, and then integrated into a working Braille cell for usability.

7976-37, Session 9a

Combined driving and sensing circuitry for dielectric elastomer actuators in mobile applications

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Dielectric elastomer stack actuators (DESA) promise breakthrough functionality in user interfaces by enabling freely programmable surfaces with various shapes.

Besides the fundamental advantages of this technology, like comparatively low energy consumption, it is well known that these actuators can be used as sensors at the same time.

The work we present in this paper is focused on the implementation of a DEA-based tactile display into a mobile device. The generation of the driving voltage of up to 1.5 kV out of a common rechargeable battery and the implementation of the sensor functionality are the most challenging tasks.

To realize a large range of tactile experiences, both static and dynamic driving voltages are required. We present several structures combining different step up topologies to realize the driving unit. Keeping in mind typical requirements for mobile devices, like small size, low weight, high efficiency and low costs, we derive the final circuitry layout.

The sensing functionality has to be realized for different actuator elements regardless of their actual state. An additional sensing layer on top or within the actuators would cause a higher fabrication effort and additional interconnections. Therefore, we developed a high voltage compatible sensing system. The circuitry allows non-reactive sensing of active and inactive actuators as well.

Both circuits are implemented into a handheld-like device. In the full paper, a characterization of the whole system will be presented and compared to simulation results.

7976-38, Session 9b

Effects of TEOS concentration on the mechanical properties of ionic polymer metal composite

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IPMC is an electrically activated polymer (EAP) actuator, which is composed of a perfluorinated polymer membrane coated with a noble metal on both sides. Typically, the strip of the perfluorinated ionic polymer membrane bends toward the anode (in the case of cation exchange membranes) under the influence of an electric potential. And it has been widely applied to the artificial muscles, soft robotic actuators and dynamic sensors since it has great advantages such as large deformation, low noise, light weight, flexibility and low driving voltage. However, IPMC has the major drawback of a low generative blocking force. This paper reports a new method to prepare organic-inorganic hybrid Nafion/SiO₂ membranes by adding different contents (0 wt.%, 0.5 wt.%, 1 wt.%, 1.5 wt.%) of tetraethyl orthosilicate (TEOS) into the perfluorosulfonate acid ionomer, which are applied to fabricate ionic polymer metal composites (IPMCs). In the fabrication procedure, the TEOS was hydrolyzed and polymerized in situ with sol-gel reaction, and silicon oxide were formed, co-crystallizing with the perfluorosulfonate

acid ionomer. The elastic modulus of the casted Nafion membranes were measured with nano indenter, the water contents were also calculated, the cross sections of Nafion membranes were observed with scanning electron microscopy (SEM). The results showed that as TEOS concentration increased, the elastic modulus, the water content and the porosity increased too. The IPMCs were fabricated with the related casted Nafion membranes by electroless plating. Also, the blocking force, the displacement and the electric current of IPMCs were measured on the test apparatus. The results showed that with the gradually increased TEOS concentration the blocking force increased, both the displacement and the electric current firstly decreased, then increased. When TEOS concentration was about 1.5 wt.%, IPMC showed the best improved performance.

7976-39, Session 9b

Frequency response of IPMC actuator with palladium electrode

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After obtaining a way to fabricate IPMC actuator with palladium electrodes, the deformation behavior of IPMC actuator is evaluated under various solvents, various temperatures, and various frequencies of input voltages. IPMC actuator with palladium electrodes is fabricated by using the non-electrolytic plating method. The total time for obtaining IPMC actuator with palladium electrodes is 60~70 minutes, which is much shorter than the time for fabricating conventional IPMC actuator with gold or platinum electrodes. The surface resistivity of palladium electrodes is $2.88 \pm 0.18 \Omega/\text{sq.}$, which provides enough conductive properties. From FE-SEM observation, palladium plates are evenly coated, and its thickness is about 10 micro-meter. When IPMC actuator with palladium electrodes is subjected to voltage of 3.0 V, the ratio of the tip displacement to the IPMC length is 0.29, which is larger bending than Pt-plated IPMC actuator, whose ratio is 0.16. In the experiment of effect of cation on deformation behavior, it is found that as the increase of the ionic radius the bending response of IPMC actuator becomes predominant. This is because the bigger ion can cause large bias of volume between two sides. When the electric field across its cross section is unloaded, IPMC actuator shows a large back relaxation under high temperature because of the high diffusion coefficient for water molecules and cations. In the experiment of the frequency response of the input voltage, IPMC actuator shows a good response to various frequencies from 0.1 to 6.0 Hz in which the resonant peak is observed at 5.5 Hz.

7976-40, Session 9b

Millimeter thick ionic polymer membrane-based IPMCs with bimetallic Pd-Pt electrodes

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Ionic polymer metal composites (IPMC) are a low-voltage driven Electroactive Polymers (EAP) that can be used as actuators or sensors. This paper presents a comparative study of millimeter thick ionic polymer membrane-based IPMCs with high-performance Pd-Pt electrodes and conventional Pt electrodes. IPMCs assembled with different electrodes are characterized in terms of electromechanical, -chemical and mechanoelectrical properties. The SEM and energy dispersive X-ray (EDS) analysis are used to investigate the electrode surface morphology and cross-section of IPMCs. The study shows that IPMCs assembled with millimeter thick ionic polymer membranes and bimetallic Pd-Pt electrodes are superior in mechanoelectrical sensing and, also, show considerably higher blocking forces compared to the conventional type of IPMCs. Blocking forces more than 30 grams are measured under 4V DC. However, the strain rate is much less than conventional IPMCs.

7976-41, Session 10a

Opportunities for micro-steerable catheters and tactile feedback technology with high performance electrostrictive EAPs

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Polyvinylidene fluoride (PVDF) based electrostrictive electroactive polymers (EAPs) provide many advanced features such as large strain, high elastic modulus and fast response for high performance actuator applications. Recently, polymer blends of poly(vinylidene-trifluoroethylene-chlorofluoroethylene) (P(VDF-TrFE-CFE)) terpolymers and other polymers have been developed, exhibiting both an elastic modulus of 700 MPa and electromechanical strain of 2.5% under an electric field of 100 V/ μm , and hence large elastic energy density. These EAPs are of great promise in many applications requiring compact size and flexible structure actuators, while maintaining large mechanical energy output. To reduce operation voltage, ultrathin films with thickness down to 3 μm have been developed. Multilayer thin film structures have been fabricated for increased force output. With these developments, several commercial applications are able to be unlocked, including micro-steerable catheters and tactile feedback systems. Steerable catheters, with large bending angles, fast response and reasonable lifetime are demonstrated. In addition, fabrication capabilities are presented for catheters with variable dimensions. Tactile feedback or haptic applications are demonstrated through EAP material impulse responses which are congruent with human sensitivities. Specifically, a single degree of freedom mass spring system excited by an EAP actuator with an impulse is shown to generate a similar profile of force feedback with one caused by human interaction with normal keypad buttons. The test capabilities are also presented which are specially designed to characterize the dynamic response and reliability of active EAP actuators and devices.

7976-42, Session 10a

Haptic device development based on electrostatic force of cellulose electro active paper

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Haptic is one of well-considered device which is suitable for demanding virtual reality applications such as medical equipment, mobile devices, the online marketing and so on. Nowadays, many of concepts for haptic device have been suggested to meet the demand of industries.

Cellulose has received much attention as an emerging smart material, named as electro-active paper (EAPap), which has varieties of actuation mechanism consisting of piezoelectricity, ion migration, electrets characteristic and electrostatic force. EAPap has too attractive characteristics as mobile haptic devices, for instance, low actuation power, suitability for thin devices, and transparency. With various advantages, 3-Dimensional micro structure based electrostatic force of cellulose is fabricated by using MEMS process. In this paper, we suggest a new concept of haptic actuator with the use of cellulose EAPap. Its performance is evaluated depending on various actuation conditions. As a result, cellulose electrostatic force actuator shows a large output displacement and fast response, which is suitable for the frequency range of haptic devices.

7976-43, Session 10a

Opportunities of hydrostatically coupled dielectric elastomer actuators for haptic interfaces

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As a means to improve versatility and safety of dielectric elastomer actuators (DEAs) for several fields of application, so-called 'hydrostatically coupled' DEAs (HC-DEAs) have recently been described. HC-DEAs are based on an incompressible fluid that mechanically couples a DE-based active part to a passive part interfaced to the load, so as to enable hydrostatic transmission. This paper presents ongoing developments of HC-DEAs and potential applications in the field of haptics. Three specific examples are considered. The first deals with a wearable tactile display used to provide users with tactile feedback during electronic navigation in virtual environments. The display consists of HC-DEAs arranged in contact with finger tips. As a second example, an up-scaled prototype version of an 8-dots refreshable cell for dynamic Braille displays is shown. Each Braille dot consists of a miniature HC-DEA, with a diameter lower than 2 mm. The third example refers to a device for finger rehabilitation, conceived to work as a sort of active version of a rehabilitation squeezing ball. The device is designed to dynamically change its compliance according to an electric control. The three examples of applications intend to show the potential of the new technology and the prospective opportunities for haptic interfaces.

7976-44, Session 10b

Multi-component single-substrate conducting polymer actuation systems and fabrication techniques

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Conducting polymer materials can act as actuation elements, length sensors, force sensors, energy storage elements, and electrical components. Combining the various functionalities of conducting polymers to create single-substrate, integrated systems remains a challenge, as chemical barriers, adhesion techniques, and the possibility of scaling need to be taken into consideration. Here fabrication techniques for combining multiple conducting polymer components by means of electrically insulated, mechanical attachments are developed. Electrochemically synthesized polypyrrole substrates were coated with thin films of polystyrene, parylene, and polyimide. The isotonic actuation performance of each coated film was evaluated in comparison to non-coated films, with an observed decrease in peak-to-peak maximum strain output near 95% (polystyrene and Parylene), 80% (vacuum, 0.8 Pa), 50% (curing at 110°C) and 25% (localized polyimide deposition). The chemical barrier properties of each manufacturing technique were evaluated by exposing the coated polypyrrole substrates to an oxidative chemical vapor deposition of Poly(3,4-ethylenedioxythiophene) (PEDOT). Vapor-deposited PEDOT made the insulation layers of polystyrene and parylene conductive at thicknesses up to four microns. Spin-coated films of polyimide, greater than ten microns thick, maintained electrical insulation properties after PEDOT depositions. Conducting polymer film-to-film attachments using each manufacturing technique were attempted, with polyimide working successfully when employed under a specific deposition, drying, and curing protocol, as discussed. Three dimensional conducting polymer actuation systems, composed of actuators, length sensors, and energy storage devices were constructed on flexible, single substrates and were operated simultaneously. These results build a foundation upon which scalable, self-powered, polymer actuation systems can be developed.

7976-45, Session 10b

TiO₂-doped ionic polymer-metal composite

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This study is mainly focused on the characterization of optical, thermal, mechanical, and electrochemical properties of TiO₂-doped ionic polymer membranes and IPMCs prepared by a sol-gel method which chemically achieves uniform distribution of the particles inside the polymer membrane. X-Ray and UV-Visible spectra of the fabricated membranes indicate the presence of anatase-TiO₂ in the modified membrane. Water uptake of TiO₂-doped membrane with 0.16 wt% of doping level shows the highest value among the samples. The glass transition temperature measured using Differential Scanning Calorimetry (DSC) increases with the increase of TiO₂ amount in the membrane. Dynamic Mechanical Analysis (DMA) results tells that storage modulus of dried TiO₂-doped samples increase as the amount of TiO₂ in the membrane increases, whereas storage modulus of hydrated samples are strongly related to the level of water uptake.

7976-46, Session 10b

Ionic actuators derived from selectively solvated block copolymers

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Nanostructured organic materials derived from microphase-separated block copolymers swollen by selective solvents have been previously reported as electronic electroactive polymers (EAPs), more specifically, as dielectric elastomers. The design paradigm used to generate these elastomers can be extended to produce actuators that belong to another class of EAPs that actuate due to a completely different mechanism: ionic EAPs. We demonstrate for the first time that a commercial multiblock copolymer possessing a unique molecular architecture and composed of an ionic block can be selectively swollen by a polar solvent, thereby generating a networked system that then can be used to fabricate bending actuators collectively known as ionic polymer metal composites (IPMCs). These IPMCs consist of a copolymer film with Pt/Ag electrodes plated on the two opposing surfaces. The assembly is swollen by a solvent, such as glycerol or water, which contains mobile cations. When an electrical potential is applied across the assembly, the cations and associated solvent molecules migrate to the negative electrode, thus swelling the cathode region and deswelling the anode region of the film. The resultant stresses bend the film towards the anode. This bending motion can be used to perform work. Nafion® has been the conventional material of choice for IPMCs, but suffers from problems due to limited solvent uptake and back-relaxation during actuation. These problems significantly hamper IPMC performance. Our results demonstrate that our block copolymer-based IPMCs overcome some of these issues and illustrate that block copolymers are versatile materials in the design of EAPs beyond dielectric elastomers.

7976-47, Session 10b

Multi-segment IPMC sensor-actuators

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Segmentation of ionic polymer metal composite (IPMC) surface electrodes is fundamental to their use in any application involving more than simple constant radius bending. By appropriate segmentation almost any arbitrary flexural shape can be approximated by a piecewise-curved actuator. Additionally, simultaneous sensing and actuation can be achieved by dedicating separate regions to each activity. This paper presents a multi-segment IPMC sensor-actuator fabricated by the segmentation of gold surface electrodes using a novel method based on micro electro-discharge machining (MEDM). MEDM removes

metallic electrode material through a process of spark-gap plasma generation. Previously the segmentation of IPMCs has been achieved using a number of methods including laser ablation, machining and manual scraping. These each have their own disadvantages including cost, availability, safety issues and poor performance. In contrast to these methods MEDM is extremely cheap, simple, safe and accurate. Due to the self-limiting nature of the method MEDM is even suitable for hand-held use. This paper presents the fabrication and analysis of a multi-segment sensor actuator using MEDM. The multi-segment actuator can flex and deform in a manner similar to a biological cilia, achieving asymmetrical motion, and is suitable for many robotic and fluid control applications.

7976-48, Session 10b

Development of high-performance electro-active polymer actuators via optimization of conductor network composite layer using self-assembled nanoparticles

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The performance of ionic electroactive-polymer (IEAP) actuators is determined by the mobility of the ions and complex nanoscale interactions between ions and membranes. The number density, charge and size of ions as well as the permeability of the membranes dominate the mobility of ions within and through the ionic device. Thus, choosing ions with proper characteristics along with development of an optimally porous and permeable membrane, capable of up-take of more ions, is necessary for construction of a high-performance IEAP actuator. In this work, we present design and fabrication of IEAP actuators, optimized via alterations to their conductive network composite (CNC) layer. Significant improvements in the actuation-curvature and strain were obtained via embedment of gold nanoparticles (AuNPs) in the CNC layer and modulation of the thickness of CNC. We have studied samples consisting of different thickness CNC layers and have verified that actuators with thicker CNCs exhibit larger actuation curvature. Thicker CNCs are capable of up-taking more electrolyte; thus upon application of voltage more ions are accumulated at the electrodes, which results in larger bending. Fast IEAP actuators were also constructed by altering the volume fraction of AuNPs in CNC layer. Samples with lower AuNP volume fraction tend to respond faster to polarity changes as the pore size in CNC layer is larger compared to more packed structures, such that the mobility of ions is eased. We have verified that control over the properties of the CNC can lead to construction of actuators optimized for specific applications.

7976-49, Session 11a

Actuators, biomedicine, and cellbiology

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Conducting polymers such as polypyrrole are well known for their volume changing capacity and their use as actuating material. Actuators based on polypyrrole have been demonstrated in dimensions ranging from centimetres down to micrometres as well as in linear strain and bending beam actuation modes. The polypyrrole (micro-)actuators can be operated in salt solutions including cell culture media and blood. In addition, polypyrrole is known to be biocompatible making them a good choice for applications within cell biology and medicine.

Applications of polypyrrole actuators within micromechanical devices, such as microrobotics and valves, will be presented. Opportunities and devices for the medical device industry, especially vascular surgery will be shown. This includes a rotating PCTA balloon system and an implantable drug delivery system. In addition, novel mechanostimulation chips for cell biology will be introduced. Using these devices, we

can stretch cells and show the cellular response to this mechanical stimulation. Since the dawn of eukaryotic cells many parallel molecular mechanisms that respond to mechanical stimuli have evolved. This technology allows us to begin the investigation of these mechanisms on a single cell level.

7976-50, Session 11a

Accurate freeform surface actuation using a non-pre-stretched silicone dielectric polymer actuator

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Dielectric polymer actuators promise to revolutionize user interfaces by enabling surface actuators that can change surface shape and give tactile feedback from a thin layer. A key challenge in realizing a surface actuator for tactile applications is finding the right balance between force and deformation performance, and realizing 'free-form' actuation.

Several actuator architectures have been suggested in literature using either multiple stacked actuator layers or thickness enhancement layers, realizing different tradeoffs between force and deformation, and different freedoms in actuation shape.

We have realized a hybrid bend/stretch programmable surface actuator architecture, based on non-pre-stretched silicone, that is capable of realizing large free-form surface deformations from relatively thin layers, while maintaining very good control over the shape of the actuated surface. Moreover, the actuator setup allows the use of a thin, stiff top layer, which addresses friction and stickiness problems commonly associated with using soft elastomers in tactile displays. Depending on the exact implementation, out-of-plane deformations exceeding 300 microns are possible from a total layer thickness of 1 mm, facilitating 'tactile exploration' of the actuated shapes.

In the paper, we will present the actuator architecture and some implementations. We will also report on the surface shape that is generated, and discuss the advantages and disadvantages of using this actuator setup for tactile display or switchable logo applications. Moreover, we will compare the experimental results to finite element simulations.

7976-51, Session 11a

A comparison of dielectric materials for the activation of a macro-scale hinge configuration

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While much of the research on dielectric elastomer actuators used to concentrate on VHB 4910 as dielectric material, lately many new, specifically developed materials have come into focus. The acrylic VHB has been thoroughly characterized in a macro-scale agonist-antagonist configuration on an active hinge. This was carried out with the aim of using it on an airship, which was activated, undulating body and a fin and thus propelled in a fish-like manner. The concept was proved in flight, but still lifetime and viscosity of the actuators and the time-costing fabrication due to the necessary large pre-stretches of the dielectric membrane caused severe inconveniences. In order to evaluate the usability of other materials for this specific purpose, several other materials, e.g. PolyPower DEAP film and the acrylic with interpenetrating network (IPN) developed at the UCLA, were characterized under the exact same conditions. The influence of the material on performance and design of the actuators and the conclusions for the use of the materials on the airship (and on applications with similar performance requirements) are presented.

7976-52, Session 11a

Control concepts for dielectric elastomer actuators

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When using smart actuators as actuating elements in various applications or even as a replacement of common electromechanical actuators, an appropriate power electronics and a well designed force control are necessary in order to utilize proven control concepts for the superimposed motion control. Having a commonly used force interface for Dielectric Elastomer Actuators (DEA), different control tasks like a velocity or position control and applications like vibration damping and impedance control can be realized easily.

To drive the DEAs at high voltages and typically low currents, specially designed power converters are required. For a high efficiency and bandwidth of the power electronics, allowing a bidirectional energy flow, special topologies have to be selected, which can be controlled with approaches ensuring a smooth voltage adjustment or minimized electromagnetism interferences.

Based on this, the force control for DEAs can be designed without the necessity of additional force sensors. Therefore two measures have to be implemented. On the one hand the nonlinear relation between voltage and Maxwell stress has to be linearized, while the mechanical hysteresis has to be measured, modeled and compensated on the other hand. The resulting linearized open-loop force control of the DEA represents a common force interface on which superimposed motion controls like velocity, position, vibration or impedance controls can be implemented, e.g. for applications in human robotics. Potential applications of such control concepts will be presented in the final paper and demonstrated by measurements.

7976-53, Session 11a

Dielectric elastomers for active vibration control applications

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Dielectric elastomers (DE) have proved to have high potential for smart actuator applications in many laboratory setups and also in first commercially produced components. Because of their large deformation ability and the inherent fast response to external stimulation they proffer themselves to applications in the field of active vibration control, especially for light-weight structures. Typically such structures tend to vibrate with large amplitudes even at low excitation forces. Here, DE actuators seem to be ideal components for setting up control loops to suppress unwanted vibrations.

Due to the underlying physical effect DE actuators are generally nonlinear elements with an approximately quadratic relationship between in- and output. Consequently, they automatically produce higher-order frequencies. This can cause harmful effects for vibration control on structures with high modal density. Therefore, a linearization technique is required to minimize parasitic effects.

This paper shows and quantifies the nonlinearity of a commercial DE actuator and demonstrates the negative effects it can have in technical applications. For this purpose, two linearization methods are developed. Subsequently, the actuator is used to implement active vibration control for two different mechanical systems. In the first case a concentrated mass is driven with the controlled actuator resulting in a tunable oscillator. In the second case a more complex mechanical structure with multiple resonances is used. Different control approaches are applied likewise and their impact on the whole system is demonstrated. Thus, the potential of DE actuators for vibration control applications is highlighted.

7976-54, Session 11a

Physical model-based internal model control of a DE actuator

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The Internal Model Control (IMC) philosophy relies on the Internal Model Principle, which states that 'control can be achieved only if the control system encapsulates, either implicitly or explicitly, some representation of the process to be controlled'. If the IMC is developed based on an exact model of the process, then perfect control is theoretically possible.

This contribution investigates the use of IMC for both disturbance rejection and servo control of a dielectric elastomer actuator. IMC is fairly popular among process control practitioners because in the face of model mismatch there is a robustness related term that can be designed to take this mismatch into account.

An accurate physical-based electromechanical model of a commercially available tubular dielectric elastomer actuator has been developed. This model has been validated for a range of different periodic input voltage signals as well as for different loading conditions. Both the full nonlinear electromechanical model as well as a linearized inverse of the electromechanical model will be used in the IMC control scheme. Both simulation studies and experimental studies will be carried out to examine the servo performance of the physical model-based IMC scheme in the face of changing loading conditions on the DE actuator. The sensitivity of the controlled positioning performance to errors in a number of the electromechanical model parameters, as well as different choices of the robustness parameter will also be examined.

7976-56, Session 11a

Polypyrrol/chitosan hydrogel hybrid micro fiber as sensing artificial muscle

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An electrochemical actuator demands that it should act as a sensor of the working conditions for its efficient application in devices. Sensing characteristics of a biopolymer/conducting polymer hybrid microfiber artificial muscle fabricated through wet spinning of a chitosan solution followed by in situ chemical polymerisation with pyrrol employing bis(trifluoro methane sulfonyl) imide, (TFMSI) as dopant and ferric chloride as a catalyst is presented. The polypyrrol/chitosan hybrid microfiber was investigated by FTIR, Scanning Electron Microscopy (SEM), electrical conductivity measurement, cyclic voltammetric (CV) and chronopotentiometric (CP) methods. The electrochemical measurements related to the sensing abilities were performed as a function of applied current, concentration and temperature keeping two of the variables constant at a given time using NaCl as electrolyte. Cyclic voltammograms confirmed that the electro activity is imparted by polypyrrol. The fiber showed an electrical conductivity of $3.21 \times 10^{-1} \text{ Scm}^{-1}$ and an average linear electrochemical actuation strain of about 0.54%. The chronopotentiometric responses during the oxidation/reduction processes of the microfiber for the different anodic/cathodic currents and the linear fit observed for the consumed electrical energy during the reaction for various applied currents suggested that it can act as a sensor of applied current. The chronopotentiometric responses and the linear fit of consumed electrical energy at different temperatures suggested that the actuator can act as a temperature sensor. Similarly a logarithmic dependence of the consumed electrical energy with concentration of the electrolyte during reaction is suggestive of its applicability as a concentration sensor. The demand that an electrochemical actuator to be a sensor of the working conditions, for its efficient application in devices is thus verified in this material.

Acknowledgments

Authors acknowledge financial support from Spanish Government, Project MAT2008-06702, Seneca Foundation, Project 08684/PI/08, Consejería de Educación de Murcia, Plan Regional de Ciencia y Tecnología 2007-2010 and the financial support from University of Nizwa, Sultanate of Oman through the Project P- 09-10/UoN/29/CA&S.

7976-106, Session 11a

Dielectric elastomer stack actuators for integrated gas valves

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In this paper we present the design, fabrication process and evaluation of a gas valve using dielectric elastomer stack actuators. The elastomer actuators are integrated into the micro system consisting of the valve seat and spring structure to produce the closing force for the valve.

Based on the application as gas valve for a micro burner the required flow rate and the allowed pressure drop are derived. With these requirements the design of the valve seat, actuator and spring can be defined. This includes dimensions and shape of the valve seat with the outlet and channels for the gas flow. One valve in an array has the size of 15 x 15 mm². The actuator thickness and the shape of its active region are determined to achieve a deflection of up to 50 μm by the use of a finite element simulation. To generate the closing force a spring structure made of nickel with intrinsic layer stresses is fabricated using an electroplating process.

For the fabrication of the whole gas valve two different processes are evaluated: A Top-Down process and a Bottom-Up process. In both variants the dielectric elastomer actuator is directly fabricated either onto a sacrificial substrate containing the spring structure or onto a carrier substrate with the valve seat.

The fabricated valves are characterized with respect to the simulation results of the thickness change of the actuator. Furthermore, the pressure drop of the valve for different flow rates is measured. The results will be present in the full paper.

7976-57, Session 11b

Electromechanical instability and nonlinear dynamics of dielectric elastomers

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As a robust, high performance, cost effective solution in medical devices, space robotics, etc, soft active materials (such as dielectric elastomers and polymeric gels) have received much attention recently due to their large deformation under mechanical or electrical stimulation. Here we will focus on electromechanical instability and nonlinear dynamics of dielectric elastomers.

Electromechanical instability is understood as follows. As the voltage increases, the elastomer thins down, so that the same voltage will induce an even higher electric field. Depending upon the nonlinear hyperelastic properties of the material, this positive feedback may cause the elastomer to thin down drastically, resulting in electrical breakdown. For the dielectric elastomers with homogeneous deformation, electromechanical instability occurs when the determinant of the Hessian vanishes. For the dielectric elastomers with inhomogeneous deformation, electromechanical instability occurs when the fundamental natural frequency vanishes.

Much of the existing literature on dielectric elastomers has focused on quasi-static deformation. However, in some of the potential applications, the elastomer deforms at high frequencies and undergoes nonlinear

oscillation. We use finite element method to analyze dynamic behavior of a dielectric elastomer subject to a combination of pressure and voltage. When the pressure and voltage are static, the elastomer may reach a state of equilibrium. When the voltage is sinusoidal, the elastomer resonates at multiple frequencies of excitation, giving rise to superharmonic, harmonic, and subharmonic responses. We will illustrate nonlinear dynamics of dielectric elastomers with several examples.

7976-58, Session 11b

Constitutive relation and electromechanical stability of compressible dielectric elastomer

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The constitutive relation and electromechanical stability of Varga-Blatz-Ko-type compressible isotropic dielectric elastomer is investigated in this paper. Free-energy in any form, which consists of elastic strain energy and electric energy, can be applied to analyse the electromechanical stability of dielectric elastomer. The constitutive relation and stability is analyzed by applying a new kind of free energy model, which couples elastic strain energy, composed of Varga model as the volume conservative energy and Blatz-Ko model as the volume non-conservative energy, and electric field energy with constant permittivity. The ratio between principal planar stretches (λ_1, λ_2), the ratio between thickness direction stretch and length direction stretch (λ_3), and power exponent of the stretch are defined to characterize the mechanical loading process and compressible behavior of dielectric elastomer. Along with the increase of material parameters ν , μ , and poison ratio ν , the nominal electric field peak is higher. This indicates that the dielectric elastomer electromechanical system is more stable. Inversely, with the increase of the material parameter ν , the nominal electric field peak, critical area strain and the critical thickness strain increase, coupling system is more stable. When ν , the critical nominal electric field of compressible dielectric elastomer electromechanical coupling system is E_c , where is the critical nominal electric field taking the nominal stress in the second direction, and when ν , we have E_c .

7976-59, Session 11b

Chemo-electro-mechanical modeling of pH-sensitive hydrogels

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Hydrogels are viscoelastic active materials. They consist of a polymer network with bound charges and a liquid phase with mobile anions and cations. In water based solutions these gels show enormous swelling capabilities under the influence of different possible stimulation types, such as chemical, electrical or thermal stimulation.

In the present work a coupled chemo-electro-mechanical formulation for polyelectrolyte gels using the Finite Element Method (FEM) is applied. Additionally to the three given fields, the dissociation reactions of the bound charges in the gel are considered.

So, we are able to model and simulate both pH-stimulation and change of salt concentration in the gel-surrounding solution and to give the different ion concentration, the electric potential and the mechanical displacement versus time.

Depending on the initial conditions, different kinds of stimulation cycles can be simulated which confirm the hysteretic swelling behaviour found in experiments.

Concluding, the developed model is applicable for chemical stimulation and can model both, hydrogel actuators and sensors.

7976-60, Session 11b

Charge modeling of ionic polymer-metal composites for dynamic curvature sensing

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Introduction:

Ionic Polymer - Metal Composites (IPMCs) have been extensively studied in recent years as a new class of electro active polymer sensors and actuators. Various mechanical stimulation modes such as sharp bending response of IPMC sensor for joint angular measurements in wearable sensors and prostheses applications have been studied. Here we are interested in curvature deflection of IPMC sensors in order to monitor the dynamic shape of inflatable space structures to which IPMC sensors are attached as dynamic curvature sensors. The need for a flexible sensor in these types of space structures is further underlined according to the fact that using the traditional high power optical device is not practical in these types of structures.

Goal: It has been already reported that there is a dependency of generated signal of IPMC on the rate of deformation. On the other hand there is a phase delay between the input and the output response of the IPMC sensor. The specific goal of this paper is to characterize the IPMC sensor for dynamic curvature measurement to develop a low power flexible curvature sensor. Consequently it is important to consider the linearity of output signal of sensor for calibration, the effect of deflection rate at low frequencies on linearity of output signal and finally the phase delay between the output signal and the input deformation of IPMC curvature sensor.

Method: A theoretical model for charge dynamic of IPMC sensor is presented. We use Nernst-Planck constitutive equation which relates the ion flux to diffusion and migration of ions. Using this equation with charge continuity and Poisson's equations, the partial differential equation for charge dynamics is derived which is then solved analytically to derive the harmonic response of IPMC sensor at different frequencies and bending rates. We are especially interested in ramp response of sensor to model the inflation of the inflatable space structure.

In order to calibrate the IPMC sensor we provide an experimental setup which enables us to control the curvature of a cantilevered beam to model the curvature variation of inflatable space structure. The experimental setup includes a cantilevered beam to which a Nafion based IPMC sensor strip with gold electrodes is attached, a servomotor controlled by LabView software, an AD NI-DAQ data acquisition module for measuring the output signal, a virtual amplifier and band-pass filter for further signal processing.

Results:

1- Theoretical model based on Nernst-Planck equations shows good compatibility with experimental results and provides a strong background for predicting the general characteristics of IPMC sensor such as rate dependency of output signal in response to step, harmonic and ramp inputs. Both analytical model and experimental results exhibit an increase in output signal as well as decrease in phase delay with increase in deformation rate.

2- According to the various types of conducted tests it can be concluded that the IPMC sensor maintains important characteristics of sensors including linearity, sensitivity, and repeatability for dynamic curvature sensing of inflatable structures.

7976-61, Session 11b

A validated finite element model of a fully soft artificial muscle rotary motor

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Dielectric Elastomers (DE) are a class of Electro Active Polymers (EAP) which find use in actuators, generators and sensors. The Biomimetics Laboratory has used DE technology to produce a non-metallic, light weight, low complexity, flexible rotary motor. Drawing on biomimetics,

the motor works by gripping and turning the rotor as one would do with one's own fingers. A number of variables and their interactions affect the motor's performance; these include but are not limited to: actuation waveform, electrode patterning, geometric dimensions and contact tribology between the rotor and stator.

In this paper we introduce a design tool for evaluating and enhancing our motor's performance. More specifically, a finite element model of the motor will be presented that uses the software package ABAQUS. The model enables the prediction of torque. Our study will demonstrate that the modelling approach is a time and resource efficient method for understanding the motor's performance; as compared to varying the aforementioned variables in prototyping and through physical testing. We conclude by validating the model and suggesting how it can be applied in robotic applications.

7976-62, Session 11b

Finite element implementation of a viscoelastic model for dielectric elastomers based on a continuum mechanical formulation

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Smart materials are active and multifunctional materials, which play an important part for sensor and actuator applications. These materials have the potential to transform passive structures into adaptive systems. However, a prerequisite for the design and the optimization of these materials is, that reliable models exist, which incorporate the interaction between the different combinations of thermal, electrical, magnetic, optical and mechanical effects.

Polymeric electroelastic materials, so-called electroactive polymer (EAP), own the characteristic to deform by the application of an electric field. However, the description electroactive polymer is a generic term for many kinds of different microscopic mechanisms and polymeric materials. This presentation deals with dielectric elastomers. Based on the laws of electromagnetism and elasticity, a nonlinear visco-electroelastic model is developed and implemented into the finite element method (FEM). The continuum mechanics model contains finite deformations, the time dependency and the nearly incompressible behavior of the material. To describe the possible, large time dependent deformations, a finite viscoelastic model with a split of the deformation gradient is used. Thereby the time dependent characteristic of polymeric materials is incorporated through the free energy function. Within the finite element method problems can occur by incompressible material. In order to overcome the described problems a mixed finite element method formulation is introduced. The electromechanical interactions are considered by the electrostatic forces and inside the energy function.

The presentation outlines the theoretical foundation and the consistent finite element implementation. Numerical examples illustrate the presented formulation.

7976-63, Session 11b

Modeling and designing IPMCs for twisting transduction

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The current paper presents the study of IPMCs for twisting transduction. To accomplish the twisting electromechanical transduction of the IPMC, patterned electrodes were used. Here we present a three dimensional finite element (FE) model based on the fundamental physical principles. The model was used to design the patterns on the IPMCs to achieve the desired twisting actuation. The modeling results are compared to the experimentally measured data. Furthermore, we present a novel hp-FE

modeling approach for modeling the IPMC actuation. The advantages of the hp-FEM model are the controlled calculation accuracy and reduced problem size, based on the irregular multi-meshes and adaptive mesh refinements. In the second part of the paper, the mechano-electrical twisting transduction study of the IPMCs is introduced. A voltage signal is measured on the different sections of the patterned IPMC while the bending or twisting of the material is applied. A 3D FE model, again based on the fundamental physical principles, was developed to estimate the generated signal.

7976-64, Session 12a

Flexi-drive: a soft artificial muscle motor

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Devices, such as electric motors, are predominately composed of hard and stiff materials. But many natural mechanisms are relatively soft. A control knob on a stereo system is turned by moving our 'soft' finger relative to our thumb. Motion is imparted without sliding and in a precise manner. In this paper we demonstrate how an artificial muscle motor, the "Flexi-drive" can mimic this action. This is achieved by embedding a soft gear within the membrane. Deformation of the membrane results in deformation of the gear and this can be used for turning a shaft.

Soft motors were fabricated from pre-stretched 3M VHB4905 membranes. Each membrane had polymer acrylic soft gears inserted at the center. Sectors of each membrane (60° sector) were painted on both sides with conducting carbon grease leaving gaps between adjoining sectors to avoid arcing between them. The motors were supported in rigid acrylic frames aligned concentrically. A shaft was inserted through both gears. The segments were charged using a controlled sequence so that the soft gears formed a rotating ellipse.

A rich set of outcomes could be produced that included rotation without sliding, both forward and backward. This new development opens the door to complex multi-degree-of-freedom artificial muscle machines molded as a single part.

7976-65, Session 12a

In-plane DEAP stack actuators for optical MEMS applications

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Recently, stacked dielectric polymer actuators have gained a lot of attention as MEMS actuators. In this paper we present a new kind of in-plane stack actuator. In contrast to its multilayer counterparts, it consists of only one active layer with inter-digitated microstructured soft electrodes which allow for a linear, radial or even asymmetric pulling motion in the working plane. The single layer design makes it compatible with standard MEMS processes like deep reactive ion etching as well as silicone casting for optical components. Nevertheless, the wafer level fabrication process does not require any photolithography or cleanroom processes. The actuator consists of a microstructured layer of carbon nanotube filled PDMS which is suspended over a KOH etched trench on a (111) silicon wafer. The conductive PDMS electrodes are structured by laser ablation and subsequently embedded in a dielectric. The use of a (111) silicon wafer enables a maskless definition of the trench as the (111) layer is almost not attacked by the KOH etchant. The trench is defined by laser induced damage of the silicon wafer, so only exposed areas are etched. This allows for a true rapid prototyping of actuators with a fabrication time of less than one day.

The fabricated devices are capable to perform almost arbitrary in-plane motion depending of the chosen shape of the electrodes. We demonstrate and qualify different pulling scenarios through diverse electrode designs and their potential of application in Optical MEMS through integration of an adaptive fresnel zone plate.

7976-66, Session 12b

Determination of the sinking and terminating points of action unit on humanoid skull through GFEAD

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This study describes modeling and computational technique for design of robotic head prototype that can generate human-like facial expression. Current humanoid prototypes utilize either traditional servo motors or other form of bulky actuators such as air muscles to deform soft elastomeric skin that in turn creates facial expression. However, these prior methods have inherent drawbacks and do not resemble human musculature. In this paper, we report the advances made in design of humanoid head using shape memory alloy actuators. These muscle-like actuators are often in discrete form and finite in number. This brings the fundamental question about their arrangement and location of terminating and sinking points for each action unit. We address this question by developing a Graphical Facial Expression Analysis and Design (GFEAD) technique that can be used to optimize the space, analyze the deformation behavior, and determine the effect of actuator properties. GFEAD will be described through generic mathematical models and analytical geometry confining the discussion to two-dimensional planes. The implementation of the graphical method will be presented considering different cases on a prototype humanoid head.

7976-67, Session 12b

Shape memory polymer composites: multifunction and nanotechnology

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Due to many novel properties and a great number of potential, shape memory polymers (SMPs) have been one of the most popular subjects under intensive investigation in recent years. These SMPs by far surpass over their counterparts, shape memory alloys (SMAs) and shape memory ceramics (SMCs) in many profiles, e.g. easy manufacture, programming, high shape recovery ratio and low cost, and so on. In this paper, we show some progress in SMP based composites in Harbin Institute of Technology (HIT), China, from synthesis, (activation approach to engineering applications. When a variety of actuation methods (e.g., electroactive, infrared-laser activated and solution responsive) has been developed, the SMPs are simultaneously enabled with multifunctional properties. Meanwhile, as reinforcements, nanofiber and nanotube are incorporated into the SMPs material to form nanocomposites or nanopapers. The overall performances of SMPs, such as electrical, mechanical and some other properties are significantly improved. Finally, potential applications of SMP in aerospace (e.g., space deployable structures and morphing skin) are introduced to provide meaningful guidance for further development of SMPs.

7976-68, Session 12b

Mechanical modeling of thermally actuated LCE-CNT composite

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Optoactive polymer actuators and devices (OAPAD) are, undoubtedly, promising technologies. Analytical and finite element models describing dynamics of photo-induced deformation in OAPADs have already been developed, particularly for liquid crystal elastomers (LCE). Advanced materials like LCE - Carbon Nanotube (CNT) composites, require a more complex physical analysis involving different coupled phenomena like photochemistry, photophysics and chemomechanical coupling. The need for rigorous modeling of such complex physics as well as the imminent implantation and development of ground-breaking practical OAPADs like tactile tablets, demand a fast way to model the light-induced deformation of the material.

Our European Union FP7 NOMS (Nano Optical Mechanical Systems) Consortium aims at building a tactile tablet for the visually-impaired. Hence, modeling of optoactive polymer blister - Braille dot - geometries is the basis of further tactile tablet design.

The purpose of this work is to build a finite element model serving as a bridge between basic elastomer physics and device engineering and design. We take advantage of experimental actuation data to build a phenomenological model describing material deformation. The proposed model considers the LCE-CNT composite as an assembly of sub-bodies. Each sub-body behaves as an independent mechanical actuator which is characterized by an actuation vector pointing always on the actuation direction. The mechanical response is derived from previously calculated potential energy, extracted after experimental data analyses. Consequently, an opto-mechanical system based on LCE-CNT can be evaluated and the mechanical response optimized.

7976-69, Session 13a

Multilayered relaxor ferroelectric poly(vinylidene fluoride-trifluoroethylene-clorotrifluoroethylene) polymer actuators to operate a liquid-filled varifocal lens

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The poly(vinylidene fluoride-trifluoroethylene-clorotrifluoroethylene) [P(VDF-TrFE-CTFE)] is one of promising electroactive polymers (EAPs), which shows relaxor ferroelectric characteristics and thus enables a transverse strain of more than 5 % under an electric field of 150 V/ μm . However, the high driving voltage of P(VDF-TrFE-CTFE) actuators limits their wide applications in hand-held electronic devices. In order to allow P(VDF-TrFE-CTFE) actuators to operate at a low level voltage range, we developed the multilayered structure and fabrication processes for P(VDF-TrFE-CTFE) actuators. There was no method previously available to fabricate and stack P(VDF-TrFE-CTFE) films having a thickness of about 1 μm . In this study, we developed a new original film transfer method, with which the P(VDF-TrFE-CTFE) films of about 1 μm thickness are fabricated and transferred onto a silicon wafer structured with four microfluidic chambers and a circular hole working as a lens aperture via microfabrication processes. Meanwhile, aluminum electrode was deposited on top of each P(VDF-TrFE-CTFE) film. Finally, multilayered aluminum electrodes were electrically interconnected through via interconnection. We also designed and fabricated a liquid-filled varifocal lens, in which four P(VDF-TrFE-CTFE) actuators push optical fluid so that an elastomer membrane together with the internal fluid changes their

shape, which alters the light path of the varifocal lens. When only 24 V is applied to the multilayered P(VDF-TrFE-CTFE) actuators, the varifocal lens changes its focus from infinity to 10 cm. Therefore, the liquid-filled varifocal lens together with the multilayered P(VDF-TrFE-CTFE) actuators can be used to realize the auto-focus function in mobile phone cameras.

7976-70, Session 13a

Antagonistic dielectric elastomer actuator for biologically inspired robotics

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For optimal performance, actuators designed for biologically-inspired robotics applications need to be capable of mimicking the key characteristics of natural musculoskeletal systems. These characteristics include a large output stroke, high energy density, antagonistic operation and passive compliance. The actuation properties of dielectric elastomer actuators (DEAs) make them viable for use as an artificial muscle technology. However, much like the musculoskeletal system, rigid structures are needed to couple the compliant DEA layers to a load. In this paper, a cone DEA design is presented that produces an antagonistic, multi-DOF output stroke from a simple support structure, making it ideal for biologically-inspired robotics applications. The design has the advantage of overcoming two inherent issues that typically limit the performance of DEAs: (i) maintaining pre-strain through a support structure without substantially lowering the overall mass-specific power density and (ii) utilising multiple dielectric layers to maximise power output. This is achieved through a simple yet extremely versatile design which consists of just three rigid components and two DEA films (or two stacks of DEA films). The cone actuator can produce either a linear, rotational or combined multi-DOF stroke, depending on electrode segmentation and drive signal. The fabrication of prototype cone actuators using the VHB 4910 acrylic elastomer is described. The performance characteristics of single-layered and multi-layered prototypes are compared experimentally and it is demonstrated that the former can produce a rotational output stroke of over 60°.

7976-71, Session 13a

Closed loop control of dielectric elastomer actuators

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Sensing the electrical characteristics of Dielectric Elastomer Actuator(s) (DEA) whilst they are being actuated is critical to improving accuracy and reliability. Self-sensing in the prior art has focused on sensing the capacitance of the DEA and/or the resistance of the electrodes. None have demonstrated sensing of the leakage current through the membrane of the DEA, which can become significant at high electric fields. Furthermore, there are limited examples of self-sensing feedback being used to control a DEA when it is being subjected to a disturbance other than changes in the actuation signal.

We have created a new transform that is capable of measuring the Equivalent Series Resistance (ESR) of the electrodes, the Equivalent Parallel Resistance (EPR) of the dielectric membrane, and the capacitance of the DEA whilst it is being actuated. This uses Pulse Width Modulation (PWM) to simultaneously generate an actuation voltage and a periodic oscillation that enables the electrical characteristics of the DEA to be sensed. This transform has been specifically targeted towards low-power, portable devices. In this paper we experimentally validate the transform in a DEA device and use it to compare the effects of maintaining a constant voltage versus maintaining a constant charge on an active DEA as it is being acted upon by a disturbance force. We also use the self-sensing system to actively control the area of a planar DEA.

7976-72, Session 13a

Dielectric elastomer memory

B. M. O'Brien, T. G. McKay, S. Q. Xie, The Univ. of Auckland (New Zealand); E. P. Calius, Industrial Research Ltd. (New Zealand); I. A. Anderson, The Univ. of Auckland (New Zealand)

Life shows us that the distribution of intelligence throughout flexible muscular networks is a highly successful solution to a wide range of challenges. In order to recreate this success there is a need to embed sensing and intelligence into soft actuator technologies. Dielectric Elastomer Actuator(s) (DEA) are promising due to their large stresses and strains, as well as quiet, flexible, and multimodal operation. Recently dielectric elastomer devices were presented with built in sensor, driver, and logic capability enabled by a new concept called the Dielectric Elastomer Switch(es) (DES). DES use electrode piezoresistivity to control the charge on DEA and enable the distribution of intelligence throughout a DEA device.

In this paper we push the capabilities of this distributed intelligence further with the first use of DES to form volatile memory elements. A Set Reset (SR) flip flop was developed based on DES and DEA. The flip-flop behaved appropriately and demonstrated the creation of dielectric elastomer memory. Dielectric elastomer memory opens up applications such as oscillator, de-bounce, timing, and sequential logic circuits; all of which could be distributed throughout biomimetic actuator arrays.

Future work includes miniaturisation to improve response speed, implementation into more complex circuits, and investigation of longer lasting and more sensitive switching materials.

7976-73, Session 13a

Modeling approaches for a novel balloon-shape actuator made of electroactive polymers

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The focus of this paper is on the modeling of a novel balloon-shape actuator (BSA) based on electroactive polymers which has a spherical shape and it is internally pressurized and pre-strained by a compressible fluid (air in this work). Under electrical activation and as a result an induced electrostatic pressure, balloon-shape actuator can provide deformation. Due to the attraction of the opposing charges, the electrodes on the inner and outer surfaces of the BSA squeeze the elastomer in its radial thickness direction which results in a radial expansion of the BSA. This actuator has the potential to display large deformations under high compression loads. In order to determine the mechanical properties of these materials, the nonlinear behaviour of the used elastomer is predicted by fitting experimental uniaxial data. Hyperelastic models are used and the material parameters are obtained for different strain energy functions. A finite element model of the BSA is created by using ANSYS11 software, and the mechanical behaviour of it is studied and the simulation results are presented in this paper.

7976-74, Session 13b

An artificial eye actuated by IPMC actuator

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In this paper, we will report an artificial eye actuated by IPMC. It consists of body structure and control system. The entire body structure is composed of a transparent hemispherical shell, artificial eye, spring (or no spring), IPMC and a baseboard. The shell is fixed on the surface of the baseboard. The space between them is filled with water, supplying a wet

condition for IPMC. One end of IPMC is fastened by the groove of the baseboard, with sheet coppers on its both sides as electrodes. The other end of it is used for actuating the artificial eye. IPMC will bend under a low voltage. When there is no spring, the device can make the artificial eye realize one dimensional motion. And with a spring, the bionic eye can move in two dimensions. The weight of the artificial eye is about 1.2g. Based on the previous experiments, we found that sine wave and square wave have a better effect on the motion of IPMC than others. In order to facilitate the use of the device, we also design a signal generator as a control system, which can be powered by lithium battery and generate sine wave and square wave by different frequencies and voltages. In addition to this, it can display the wave style, the value of frequency and voltage. It is found that it can satisfy our desire. In the previous experiments, we have confirmed that IPMC can actuate the bionic eye effectively. In the future, we will study what influences artificial eye's motion property and optimize it.

7976-75, Session 13b

Design and development of bio-inspired underwater jellyfish-like robot using ionic polymer metal composite (IPMC) actuators

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This study presents the design and development of an underwater Jellyfish like robot using Ionic Polymer Metal Composites (IPMCs) as propulsion actuators. For this purpose, IPMCs are manufactured in several variations. First the electrode architecture is controlled to optimize the strain, strain rate, and stiffness of the actuator. Second, the incorporated diluents species are varied. The studied diluents are water, formamide, and 1-ethyl-3-methylimidazolium trifluoromethanesulfonate (Eml-Tf) ionic liquid. A water based IPMC demonstrates a fast strain rate (1%/s), but small peak strain (0.3%), and high current (200mA/cm²), as compared to an IL based IPMC which has a slow strain rate (0.1%/s), large strain (3%), and small current (50mA/cm²). The formamide is proved to be the most powerful with a strain rate of approximately 1%/s, peak strain larger than 5%, and a current of 150mA/cm². The IL and formamide based samples required encapsulation for shielding the diluents from being dissolved in the surrounding water. PDMS and silicon materials are studied for encapsulation. Three jellyfish like robots are developed each with an actuator with different diluents. Several parameters on the robot are optimized, such as the input waveform to the actuators, the shape of the belly, and the geometry of the attached fins. The shape of the belly is compared in all three robots with biological jellyfish such as the Aurelia-Aurita.

7976-76, Session 13b

Multilayered polypyrrole-gold-polyvinylidene fluoride composite actuators for increased force generation in biomimetic jellyfish robot

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Multilayered polypyrrole-gold-polyvinylidene fluoride (PPy-Au-PVDF) composite actuators were produced using multiple methods of fabrication. Single layered conducting polymer and metal composite actuators were previously found to produce force and displacement characteristics that mimic the motion of natural jellyfish medusa. Force generation has long been the lagging factor in electroactive polymers and devices. A multilayered approach has been taken to increase force generation in the actuator while retaining a fast actuation rate. This is possible since response time is highly dependent upon PPy layer thickness. PVDF membrane was produced with electrospinning techniques, which produced a nanofiber mat with micron-sized pores.

Membrane was also produced by casting knife and water bath method. Polypyrrole was electrochemically polymerized onto PVDF membrane sputter coated with gold by cyclic voltammetry method. Additionally, a chemical solution including pyrrole monomer was used to polymerize PPy onto the actuators. The multilayered design was found to increase force characteristics of the actuator while retaining displacement and actuation rate similar to single layer actuators.

7976-78, Session 13b

Cell-inspired electroactive polymer materials incorporating biomolecular materials

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A new class of electroactive polymer material is demonstrated that utilizes biomolecules as the primary component of electromechanical transduction. Two common types of electroactive polymer material are electrostrictive polymers, such as dielectric elastomers, and ionic materials such as conducting polymers and ionic polymers. It is well established that these two physical mechanisms can be utilized to create voltage-induced actuation and stimuli-responsive sensing. In this paper we demonstrate a new class of material consisting of cell-like compartments that exhibit both actuation and sensing properties due to electrostriction and ion transport. Individual cell-like compartments containing lipid vesicles and hydrogels are separated from one another by a thin layer of oil. A lipid monolayer approximately 2-3 nanometers thick self-assembles at the oil-hydrogel interface of each compartment such that a lipid bilayer on the order of 5 nanometers thick forms at the interface between two "cell" compartments. As with biological systems, the lipid bilayer serves to limit ion transport across the interface and isolate compartments from one another. Actuation is induced by the application of a small voltage (10-100 mV) across the bilayer membrane, resulting in area changes on the order of 20-30% in the interfacial bilayer. Sensing is induced by the motion of ions that occurs upon application of external physical stimuli such as a mechanical stress or a chemical gradient. The sensing behavior can be tailored through proper choice of the biomolecule that is inserted into the bilayer membrane. Experiments on a two-cell network are conducted to measure the fundamental transduction properties of the new type of material.

7976-88, Session 13b

Localization of source with unknown amplitude using IPMC sensor arrays

A. T. Abdulsadda, F. Zhang, X. Tan, Michigan State Univ. (United States)

Lateral line systems are an important sensory organ for fish that enables them to detect predators, locate preys, perform rheotaxis, and coordinate schooling. A lateral line system consists of arrays of neuromasts that effectively function as flow sensors. Creating artificial lateral line systems is of significant interest in underwater robotics, since it will provide an important sensing mechanism for control and coordination of underwater robots and their fleets.

In this paper we present, to our best knowledge, the first ionic polymer-metal composite (IPMC)-based artificial line system, and use it to localize a vibrating sphere (called a dipole source) underwater with unknown amplitude. A dipole source is frequently used in the study of biological lateral lines, as a surrogate for underwater motion sources such as a flapping fish tail. We first formulate a nonlinear estimation problem based on an analytical model that describes the dipole-generated flow velocity field, which is validated using a Digital Particle Image Velocimetry (DPIV) system. A recursive algorithm is developed to solve the nonlinear estimation problem, by solving a succession of linear least squares estimation problems, to obtain the source location and vibration

amplitude. Analysis and simulation are conducted to understand the convergence properties of the recursive algorithm.

A prototype of IPMC-based lateral line is created and used to detect the location of a custom-built dipole source. Experimental results have established the feasibility of using IPMC sensor arrays as artificial lateral lines, and validated the effectiveness of the proposed estimation algorithm.

7976-79, Session 14a

A dual axis force film sensor for robotic tactile applications

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Sensing and delivering tactile information is of interest not only in robotic researches but in most of broad sensor technology areas since along with olfactory it is one of the most difficult sensory information to detect and transfer. Most of the tactile sensors developed are using either brittle ceramic base material or bulky electro-magnetic material. Although those tactile sensors provides some advantages like a certain level of accuracy in terms of the applied force measurement and reliable fabrication methods such as MEMS, there is still a significant drawback due to its brittle material characteristics. Especially for biomimetic applications the material flexibility might be the major concern in order to achieve the application objectives. In the present work, a multi-axis force sensor using polymeric material are developed. The sensor has ability to differentiate applied force directions such as normal and tangential and it to be deployed as an massive array so that a set of tactile sensors can be easily organized. Having the material flexibility, the present work successfully demonstrates a tactile sensor array affixed on a human-hand-like robot finger tip.

7976-80, Session 14a

Dielectric elastomer tubular pump

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This paper presents a dielectric elastomer (DE) based tubular pump, where fluid displacement results from direct actuation of the tube wall as opposed to excitation by an external body.

The pump consists of a DE tube moulded from Silastic 3481 silicone, held in a negative pressure chamber which is used to prestrain the actuator. The pump is coupled with custom designed polymeric check valves in order to rectify the fluid flow and assess the performance of the unit. The valves exhibited the necessary low opening pressures required for use with the tube. The pump and valve system has achieved flowrates in excess of 40 μ l/s.

The pump's actuation characteristics were measured both with and without fluid in the system. The effects of voltage, prestrain, frequency and backpressure on the system were investigated by recording the pressure stroke and the flowrate produced by the pump. Based on this data the optimal operating conditions for the pump are discussed.

The average power consumption of the pump was also measured. The results compare favourably with published results for piezoelectric pumps, often used where low power consumption is important. The presented DE pump design therefore seems promising for low energy applications. The 'soft pump' concept is also suitable for biomimetic robotic systems, or for the medical or food industries where hard contact with the delivered substrate may be undesirable.

This radially contracting/expanding actuator element is the fundamental component of a peristaltic pump. Future work will look at connecting multiple tubes in series in order to achieve peristalsis.

7976-81, Session 14a

Interconnection concepts for rigid micro-electrodes of a dielectric elastomer bending tube actuator

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A new concept for a tube-like dielectric elastomer actuator (DEA) utilizes rigid micro-electrodes to stabilize the tube structure in azimuthal direction. The individual electrodes are stacked in axial direction within the tube wall. An axial arrangement of a number of those electrode stacks forms a single actuator filament. Application of electrical voltage induces mechanical tension into those stacks by the effect of Maxwell-stress. The interaction of individual electrodes causes a change of the total length of selected actuator filaments. A circular arrangement of a number of actuator filaments allows bending of the tube in any direction.

The desired tube actuator is focused on thin walled structures with an outer diameter less than 6 mm and an available wall thickness of less than 0.4 mm. To supply individual electrode stacks with different electric potentials an efficient electrical circuit has to be integrated within the DEA structure. The challenges for the design and fabrication of this circuit primarily lie on the micro-electrode dimensions, the minimization of electrical resistances and severe requirements regarding low mechanical interference.

As assumed condition the actuator electrodes are already stacked and each individual electrode must be accessible at the edge. Considering different surface manufacturing technologies an especially shaped conductor geometry should be deposited onto the electrode edges and the surrounding dielectric. The design of the interconnections considers electrical and mechanical requirements as well as the definition of applicable material parameters.

The present work details different concepts for interconnecting rigid electrodes of a thin walled tube-like DEA and discusses related manufacturing technologies.

7976-82, Session 14a

Considerations for contractile electroactive polymer based materials and actuators

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Ras Labs produces EAP based materials and actuators that contract. Expansion occurred with reversed polarity for selected formulations. This contraction-expansion could be cycled repeatedly. Molecular modeling explored this phenomenon, followed by experimentation with various electrolyte systems, pH effects at the electrodes, and synthetic optimizations. Electrode optimization with plasma treatment and geometries improved the metal-polymer interfaces within the actuator. Applied voltage step functions were also investigated. High voltage steps followed by low voltage steps produced larger contraction followed by smaller contraction. Actuator control by simply adjusting the electric input is extremely useful. Muscles are able to partially contract. If muscles could only completely contract, nobody could hold an egg, for example, without breaking it. A combination of high and low voltage step functions can produce gross motor function and fine manipulation within the same actuator unit.

7976-83, Session 14a

Design of a novel dielectric elastomer powered jet valve

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Binary Pneumatic Air Muscles arranged in an elastically-averaged configuration can form a cost effective solution for many MRI-guided robotic interventions like, for example, prostate cancer biopsies and brachytherapies. Such manipulators require about 10 to 20 MRI-compatible valves to control the pressure state of each air muscle. DEAs are MRI compatible actuators which are well adapted to maintain the cost-efficiency of the binary manipulation approach. This paper presents the design of a novel dielectric elastomer actuator (DEA) driven jet-valve. A 1D second order Ogden hyperelastic model is used to design a Rotary Antagonistic DEA (RA-DEA) made with acrylic polymer films. The low actuation strains enabled by the rotary configuration limit the viscoelastic impedance and thus maximize the frequency response of the actuator. The prismatic geometry also integrates the jet pipe within the DEA volume to provide a compact embodiment with low number of parts. A compressible fluid flow model is used to size the jet, spool, and fluidic channels. MRI-compatibility is experimentally validated inside a 7 Tesla MRI and shows no image degradation. The DEA measured frequency response is ~1Hz. The valve outlet maximal pressure is estimated at 800 kPa. Altogether, the experimental time response of the complete assembly is 300 ms and the total leakage by the jet pipe is ~0.1 g/sec. In all, the DEA driven jet valve has great potential for mechanical switching device such as a MRI compatible pneumatic manipulator.

7976-84, Session 14b

Biochemical microsensors on the basis of metabolically sensitive hydrogels

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With respect to diabetes management, there is a critical societal need for a sensor that can be used to continuously measure a patient's blood glucose concentration twenty four hours a day on a long-term basis. In this work, thin films of "stimuli-responsive" or "smart" hydrogels were combined with microfabricated piezoresistive pressure transducers to obtain "chemomechanical sensors" that can serve as selective and versatile wireless biomedical sensors. The sensitivity of hydrogels with regard to the concentration of such analytes as H⁺ ions (pH sensor) and glucose in solutions with physiological pH, ionic strength and temperature was investigated in vitro. The response of the glucose-sensitive hydrogel was studied at different regimes of the glucose concentration change. Sensor response time and accuracy with which a sensor can track gradual changes in glucose was estimated. The influence of analyte-polymer interactions on the sensor response time is considered at the modelling of the swelling behaviour of metabolically sensitive hydrogels. The design variants and biocompatible encapsulation of micro sensor systems are discussed concerning the long-term stability and enduring functionality that is desired for permanent implants.

7976-85, Session 14b

Cross-linking of super-growth carbon nanotubes improves linear and bimorph bucky gel actuators performance

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In 2003 Takuzo Aida and coworkers reported that single-walled carbon nanotubes (SWCNTs), when ground with imidazolium based ionic liquids (ILs), create a physical gel, named "bucky gel" [1]. This gel was used to prepare bimorph electrochemical actuators using a polymer-supported internal IL electrolyte layer [2]. These actuators can operate in air at low voltage showing improved frequency response and strain. Usual bucky gel actuators rely on a bimorph configuration where the electrodes are used alternatively as cathode and anode thus producing a bending motion. This kind of motion is limiting the possible applications, especially when, like in artificial muscles, linear strain and motion are required.

We present a novel actuator capable of both linear and bending motion that uses a three electrode configuration with two active electrodes and a third passive one, made from a metal spring, acting as counter plate. Moreover we have successfully cross-linked Super-Growth single walled carbon nanotubes and used the resulting nanostructured material for the preparation of bucky gel actuators. This cross-linking gives rise to an increase in the specific capacitance of the composite material that, when used in bucky gel actuators, results in a dramatic performance improvement in terms of strain and efficiency.

Our latest results on linear and bimorph bucky gel actuators composed of chemically modified CNTs will be given.

[1] T. Fukushima et al., Science 2003, 300, 2072

[2] T. Fukushima et al., Angew. Chem. 2005 117, 2410

7976-86, Session 14b

Bio-derived ionic transistor framework for artificial muscles

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Bioactuation and electromechanical function in conducting polymers share ion transport as the fundamental process for generating force and displacement. Inspired by the similarity in their fundamental processes, our group had reported the development of a bio-derived ionic transistor device that behaves like an actuator. This chemomechanical actuator is developed by combining the ionic function of a bio-derived membrane and conducting polymer into a single device that develops 36 μ Strain in extensional mode and 500 μ m displacement in a 15 mm long actuator in bending. This proceedings article will present the microfabrication steps to prototype a micron-scale chemomechanical actuator and experimentally characterize its actuation properties. It is proposed that this micron-scale actuator will serve as the fundamental device for actuation in millimeter scale artificial muscles. The microactuator comprises of a submicron thick bilayer lipid membrane (BLM) with a voltage-gated sodium transporter protein formed on a submicron thick polypyrrole membrane. The layer-by-layer assembly of this actuator is done on a micromachined gold foil through the following steps: (1) Electrodeposition of polypyrrole; (2) Impregnation of electrolyte; (3) Addition of gel layer; (4) Vesicle fusion and (5) Encapsulation. The thin-film obtained between the fabrication steps are characterized by atomic force microscopy and electrical impedance microscopy for a highly ordered device. The transistor function and actuation characteristics of this device will be characterized by electrical and optical measurements. The actuation characteristics of the microactuator will be applied to a theoretical design of a MEMS device that will function as an artificial muscle in a biological environment.

7976-87, Session 14b

An automatic tuning method of the largest amplitude vibration of Au-nafion IPMC

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In this paper, we investigated two driving methods for Au-Nafion IPMC. First, to induce one large spike deformation, we apply saw teeth shaped AC voltage to the IPMC. IPMC generated large spike deformation at the moment of the polarity of the application voltage was reversed quickly. Generally, the longer the applied frequency is, the larger deformation quantity is. The shape of the part that the application voltage is gradually changed is not important, the application frequency dominates the deformation quantity. The next method is an automatic tuning method of the largest amplitude vibration. We applied AC rectangular pulse wave of 50% duty ratio and the frequency of the applied voltage was controlled by the PC controller. The control program assessed the vibration of IPMC by the information of a laser distance sensor. Generally, the optimum frequency that induce the largest deformation in the air is much higher than the optimum frequency in the water. The optimum frequency is also changed by the change of the inner condition of IPMC, pH of the surroundings, and by the thickness of the Nafion, etc. The seeking algorithm of the optimum frequency is a simple slope descending method. By using this program, however, IPMC always vibrates at the frequency of the largest deformation even if we change the surroundings from water to air.

Conference 7977: Active and Passive Smart Structures and Integrated Systems V

Monday-Thursday 7-10 March 2011

Part of Proceedings of SPIE Vol. 7977 Active and Passive Smart Structures and Integrated Systems 2011

7977-01, Session 1

Electrical power generation from insect flight

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This article presents an implementation of a miniature energy harvester (weighing 0.292 grams) on an insect (hawkmoth *Manduca sexta*) in un-tethered flight. The harvester utilizes a piezoelectric transducer which converts the vibratory motion induced by the insect's flight into electrical power (generating up to 59 μ Wrms). By attaching a low-power management circuit (weighing 0.200 grams) to the energy harvester and accumulating the converted energy onboard the flying insect, we are able to visually demonstrate pulsed power delivery (averaging 126 mW) by intermittently flashing a light emitting diode. This self-recharging power system offers biologists a new means for extending the lifetime of the onboard electronics used to study small flying animals. Using this approach, the lifetime of the electronics would be limited only by the lifetime of the individuals, a vast improvement over current methods.

7977-02, Session 1

Energy harvesting from heartbeats for pacemakers

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A micro-scale vibrational energy harvester is proposed to harvest power from the vibrations induced by heart beat and eliminate the need for oversized batteries in pacemakers. Artificial pacemakers are medical devices which help regulate the beating of the heart. The electrodes connected to the pace makers send low voltage electric pulses to the heart muscle and stimulate a heartbeat. The device operates by monitoring the heartbeats and when it fails to sense a natural beat in the expected time range, stimulates the heart. The pacemakers are implanted inside the body and reducing their size means reducing the size of external object present in patient's body. Significant advances have been made over the past 50 years in design of pacemakers and they have minute power consumption. However as the device has to operate for an extensive period of time, a large battery is required. The battery takes the majority of the size of conventional pacemakers.

We incorporate the previous advances in design of MEMS energy harvesters to develop a vibrational energy harvester which is tuned to the heart beat frequency. The zigzag geometry previously proposed by the authors [1] allows reduction of the natural frequency of the harvester to about 1.5 Hz. This assures the harvester is excited about resonance and therefore produces the maximum power. We also investigate incorporation of a passive magnetic force [2] to make the structure nonlinear. The frequency bandwidth of the harvester can be significantly improved when it is nonlinear. The wider frequency range assures insensitivity of power generation to the heartbeat rate. This ensures that the pace maker is powered whether the patient is at rest or has a high cardiac activity.

We also investigate the optimal positioning of the harvester in the body. The key objectives are exposing the harvester to vibrations due to the heart beat and avoiding impeding the beating action. Since the harvester has a micro size and superlight weight the later objective is not difficult to meet. The power requirement of a typical pacemaker is less than 10 microwatts. This demand is confidently within the power generation range of the zigzag MEMS energy harvester [3]. As a result the need for surgical replacement of the pacemaker for battery replacement

is eliminated. Also the size of the device is significantly shrunk. This reduces the burden and complications of having the external object in the body.

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[2] M. A. Karami and D. J. Inman, "Nonlinear Hybrid Energy Harvesting utilizing a Piezo-magneto-elastic spring," presented at the 17th SPIE Annual International Symposium on Smart Structures and Materials & Nondestructive Evaluation and Health Monitoring, San Diego, CA, 2010.

[3] M. A. Karami and D. J. Inman, "Electromechanical Modeling of the Low Frequency MEMS Energy Harvester," presented at the IDETC, San Diego, CA, 2009.

7977-03, Session 1

A practical application of using tree movement to power a wireless sensor node

S. A. McGarry, C. G. Knight, Commonwealth Scientific and Industrial Research Organisation (Australia)

A novel energy harvester based around capturing the motion of trees has been built and tested. The device consists of an electromagnetic generator located close to ground level, attached via an inelastic cord to a point on the trunk of a 5m tall eucalyptus tree. The device uses the movement of the tree to drive the generator in one direction, rotationally, and a mass to keep the cord taught when the tree returns to its resting position. The electrical output is sent to electrical circuitry that rectifies, stores and switches the power to supply a wireless sensor node. The energy is stored in a super-capacitor, the voltage of which indicates storage charge level. Once there is sufficient power to operate the sensor node it transmits local information such as temperature, and energy state, in terms of capacitor voltage, to a base node located approximately 100m away. Results show that there is sufficient energy in this method to power a wireless sensor node continuously in wind as low as 3-4m/s. In order to allow continuous operation in lower wind speeds a number of alterations have been investigated. These are reported here and include; operation with a secondary battery in place of the storage capacitor, increasing the electrical storage capacity and varying the connection point on the tree and the electronic duty cycle.

7977-04, Session 1

Sensor seeking, wireless power transfer and management

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A system has been designed that will allow a network of sensor nodes to request power from a base node and receive the power wirelessly. The system consists of a central transmitting node which can be powered from an indefinite power source or from a reliable source of energy harvesting such as solar. This energy is converted into UHF radio waves and transmitted to individual stationary or mobile nodes making up the remainder of the network. When a sensor node detects that its on board power supply is at a critical level it will request a top up from the base station. The base station will scan through 360 degrees for the sensor node and once located begins charging. The charging station will remain in this position until the sensor batteries are fully charged. At this point the base station will seek out another sensor node if required, or go into a

standby mode. If a mobile node is moved out of the charging position or interference of the beam occurs this is indicated to the charging station and the transmitting node will scan again until another node is located. Results indicate that charging can be obtained within a radius of up to 2.5 meters. The system has the advantage that if sufficient solar energy can be captured during the day, charging of the sensor nodes can be maintained over night allowing the battery size and cost of each sensor node to be reduced significantly.

7977-05, Session 2

Active flutter control of composite plate with embedded and surface bonded piezoelectric composites

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Abstract

Aeroelastic instability such as flutter is a catastrophic structural failure, which needs to be avoided within the flight envelope of an aircraft for safety operation. Structures made of composite materials are very thin and light weight; as the result they become lightly damped systems. When the orthogonality of elastic modes in such system is influenced by the unsteady aerodynamics, the aerodynamic damping destabilizes the vibration, meaning the structural modes draw energy from the air stream. Frequency and damping change can cause coupling between two adjacent modes. In recent years, a considerable amount of efforts are made to develop active flutter suppression system (AFS), using piezoelectric materials. On set flutter monitoring is also drawing much attention as a safety warning system. Modelling, simulation and wind tunnel testing have shown promising results towards building the feasible AFS for future fixed wing aircraft.

The present paper brings a novel idea of combining two kinds of electro-mechanical couplings to build AFS strategy for composite structures. The commercially available MFC and a newly proposed shear actuated fiber composite (SAFC) are considered. MFC induces normal strains and SAFC can be made to couple the transverse shear strains [1]. A four noded plate element is employed to build the clamped-free smart laminated plate with a pair of MFC and SAFC. The stiffness, mass, actuators and sensors matrices are obtained from the electro-mechanical coupling analysis. The open loop flutter velocity is computed (49.77 m/sec) using the linear aerodynamic panel theory (DLM). Further, the structural and unsteady aerodynamic matrices are represented in state-space form to build the aero-servo-elastic plant. Here, the unsteady aerodynamics is approximated using a rational polynomial approach. A Linear Quadratic Gaussian control is designed to perform the closed loop flutter calculations. The closed loop damping of the flutter mode (torsion) is presented for different sizes of actuators. Same control voltage is applied, while evaluating the performance of MFC and SAFC. The results have significantly encouraged the concept of simultaneously targeting the normal and shear strains of aeroelastically excited mode through electro-mechanical couplings to build an efficient active flutter suppression system.

RESULTS AND DISCUSSION:

Angle Orientation Observation:

In case of MFC, normal strain coupled MFC appears to be very efficient when it is oriented at 45° i.e The MFC behaves like a torsional actuator, since the torsional mode is unstable one it controls the same. Interestingly, it is nearly twice the performance compared to MFC oriented at 0° and 30% more than MFC at 90° .

It is also noticed from the complex eigen value, the active damping effect is moderately predominant when the active fiber is oriented at 45° in comparison to the stiffness in zero degree.

On the other hand Shear strain coupled PZT actuator shows a nearly consistent performance with respect to fiber orientation.

Active Area augmentation study:

In the case of MFC actuator, When the active area is extended the actuator elastic stiffness appears to play a significant role in influencing

the open loop flutter characteristics. (Twice the increase in area has increased 4.5%).

In terms of absolute flutter velocity enhancement a very moderate improvement is noticed which shows the actuator stiffness (electromechanical stiffness) doesn't improve vastly as expected with increment in area.

Twice the active area could increase the closed loop flutter velocity only by an amount of 0.56% (4.46-5.02) increment.

Therefore, the active area must be optimized in order to have maximum performance in structural application.

In case of shear actuator it does appears to show any increment beyond certain area. It may be considered that rather than using a big actuator, distribution of actuator could improve the performance of active aeroelastic system.

7977-06, Session 2

Finite element formulation of laminated plate with flexible piezoelectric actuators and vibration control analysis

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Abstract

The use of surface bonded (MFC) and embedded piezoelectric composite actuators (SAFC) is examined through a numerical study. Modelling schemes are therefore developed by applying the isoparametric finite element approach to idealize normal strain to electric field and shear strain to electric field relations. A four noded coupled finite element is developed to compute the electro-mechanical responses of the plate. A linear quadratic regulator is employed to perform the active vibration control studies. The system matrices of the smart plate structure are obtained and used in the state-space control model. The closed loop system is built with a full state feedback controller, which assumes that all the states of a vibrating system are available. Two elastic modes are considered, namely bending and torsion of the plate. The focus is to evaluate the performance of the surface bonded MFC and the embedded SAFC flexible PZT actuators in structural control applications.

This is achieved through systematic case studies carried out as follows.

- First, the developed finite element is validated for modelling the surface bonded and embedded piezoelectric composite actuators.

- Induced deflection analysis of laminated plates is performed using SAFC

- Further, an active vibration control study is carried out on a laminated plate with MFC and SAFC actuators.

Interesting deflection patterns are observed with SAFC actuator. The angle of actuation 0 degree induces a better deflection than 45 degree. Nevertheless it is observed that 45 degree angle of actuation introduces the shear-extension coupling, which is absent in the case of 0 degree. Shear-extension coupling induces the extension strains, besides developing the transverse shear strains. Clamped free boundary condition is assumed in all the cases.

It is evident from the results that the piezoelectric composite actuators are efficiently controlling the bending and torsion modes. Nearly, same electric field is maintained to assess the actuation performances of MFC and SAFC actuators. The closed loop damping is inclusive of the assumed structural damping (open loop). For the zero angle of actuation, the SAFC actuators (patches 1, 2) have produced 5.89% and 1.48% damping for the bending and torsion modes, respectively. The MFC actuators have developed 3.51% and 1.15% for the first and second modes, respectively. MFC actuators have shown promising features in static and vibration control performances; however, the closed loop damping has demonstrated the efficiency of SAFC in the vibration control application. It is therefore envisaged to design and develop optimally actuated laminated smart structures using MFC and SAFC, which can be efficiently tailored to counteract the unsteady aerodynamic forces.

7977-07, Session 2

Two degree-of-freedom parallel mechanisms for high bandwidth vibration suppression and tracking

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The development of a new class of two degree-of-freedom (DOF) parallel mechanisms for application to unmanned ground vehicle sensor pointing and vibration suppression is presented. The mechanisms are extremely simple, decoupling the two end-effector DOFs with an easily fabricated and inexpensive connection of passive joints to fast actuators. Nearly collocated sensors and fast actuators result in an achievable bandwidth of approximately 100 Hz for each axis. A summary of the kinematic design is presented, and an analysis of singularity is provided. It is shown that this class of mechanisms are kinematically stable at all configurations in the workspace. An experimentally acquired 2x2 Nyquist array that indicates plant diagonal dominance is provided. This characteristic allows the design of independent single-input, single-output control designs for each axis. A very aggressive control approach is implemented to provide the requisite disturbance rejection in the 1-10 Hz decade. A Nyquist-stable control system is applied to both axes, providing 50 dB of feedback to 10 Hz. While the linear controller has excellent performance in the small signal condition, it is unstable when the actuators saturate. To mitigate this, nonlinear dynamic compensation is used to satisfy the condition of absolute stability in the presence of actuator saturation. Experimental evidence of the effectiveness of the controller is provided, along with evidence of stability in the large signal condition.

7977-08, Session 2

Semi-active vibration isolation using fluidic flexible matrix composite mounts: analysis and experiment

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Recently a variable stiffness adaptive structure based upon fluidic flexible matrix composites that can potentially achieve several orders of magnitude change in modulus has been proposed [1, 2] and modulus ratios as high as 56 have been measured in the laboratory [3, 4]. The fluidic flexible matrix composite (F2MC) tube consists of a flexible matrix composite tube containing a high bulk modulus internal fluid. Through proper tailoring of the fibers (orientation, number of layers, material, etc.) and selection of matrix materials, the composite tube can have an exceptionally high degree of anisotropy [5]. The fluidic flexible matrix composites achieve the large change in stiffness through simple valve control. When the valve is open, the composite tubes are very flexible since the fluid is unconstrained. However, when the valve is closed, the tube becomes stiff with an axial load since the high bulk modulus fluid resists the volume change caused from the fiber reorientation. Through analysis, Lotfi-Gaskarimakalle [6] investigated the use of a Zero Vibration state switch technique for the F2MC system and showed that an optimal ZV controller can suppress vibration in a system. Philen [7] recently demonstrated that the modulus of the material can be 'tuned' in the laboratory using force tracking control.

In many systems, vibration isolation systems can isolate sensitive equipment from vibratory loads by breaking the vibration transmission path from the source to the sensitive equipment [8]. These isolation systems can reduce the undesired vibration, and thus reduce the dynamic stress and fatigue. There are generally three types of vibration isolators: passive, semi-active, and active. Passive isolators that use elastomeric materials are simple and cost effective. For systems with strict vibration limits, semi-active [9, 10], and active vibration isolation systems [11-13] can provide increased performance across a wider

frequency range. For broadband passive vibration isolators, it is generally desired that the isolator be stiff and highly damped at low frequencies to minimize transmissibility. For the higher frequencies, a compliant but lightly damped mount is generally preferred for vibration isolation and acoustic comfort. Active vibration isolators can provide improved performance over a wider range of frequencies or for time varying frequencies, but these systems generally require high-power sources and complex configurations [9]. Semi-active isolators, such as the magnetorheological fluid-based semi-active isolators [9, 14-16], the electrohydraulic semi-active damper [17], and piezoelectric based treatments [18, 19], have proven to be highly effective in vibration isolation systems without the power supply requirements, complexities, and physical limitations of active systems.

The technical objective of this research is to investigate the F2MC variable stiffness system for semi-active vibration isolation. In the paper by Philen [20], a nonlinear analytical model of an isolation mount based on the F2MC tube with a proportional valve was developed. Analysis results indicated that the F2MC based isolation mount can be effective for reducing the transmission from a disturbance source to a mass. Simulation studies demonstrated that the resonant frequencies and the damping can be controlled via simple valve control, but no experimental results were presented.

Expanding upon the previous analysis work, this research will investigate the semi-active vibration isolation system in the laboratory using a simple testbed system. For the experiment, a carriage is mounted onto two linear bearings, which allows the carriage to translate in the horizontal direction. Various sizes of brass blocks (i.e. masses) with a slot in the middle can easily be secured to the carriage using a fastener. On each side of the carriage is a F2MC variable stiffness tube with the other end of the tube mounted to the foundation. Between the tubes under the carriage is an easy-set needle valve which provides for precision control of the valve orifice. An electrodynamic shaker is attached to the carriage via a stinger with a PCB force transducer measuring the force. In addition to an accelerometer attached to the carriage, a Polytec vibrometer will be used to measure the response of the mass for various valve positions. Experimental results will be compared to analysis and published in the final draft.

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7977-09, Session 2

Sound pressure damping using piezoelectric membranes with negative capacitance circuits

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Piezoelectric membranes have been studied for several years as a solution to damp vibration. This leads into research that is being conducted to determine if piezoelectric membranes would be a suitable solution to dampen acoustic loads in the hulls of sounding rockets. Two experiments were constructed to determine if that principal could be used to attenuate acoustics traveling through a piezoelectric membrane.

The first experiment was designed to isolate the sound that would be traveling through the membrane and adapt to different excitation frequencies. To do this a 3 by 3 inch square fiberglass pipe was used as an acoustic tube with a microphone was placed in the front and rear section of the acoustic tube on an adjustable power screw. The experimental location of the nodes and antinodes can be found and the microphone testing position can then be determined. This will ensure that actual damping is being seen and not a shift in the wavelength.

The second experiment was designed to more accurately represent the conditions that would be seen in a sounding rocket. To do this nine MFC strips were placed in a circular pattern by clamping to two UHMW fixtures shaped as regular nonagons. This was enclosed in an acrylic tube with twelve microphones used to collect data. The excitation was provided by three speakers evenly spaced around the structure.

In both experiments each strip was independently tuned using its own NCC. To do this nine NCC circuits were manufacture using APEX PA06 op amps.

7977-10, Session 3

An adaptive-passive support for the absorption of tonal waves in structures

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Flexible structures may be damaged by detrimental vibrations which, especially at higher frequencies, can be regarded as waves which propagate through the system. These waves can be suppressed by the attachment of localised supports such as dampers etc. These devices can be designed to absorb the energy of such waves but must be tuned to the frequency of the incident wave in order to perform optimally. The energy that can be absorbed depends on the physical properties (mass, stiffness and damping) of the support and those of the structure. In order to optimally reduce the propagation of waves in the event of changing operating conditions or of initial mistune, an adaptive support is proposed, so that the physical properties can be changed in real-time to maintain optimal tuning. The longer term aim of the research is to design a stand-alone adaptive support composed of the damping mechanism, sensors and a controller.

First a model of a support represented by a viscous damper on which a tonal wave is incident is developed. Two different situations are considered, with the support being placed either at the free end of a semi-infinite flexible beam or on an infinite beam. For the semi-infinite beam the optimal damping aims to minimise the reflection coefficient while for an infinite beam either the transmission coefficient has to be minimised or the total power absorbed must be maximised. Optimal values of the damping in the two cases are obtained and numerical simulations carried out. A novel adaptation algorithm for the tuning of the damper based on the minimisation of the reflection or transmission coefficient is proposed. The algorithm controlling the damping in the damper is based on a regulator controller which uses the phase information between the incident and reflected waves as the error signal.

Secondly more general supports are considered and in particular include systems involving spring/dampers and vibration absorbers (spring-mass-damper systems). These can be tuned to absorb greater amounts of power, but require adaptive stiffness as well as damping.

Next, various methods by which variable damping and/or stiffness devices can be realised are discussed. The former include electromechanical devices and those based on tunable fluids such as magneto-rheological (MR) fluids in the pre-yield state. Variable stiffness can be realised by the use of piezoelectric materials, MR devices and shape memory alloys, for example. Different control laws are discussed and cost functions based on real-time estimates of wave amplitudes are considered.

Finally, experimental results are presented for the case of a long beam intended to simulate a semi-infinite beam: the anechoic termination is approximated by placing one end of the beam in a sandbox. The adaptive damper is realised by an electromagnetic damper. This involves a coil, across which a variable resistance is connected, moving inside a permanent magnetic field. Changing the resistance allows the system properties to adapt to maintain optimal tune when the frequency of the incident wave might vary slowly with time. Experimental results are presented and compare well with theoretical predictions.

7977-11, Session 3

Active vibration control of a stiffened panel through application of negative capacitance shunts

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Shunted piezoelectric patches form an effective control mechanism for reducing vibrations of a mechanical system. The specific shunt of a negative capacitance circuit is capable of suppressing vibration amplitude over a broadband frequency range. Most previous work has focused on control of simple test structures such as beams and plates. This work studies the performance of the negative capacitance shunt connected to piezoelectric patches attached to a stiffened aircraft panel. The placement of the piezoelectric transducers is determined using a simplified finite element model of one bay of the panel. The numerical predictions are compared to experimental results for spatial average vibration for a point force input. The amount of control for increasing patch number is also investigated. These results give a more accurate representation of the achievable performance in real world application.

7977-12, Session 3

Performance of piezoelectric-based damping techniques for structures with changing excitation frequencies

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The performance of several piezoelectric-based damping and vibration control techniques has been studied and analyzed extensively under harmonic steady state conditions, particularly near a resonance excitation condition. Less well known is their performance when subjected to an excitation whose frequency is close to a structure's resonance frequency but varies rapidly, violating the assumptions required for a harmonic analysis. Although the frequency may vary rapidly enough to actually reduce the structure's peak vibration amplitude, some damping may still be desirable, in which case a vibration reduction system must be designed to work for such a transient condition. The current research investigates the performance of several passive and semi-active damping techniques, including resistive and resistive-inductive resonant shunts, state switching, and synchronized state switching and its inductor-based and applied voltage variants. It also considers how these techniques may be altered or improved for better damping of rapidly changing excitation frequencies, focusing in particular on their application to the damping of turbomachinery bladed disks. Turbomachinery can further complicate the design of a vibration reduction system because their structural dynamics change with their rotation speed. In these changing conditions, it is especially important to understand how well a technique can reduce the blade vibrations.

7977-13, Session 3

Active control of structures with adaptive modified positive position feedback

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The modified positive position feedback controller, an active vibration control method that uses collocated piezoelectric actuator actuators and sensors, is developed using an adaptive controller. The adaptive mechanism consists of two main parts: 1) Frequency adaptation mechanism, and 2) Adaptive controller. Frequency adaptation only tracks

the frequency of vibrations using Fast Fourier Transforms. The obtained frequency is then fed to MPPF compensators and the adaptive controller. This provides a unique feature for MPPF, by extending its domain of capabilities from controlling tonal vibrations to broad band disturbances. The adaptive controller mechanism consists of a reference model that is of the same order as the MPPF system and its compensators. The adaptive law provides the additional control force that is needed for controlling frequency changes caused by broad band vibrations. The experimental results show that the frequency tracking method that is derived has worked quite well. The results also indicate that the MPPF can provide significant vibration reduction on a cantilever beam that is used throughout the experiments.

7977-14, Session 4

A study of several vortex-induced vibration techniques for piezoelectric wind energy harvesting

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This paper discusses a preliminary study on harnessing energy from piezoelectric transducers by using vortex-induced vibration phenomena. Two different configurations of these devices are investigated. The first configuration consists of bluff bodies with different shapes and a flexible piezoelectric cantilever attached to the trailing edge. The next configuration consists of a flexible vertical cantilever clamped at the base with a bluff body tip mass. Horizontal flow of the wind vibrates the flexible part in a transverse motion due to vortex shedding on the bluff body. A new design is also discussed, which combines the two previous configurations. The flexible vertical cantilever design is attached to the bluff body configuration to investigate the combined power gain. The multi-physics software package COMSOL is used to vary the design parameters to optimize the configuration and to identify the significant parameters in the design. An integrated fluid-structure interaction with piezoelectric module is used in a global optimization routine to find the maximum output power point, amplitude range, and lock-in region. Experiments are conducted with turbulent and laminar flows inside a low-speed wind tunnel where wind gusts are produced with a non-steady generator. The harvester's motion is measured with a laser vibrometer, and particle image velocimetry is used to visualize the fluid flow. The wind tunnel experiments are used to validate the COMSOL model and to estimate the losses in the system. The device is also tested in the ambient outdoors to get real-world results for power harvested in non-uniform flow conditions.

7977-15, Session 4

Use of a piezocomposite generating element in harvesting wind energy in urban regions

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Current technology uses large windmills that operate in remote regions and have complex generating mechanisms such as towers, blades, gears, speed controls, magnets, and coils. In city, wind energy that would otherwise be wasted can be reclaimed and stored for later use. In this paper, we introduce a small scale windmill that can work in urban areas. The device uses a Piezocomposite Generating Element (PCGE) to generate the electric power. The PCGE is composed of layers of carbon/epoxy, PZT ceramic, and glass/epoxy cured at an elevated temperature. In the prototype, the PCGE performs as a secondary beam element which is vibrated to produce electrical power. One end of the PCGE is attached on the frame of the device. Additionally, the fan blade rotates in the direction of the wind and hits the other end of the PCGE. When the PCGE is excited, the effects of the beam's deformation enable it to generate the electric power. The device is tested for the capabilities of

power generation and battery charging. In wind tunnel test, charge time for a 40mAh battery is approximately 2.5 hours under wind speed of 2.8 m/ s. The results presented in this paper show that the prototype can harvest energy in urban regions with minor wind movement.

7977-16, Session 4

Applicability of synchronized charge extraction technique for piezoelectric energy harvesting

L. Tang, Y. Yang, Nanyang Technological Univ. (Singapore); Y. K. Tan, S. K. Panda, National Univ. of Singapore (Singapore)

In the past few years, various circuit techniques have been proposed to improve the efficiency of piezoelectric energy harvesting, among which the synchronized charge extraction (SCE) circuit technique has been enthusiastically pursued. In literature, the SCE technique is claimed to increase the power output from a piezoelectric energy harvester (PEH) by four times based on the assumption that the vibration of the harvester is not affected by the energy harvesting process. Under such assumption, the circuit model of a PEH is usually over-simplified as an ideal current source or voltage source with the piezoelectric internal capacitance placed in parallel or in series. In this paper, the applicability of the SCE technique is further investigated by electrical simulation. First, a more accurate circuit model of a cantilevered PEH is derived, taking into account the backward electromechanical coupling effect on vibration. The derived model is then validated by experiment. Subsequently, the SCE circuit is connected with the simplified model and the accurate circuit model of the PEH for simulation. Three cases are investigated, i.e., (1) the PEH excited at resonance, (2) the PEH excited at off-resonance, and (3) the PEH with weak electromechanical coupling coefficient. The results show that the SCE technique cannot improve and even reduce the efficiency of energy harvesting for the PEH vibrating at resonance. The SCE technique is found applicable for efficiency improvement only for the PEH vibrating at off-resonance or with a weak coupling coefficient, in which cases, the simplified and accurate circuit models are approaching equivalent.

7977-17, Session 4

Piezoelectric tire based power generation

N. Makki, Univ. of Ontario Institute of Technology (Canada)

Plug-in Hybrid Electric Vehicles (PHEVs) and Extended Range Electric Vehicles (EREVs) currently mainly rely on Internal Combustion Engines (ICE) utilizing conventional fuels to recharge batteries in order to extend their range. Even though Piezo-based power generation devices have surfaced in recent years harvesting vibration energy, their output has only been sufficient to power up sensors and other such smaller devices. The permanent need for a cleaner power generation technique still remains. This paper investigates the possibility of using piezoceramics for power generation within the vehicle's wheel assembly by exploiting the rotational motion of the wheel and the continuously variable contact point between the pneumatic tire and the road. As the tire rotates, a bender attached to the tire will experience periodic deformation and relaxation generating a periodically oscillating charge, the frequency of which is a function of tire RPM. Initial tests on generic benders of circular cross section glued directly to the tire produced voltages in excess of 25V. To increase the power output, stacking of Piezo bender elements has been implemented to create patches that cover the same area as a single bender but increase the effective height. It has been shown that by covering the inner surface of the tire with Piezo benders, considerable power can be harvested and utilized either to recharge the batteries or run onboard devices.

7977-18, Session 4

Multi-source energy harvester power management

A. D. Schlichting, R. Tiwari, E. Garcia, Cornell Univ. (United States)

Much of the work on ambient energy harvesting currently focuses on tasks beyond geometric optimization and has shifted to using complex feedback control circuitry. The goals of these circuits vary, however, an important goal is still out of reach for many desired applications: to produce sufficient and sustained power for wireless sensor nodes and their associated components. While many energy harvesters can power these electronics with a constant energy source, most ambient sources for desired wireless sensor networks only provide intermittent energy. Many applications can use an energy storage device, such as a capacitor or battery, to store excess energy later use. However, again, many desirable applications of energy harvesting lack the available energy source to make these methods feasible. One method for increasing the robustness and versatility of energy harvesting systems would utilize multiple energy sources simultaneously. If more or even all of the present energy sources were harvested, the amount of constant power which could be provided to the system electronics would increase dramatically. In order to achieve this, the problem of effectively combining multiple energy harvesting sources, including a mix of AC and DC sources, needs to be thoroughly examined. A couple of existing proposals, such as a simple series or parallel configuration, have the potential to work in certain situations, but not in others. Also, the possibility of utilizing the existing microcontroller on many wireless nodes in order to actively alter the circuit to best harvest the current available energy sources should be examined as well.

7977-19, Session 4

Array of piezoelectric energy harvesters

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The interest in powering remote sensor network nodes has motivated many research efforts for developing vibration-based energy harvesters. In particular, the use of piezoelectric materials for scavenging energy from vibration sources has recently witnessed a dramatic rise for power harvesting. Among the majority of current research studies, a harvester is commonly designed as a resonant oscillator with the cantilever beam configuration. However, such a design has enjoyed limited success in delivering reasonable power output and may suffer significant loss of power whenever frequency deviates from resonance. This motivates the development of an array of piezoelectric harvesters for power boosting and bandwidth improvement. Several research attempts have been made in designing multi-tier cantilever-beam based power generators. However, their results are only valid for AC power output in spite of the ultimate need for DC output. This talk presents the analysis of an array of piezoelectric energy harvesters endowed with AC/DC interfacing circuits. Specifically, each array is analyzed according to the connection of single or multiple rectifiers. Analytic expressions of DC power output are derived in each case. The result shows that DC power output changes from power-boosting mode to wideband mode according to different magnitudes of variations of resonance in each harvester. In particular, the multiple rectifiers system exhibits more bandwidth improvement than the single rectifier system. Finally, the PSPICE simulations are carried out for validation.

7977-20, Session 4

An improved self-powered velocity control synchronized switching piezoelectric energy harvesting device

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The most important application is to combine the energy harvesting devices with wireless sensor networks (WSN). Wireless sensor networks have been highly investigated in recent years and the major problems are the battery life time which will arise higher maintained requirements and limit the application areas. A piezoelectric energy harvesting device is an alternative energy source to extend the life time of batteries and to making that WSN can transfer more data over a longer duration. Synchronized switching harvesting techniques (SSH) are very efficient techniques to improve the power but they need an external source to supply the switches. However, it is even better to design a self-powered energy harvesting device for real applications in the long run. Previously the study presented herein, a self-powered piezoelectric energy harvesting device was proposed based on velocity control synchronized switching technique (V-SSH). Three piezoelectric patches were used in this self-powered V-SSH system: the major piezoelectric patch is for harvesting power, two small piezoelectric patches are designed for velocity control and to supplying the SSH. Although, compared to the conventional self-powered system, the self-powered V-SSH technique can harvest more energy but has the drawback to use three piezoelectric patches, which is in a non-optimal condition. In this study, an improved self-powered V-SSH is proposed. The basic system design is identical to the old self-powered V-SSH technique with three patches. The main difference is when the load voltage reaches a specified level; the piezoelectric patch used for auxiliary supply is combined with the main piezoelectric patch to supply more energy to the load. When the load voltage is under the specified level, the device works with the three piezoelectric patches. When the load voltage is high enough to supply the SSH switches, the device will work with only two piezoelectric patches. This is a new driving strategy for the self-powered interfacing circuit. The theoretical model and experimental results of improved self-powered V-SSH will be discussed and examined in this study. The experimental results will show the system can harvest more energy than conventional system and self-powered V-SSH system.

7977-21, Session 5

Piezoelectric energy harvester under parquet floor

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We have developed piezoelectric energy harvesters for parquet floors consisting of several mono-axial stretched thin layers of PVDF (Polyvinylidene fluoride). The multilayer harvester was build like a roller-type capacitor.

The harvesting modules were characterized with regard to the number of PVDF-films, load weight, the geometrical dimensions and the alignment in mean walking direction.

The energy conversion is increased by rising number of PVDF-films and rising load weight.

To gain information about best geometrical dimension and alignment a test floor was constructed. For that purpose a floor in the entrance of an institute building was reconstructed to allow the assembling of harvester modules underneath a parquet floor.

A laminated velour layer was used to fasten the parquet with the ground by Velcro strips. Modules in three different sizes were arranged underneath the parquet floor.

Each harvester module in the test area was connected with a commercial available rectifier. The charge generated was stored on a capacitor.

It was possible to generate about 1.4mWs/step with a module of 400mm x 100mm and 19 PVDF layers at a weight of 70kg by a direct pressure load. Energy conversion is lowered to 2.5μWs/step underneath the parquet floor. One possible reason for lowering the energy conversion per footstep is the random footstep distribution on the test area. Measurements have shown that small sized modules (400mm x 50 mm) generate most energy if arranged lengthwise to mean walking direction (5μWs/step).

This new energy harvesting modules for floors are characterized by simple assembly, great flexibility and cheap price. These devices promise a noticeable increase in energy conversion by, optimization in geometrical design, floor construction and by increasing the number of PVDF-layers.

7977-22, Session 5

Analysis of magnetopiezoelectric energy harvesters under random excitations: an equivalent linearization approach

F. Ali, S. Adhikari, M. I. Friswell, Swansea Univ. (United Kingdom)

Energy harvesting from ambient vibration is important for remote devices (sensors) and used for structural health monitoring, medical sensors etc. They can also be used to recharge batteries or other storage devices. Most of the devices developed are either based on piezoelectric or on magnetoelastic energy harvesters. This paper will discuss issues related to combined magnetopiezoelectric harvesters, which are designed to increase the power harvested, particularly for random base excitation. Simulations based on the nonlinear system model are performed to highlight the dynamic properties of the harvester. This paper develops a linearized model for the magneto-piezoelectric energy harvesters based on stochastic linearization. The nonlinear model is given by a Duffing equation characterized by a double well potential. The stochastic moments of the nonlinear and the linearized model outputs will be matched by reducing the expectation of the error norm. The error will be represented by the deviation of the linearized stiffness part from the nonlinear stiffness. The final goal of the paper will be to provide analytical expression for the maximum harvested power based on the stable equilibrium points. Optimal harvester parameters as a function of standard deviation of the random excitations will also be reported. A comparison of harvested power will be given for the nonlinear and the linearized model.

7977-23, Session 5

Design of linear electromagnetic transducer with both axial and radial magnets for vibration energy harvesting

L. Zuo, Stony Brook Univ. (United States)

Two new configurations of linear electromagnetic transducer with both axial and radial magnets are proposed in this paper, both of which are proved to have higher energy density than the existing configurations using axial magnets only. A design example with application to energy-harvesting vehicle suspensions is given in this paper, where the linear vibration energy harvesters are designed with taking the limited installation space as well as the damping coefficient requirement into account. The finite element analysis shows that the double-layered linear electromagnetic transducer with both axial and radial magnets can harvest the most energy and have the energy density (watts/cubic meter) of five times more than the typical configuration. Different configurations electrical coils are also analyzed in order to obtain the more energy density, including two, three, and four phases, where the one with 4-phase is proved to be the most effective. A prototype is being constructed and the experimental results will be reported in the full paper.

7977-24, Session 5

Design of electromagnetic energy harvesters for large-scale structural vibration applications

J. T. Scruggs, I. L. Cassidy, Duke Univ. (United States); S. Behrens, Commonwealth Scientific and Industrial Research Organisation (Australia)

This paper reports on the design and experimental validation of transducers for energy harvesting from large-scale civil structures, for which the power levels can be above 100W, and disturbance frequencies below 1Hz. The transducer consists of a back-driven ballscrew, coupled to a permanent-magnet synchronous machine, and power harvesting is regulated via control of a four-quadrant power electronic drive. Design tradeoffs between the various subsystems (including the controller, electronics, machine, mechanical conversion, and structural system) are illustrated, and an approach to device optimization is presented. Additionally, it is shown that nonlinear dissipative behavior of the electromechanical system must be properly characterized in order to assess the viability of the technology, and also to correctly design the matched impedance to maximize harvested power. Moreover, the worth of two-way power flow capability in the electronics is explored. Theoretically, the electronic control system must be capable of two-way power flow in order to achieve optimal power generation from broadband stochastic disturbances. However, with this capability also comes an increased level of parasitic loss, necessary to control the electronics. This paper examines the inherent tradeoff between these two issues, and identifies disturbance regimes in which the advantages of two-way power flow outweigh the disadvantages.

7977-25, Session 5

Experimental implementation of a cantilevered piezoelectric energy harvester with a dynamic magnifier

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Conventional energy harvester typically consists of a cantilevered composite piezoelectric beam which has a proof mass at its free end while its fixed end is mounted on a vibrating base structure. The resulting relative motion between the proof mass and the base structure produces a mechanical strain in the piezoelectric elements which is converted into electrical power by virtue of the direct piezoelectric effect. In this paper, the harvester is provided with a dynamic magnifier consisting of a spring-mass system which is placed between the fixed end of the piezoelectric beam and the vibrating base structure. The main function of the dynamic magnifier, as the name implies, is to magnify the strain experienced by the piezoelectric elements in order to amplify the electrical power output of the harvester. With proper selection of the design parameters of the magnifier, the harvested power can be significantly enhanced and the effective bandwidth of the harvester can be improved. The theory governing the operation of this class of Cantilevered Piezoelectric Energy Harvesters with Dynamic Magnifier (CPEHDM) is developed using the finite element method. The predictions of the finite element model are validated experimentally and comparisons are presented to illustrate the merits of the CPEHDM in comparison with the conventional piezoelectric energy harvesters (CPEH).

The obtained results demonstrate the feasibility of the CPEHDM as a simple and effective means for enhancing the magnitude and spectral characteristics of CPEH.

7977-26, Session 6

Energy-harvesting from mortar tube firing impulse to supplement fire-control electronics battery

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Novel designs are presented for piezoelectric-based energy-harvesting power sources that are attached to mortar tubes to harvest energy from the firing impulse. The power sources are constructed with innovative mass-spring unit with in-series piezoelectric elements. The power sources generate electrical energy by storing mechanical potential energy in spring elements as a result of the firing impulse during the firing. The mass-spring unit of the power source will then begin to vibrate, thereby applying a cyclic force to the piezoelectric elements. The mechanical energy of vibration is thereby converted to electrical energy during each cycle of vibration. The electrical energy is then harvested over a relatively long period of time and stored in electrical energy storage elements such as capacitors.

The power sources are shown to provide a significant portion of the required electrical energy of the fire control system. The primary design parameters of the present energy harvesting power sources are the spring rate and the effective mass of the system's vibrating mass-spring units. The natural frequency of the mass-spring unit can be readily adjusted to match the firing impulse profile for optimal energy transfer to the spring elements and to achieve the desired electrical energy generation rate.

Previously developed power sources were shown to produce enough electrical energy for many gun-fired munitions applications such as artillery and mortar fuzing, e.g., on the order of 250 - 500 mJ in a packaging that is 0.75 inch diameter and 1.25 inches long. In certain fuzing applications, the developed power sources have been shown to be capable of completely eliminating the need for chemical batteries. In fuzing applications, the developed power sources have the added advantage of providing additional safety, since with such power sources the fuzing electronics are powered only after the munitions have exited the barrel and have traveled a safe distance from the weapon platform. In addition, the power source piezoelectric stacks may also be used to detect events such as firing setback and se-forward, barrel exit time and the time and level of terminal impact for fuzing purposes (U. S. Patents number 7,231,874; 7,312,557; 7,701,120; 7,762,191; 7,762,192; 7,777,396 and several pending).

The basic construction and mode of operation of the piezoelectric-based energy harvesting power sources are described in detail. The results of extensive analytical modeling, computer simulation and prototype testing are presented. Methods to design mass-spring units and package the power source together with the piezoelectric elements to protect the latter elements and minimize losses due to friction and internal damping of the spring elements are presented. The power source components are packaged to withstand high-G firing shock loading while maximizing the amount of mechanical potential energy that can be stored in their elastic elements. It is shown that electrical energy of 1-3 Joules can be readily harvested from each firing event using a relatively small power source.

The developed energy harvesting power sources can be readily be adapted for use on many weapon platforms and machinery that subject their structure or components to shock/impulsive loading during their operation.

7977-27, Session 6

Parametric design study of an aeroelastic flutter energy harvester

M. J. Bryant, E. M. Wolff, E. Garcia, Cornell Univ. (United States)

This paper will present a novel energy harvesting device for powering wireless sensors or other low power electronics by extracting energy from an ambient fluid flow. In particular, a device driven by aeroelastic flutter vibrations has been designed to extract vibratory energy from the flow and transduce these vibrations to electrical current via cyclically straining piezoelectric patches. The energy harvester consists of a cantilevered piezoelectric beam with a small plate hinged to the beam tip. Above a critical flow speed, a flutter instability occurs causing the plate to oscillate with coupled pitching and heaving vibrations. These vibrations drive the tip of the beam, straining the piezoelectric layers and generating an electric current.

An analytic model of the system has been developed to predict the response and output of the device. A system of coupled equations that describe the structural, aerodynamic, and electromechanical aspects of the system are derived and presented. The model uses unsteady aerodynamic modeling to predict the aerodynamic forces and moments acting on the structure and to account for the effects of vortices shed by the flapping wing, while a modal summation technique is used to model the flexible piezoelectric structure. This model is applied to study the effects of various system design parameters on the aeroelastic stability characteristics of the system in order to determine which parameters are best suited to tune the device to a particular energy harvesting application and fluid flow condition. Experimental wind tunnel results are included to validate the model predictions.

7977-28, Session 6

Exploration of new cymbal design in energy harvesting

C. Mo, Washington State Univ. (United States); M. Paterson, W. W. Clark, Univ. of Pittsburgh (United States)

Harvesting wasted energy and converting it into electrical energy to use as needed is an emerging technology area. In this work, a new design of a cymbal energy harvester is developed and tested to validate analytical energy generating performance. Cymbal transducers have been demonstrated to be beneficial as energy harvesters for vibrating systems under modest load and frequency. In this paper a new design is adopted using a unimorph circular piezoelectric diaphragm between the metal end caps to deal with higher loads as opposed to the thick circular piezoelectric plate in the current design. Analytical modeling of the new cymbal design to predict energy generating performance is first carried out. The analysis includes comprehensive modeling and a parametric study to provide a design primer for a specific application. Experiments are also conducted to validate analytical results.

This device could be used in numerous applications for potentially self sustaining sensors or other electronic devices. By changing the structure between the metal end caps of cymbal harvesters the new design could be extended in higher load applications.

7977-29, Session 6

Improving an energy harvesting device for railroad safety applications

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Due to hundreds of fatalities annually at unprotected railroad crossings (mostly because of collisions with passenger cars and derailments resulting from improperly maintained tracks and mechanical failures),

supplying a reliable source of electrical energy to power crossing lights and distributed sensor networks is essential.

With regard to the high cost of electrical infrastructure for railroad crossings in remote areas and the lack of reliability and robustness of solar and wind energy solutions, development of alternative energy harvesting devices is of interest.

In this paper, improvements to a mechanical energy harvesting device are presented. The device scavenges electrical energy from deflection of railroad track due to passing railcar traffic. It is mounted to and spans two rail ties and converts and magnifies the track's entire upward and downward displacement into rotational motion of a PMDC generator.

The major improvements to the new prototype include: designing an efficient mechanism to harvest power from the upward (return) railroad track displacement in addition to the downward deflection, deploying a higher speed ratio planetary gearhead to increase the input speed at the generator, utilizing an enhanced generator with greater power production capacity for the same shaft speed, and improving the way the system is anchored into the subgrade to maximize captured motion and energy harvested.

The improved prototype was built, and laboratory testing was performed to prove the functionality of the device. On-track tests were also conducted to quantify the improvements achieved through the new design. The results of these tests are presented and discussed.

7977-30, Session 6

A vibration energy harvester using a nonlinear oscillator with self-excitation capability

A. Masuda, A. Senda, Kyoto Institute of Technology (Japan)

This study concerns a vibration energy harvester of resonance-type with a nonlinear oscillator which can convert the kinetic energy of the vibration source to electric energy effectively in a wider frequency range than the conventional ones equipped with linear oscillators. The conventional linear harvesters are designed so as to generate larger power by matching the natural frequency of the oscillator to the frequency of the source vibration. The problem is, however, that if the input frequency changes even in a slight amount, the performance of the harvester can become extremely worse because the effective band width of the resonance is quite narrow. In this study, the resonance frequency band of the oscillator is expanded by using a nonlinear oscillator with a nonlinear spring to allow the harvester to generate larger electric power in larger frequency range. However, the nonlinear oscillator can have multiple stable steady-state responses in the resonance band, typically the large and small amplitude solutions depending on the initial condition. We introduce a self-excitation circuit with a variable resistance which varies from negative to positive as a function of the induced voltage in order to enable the oscillator entrained by the excitation only in the large amplitude solution. Theoretical and numerical analyses are conducted focusing on the periodic and aperiodic solutions, their domains of attraction, the generated power, etc., and their dependence on the system parameters and the control law. Furthermore, a proof-of-concept experimental device is developed and its performance is examined.

7977-31, Session 6

Characterization of an active structural fiber for embedded energy harvesting

Y. Lin, H. A. Sodano, Arizona State Univ. (United States)

Multifunctional material has received increasing interests in the past years due to the enhanced system performance and safety when using this type of material. Among all the multifunctional materials developed so far, piezoelectric composite is extensively studied due to its inherent capability in converting energy between mechanical and electrical domains. However, the piezoelectric phase is generally separated from the structural component, making the embedding and fabrication difficult. Recently, a new multifunctional composite has been developed

by embedding active structural fiber (ASF) composed of a piezoceramic shell and structural fiber core. Previous modeling and experimental results showed that the ASF reinforced multifunctional composites possessed piezoelectric coupling coefficient as high as 50% of the active constituent used. In addition, the energy density of the ASF is higher than most of the structural capacitors developed so far, allowing it ideal for energy storage. However, the energy harvesting functionality of the ASF has not been investigated. Therefore, this paper will focus on the characterization of energy harvesting property of the ASFs as an important fulfillment of the multifunctional composites developed. Different aspect ratio (ratio of piezoelectric coating thickness and outside radius of ASF) ASFs will be fabricated and experimentally tested on a shaker to determine their capability in transforming ambient vibration energy into electrical energy. The relation between energy density and ASF aspect ratio will be characterized and the best aspect ratio for energy harvesting will be determined.

7977-83, Poster Session

Active vibration control of basic hull structures using macro fiber composite

G. Yi, L. Liu, J. Leng, Harbin Institute of Technology (China)

In the modern naval battle, enhancing submarine's hidden ability is becoming more and more important, because of the anti-detection technique developing fastly. However, in view of the worse control effect at low-frequency and weak adjustability to external influence, conventional passive vibration control can't satisfy the modern naval rigorous demands. Fortunately, active vibration control technology not only monitors the structure's real-time vibration, but also has more remarkable control effect and superior suitability. At the present time, it has a primary application in the vibration damping of ship engineering. In addition, due to functional materials rapidly developing, especially, with the coming of piezoelectric composite materials, the advanced active control technique has more applicability, larger damp amplitude and wider applied field, which basing on the piezoelectric-effect and inverse-piezoelectric-effect of piezoelectric materials.

In the end of nineties, NASA had successfully manufactured the excellent macro fiber composite (MFC), which assembles actuating and sensing abilities. Comparing with the conventional piezoelectric ceramic materials, it provides the required durability, excellent flexibility, higher electromechanical coupling factors and stronger longitudinal actuating force by using interdigital electrodes. On the basis of the application of submarine structures' active vibration control by using MFC actuators, this paper, starting with the mechanical characteristics of MFC actuators and sensors, investigates finite element models, vibration-control simulation system and physical experimental test of the submarine structures equipping with MFC. The main research contents of this thesis are as follows:

Firstly, the strain and stress distribution of composite structure are analyzed basing on the simplified piezoelectric equations. Then, MFC's actuating equations working as actuators and sensing equations using as sensors are derived. Whereafter, sensing and actuating abilities are discussed in details.

Secondly, the finite element technique using the commercial package ANSYS11.0 is applied to investigate four kinds of MFC's piezoelectric characteristics. And then, the naval structures' modal analysis is used to determine the positions of MFC. Subsequently, two-dimensional optimal piezoelectric equations, including piezoelectric-actuating-moment equation, voltage equation and piezoelectric-control proportional divisor, are renewedly derived. Numerical simulation results display two composite structures' deflection curves based on vibration controlling-on and controlling-off.

Lastly, in order to validate the theoretical analysis method, the vibration control experiment of cantilever beam and honeycomb aluminous panel are built and tested with different activating force. The experimental results verify that MFC used in submarine structures' active vibration control are feasible and effective.

7977-86, Poster Session

Research on the comparison of performance-based concept and force-based concept

Z. Wu, North China Univ. of Water Conservancy and Electric Power (China); F. Wang, D. Wang, Zhengzhou Univ. (China)

The two different design method have its unique property. In the process of people realizing the seismic response, they play a radical role. So far, tall and complex structure become more, the performance-based concept replace the force-based concept step by step. In fact, for some structure, the force-based philosophy also suit their design.

7977-87, Poster Session

Research on the parameters of response spectrum about Clough-Penzien model

Z. Wu, North China Univ. of Water Conservancy and Electric Power (China); F. Wang, D. Wang, Zhengzhou Univ. (China)

As the stochastic method is used more and more, the parameters of Clough-Penzien power spectrum become important part to analyze the seismic response of structure. In 2008, Chinese government pushed out new bridge seismic code and relative parameters to be studied.

7977-88, Poster Session

The seismic response of continuous beam bridge considering the spatial and time effect

Z. Wu, North China Univ. of Water Conservancy and Electric Power (China); F. Wang, D. Wang, Zhengzhou Univ. (China)

Although continuous beam bridge is simple style comparing with other style bridge, the seismic response is not neglected. For long span structure, the spatial and time effect should be considered.

7977-89, Poster Session

The comparison of different coherence function and application

Z. Wu, Y. Li, North China Univ. of Water Conservancy and Electric Power (China); F. Wang, Zhengzhou Univ. (China)

Different coherence function is analysed, each function only suit one earthquake curve. Through number of acceleration curve analysed, a more general law is proposed.

7977-90, Poster Session

Design and modeling of a self-sufficient shape-memory-actuator

A. Bucht, T. Junker, K. Pagel, W. Drossel, R. Neugebauer, Fraunhofer-Institut für Werkzeugmaschinen und Umformtechnik (Germany)

In machine tools several time and position varying heat sources causes complex temperature distributions. The resulting problems are varying thermal deformations which cause a loss of accuracy as well as non optimal drive conditions. An option to deal with that issue is to use structure integrated SM-actuators which use the thermal energy accumulated by machining processes to yield an actuator displacement. That creates a structure inherent control loop. There the

shape-memory-elements work as sensing element as well as actuation element. The plant is defined by the thermal and mechanical behaviour of the surrounding structure. Because of the closed loop operation mode, the mechanical design has to deal with questions of stability and parameter adjustment in a control sense. In contrast to common control arrangements this issues can only be influenced by designing the actuator and the structure.

To investigate this approach a test bench has been designed. The heat is yielded by a clutch and directed through the structure to the shape memory element. The force and displacement of the actuator are therefore driven directly by process heat. This paper presents a broad mechanical design approach of the test bench as well as the design of the SM-actuator. To investigate the thermo-mechanical behaviour of the structure-integrated actuator, a model of the test bench has been developed. The model covers the thermal behaviour of the test bench as well as the thermo-mechanical couplings of the shape memory actuator. The model has been validated by comprehensive measurements.

7977-91, Poster Session

Optimal placement of piezoelectric actuators based on dynamic sensitivity analysis

F. Liu, B. Fang, W. Huang, Harbin Institute of Technology (China)

As known to all, positions of actuator play an important role in active vibration control, they affect not only the performance of vibration control but also the stability of the whole system, especially for flexible structures.

On the optimal placement of actuator, many scholars have proposed a variety of optimization criteria, such as the optimal control cost criteria, the minimum expected performance criteria, modal coordinates extraction precision criteria, etc. Although these criteria have generality, but are complex to implement, and the results obtained by using closed-loop design idea to study the optimal placement of actuator usually affected by the initial conditions, the weight matrix and different control laws; which make the problem complicated, and this couldn't improve the effects of vibration control. In fact, before the system design, the initial conditions are difficult to determine, and the placement of the actuator should not affected by the initial conditions and control laws, but should only by the inherent characteristics of the system and the external disturbances.

In this paper, for a whole-spacecraft vibration isolator using piezoelectric stack actuators, dynamic sensitivity analysis method was used to derive an optimization criteria for piezoelectric stack actuator's placement, this criteria only related to the dynamic characteristic of the structure, and not affected by initial conditions and control methods. By using above criteria, optimal placement of the piezoelectric actuator on the whole-spacecraft vibration isolator was studied; simulation results showed that the optimized location of actuator can greatly enhance the actuation efficiency and vibration control effects.

7977-93, Poster Session

Cyclic behavior of confining RC short columns with superelastic shape memory alloys wires

H. Qian, Zhengzhou Univ. (China); H. Li, Dalian Univ. of Technology (China); G. Song, Univ. of Houston (United States)

Superelastic Shape memory alloys have the ability to undergo large deformations, while reverting back to their undeformed shape by removal of load. The unique property enables their great potentials in seismic design and retrofit of structure members. The goal of this paper is to assess the cyclic behavior reinforced concrete short columns confined with superelastic SMA wires subjected to strong earthquakes. Four circular RC columns models were tested under cyclic loading. The first one was regular RC short column, while the others were wrapped with superelastic SMA wires, CFRP bars and SMA-CFRP, respectively. The

behavior of the four specimens under reversed cyclic loading, such as the maximum drifts, residual drifts and energy dissipation were compared. The results showed that the SMA-confined RC column specimen was able to recover most of its post-yield deformation and have significant increase in the ability to dissipate energy.

7977-94, Poster Session

Mechanical deformation and tensile super-elastic behaviors of a Ti-Mo based shape memory alloy

C. Xie, Shanghai Jiao Tong Univ. (China)

Ni-free shape memory alloys are promising functional materials for medical applications. A newly developed Ti-Mo based shape memory alloy shows superelasticity after thermomechanical treatment. However, the microstructure evolution and precipitation during thermomechanical processes are still not well understood. In the present paper, compressive deformation behavior at a series of temperatures of 298K - 973K and room temperature tensile deformation behavior of the alloy after aged at 573K - 973K have been investigated systematically. It is found that the compressive yield stress and ultimate compressive strength change with the deformation temperature. The ultimate tensile strength and yield stress of aged specimens also change with the aging temperature following a non-linear relationship. Effect of aging on the superelasticity behaviors of Ti-9.8Mo-3.9Nb-2V-3.1Al (wt. %) alloy has been investigated recently. The superelasticity, especially elastic recovery behavior, is closely related with the morphology of α -phase precipitates, as well as α -phase formed during aging. Lots α -phase precipitates, distributing homogeneously in specimen aged at 773 K, result in the lost of superelasticity. A maximum recovery strain of 3.3 % is obtained for specimens aged at 873 K or 973 K for 30 minutes, with coarse short bar-like α -phase precipitates. Microstructures of aged specimens as well as effects of lattice softening and aging-induced precipitates on the deformation behaviors have been investigated and discussed.

7977-95, Poster Session

A new variable stiffness and damping isolator

M. Behrooz, X. Wang, F. Gordaninejad, Univ. of Nevada, Reno (United States)

This study presents a novel semi-active variable stiffness and damping isolator (VSDI) for vibration mitigation of structures. The proposed VSDI system consists of a traditional steel-rubber vibration absorber, as the passive element, and a magnetorheological elastomer (MRE), with a controllable (or variable) stiffness and damping behavior, as the semi-active element. An MRE is a type of material whose stiffness and damping properties can be altered by a magnetic field. In this study, a small scale prototype of this device is designed, fabricated and tested. Vibration of the system is analytically modeled and numerically analyzed to demonstrate the effectiveness of the VSDI. Quasi-static and dynamic compression and shear tests in passive and active state are carried out experimentally to show VSDI's ability to stiffness change. The results of the experimental and analytical studies show the feasibility of the proposed system for base isolation applications.

7977-97, Poster Session

Active vibration control using noncollocated piezoelectric film sensor/actuator

T. Nishigaki, Kinki Univ. (Japan)

In the authors' previous reports, it was shown that piezoelectric films were able to be used as sensors and as actuators simultaneously for free or forced vibration control of flexible thin structure without affecting total weights and motion characteristics of the structures. In these

methods, piezoelectric film sensor and actuator were shaped using the equivalent shaping functions and were collocated bonded on the surfaces of the beam, the ring and the plate. Direct velocity feedback control was successfully applied to increase damping effects to the first vibrational mode. However, multimodal active vibration control experiments using these high-polymer piezoelectric films were difficult in several reasons. Included in these difficulties were the unstable vibrations due to the electromagnetic interactions between the sensor and the actuator, and the phase lag included in the transfer functions of the controller in high frequency area. In order to overcome these difficulties, it was proposed in the author's previous reports to shape piezoelectric sensor and actuator using different shaping functions. At first, in this paper, fundamental equations and vibration responses of the structure were summarized based on the modal coordinate systems, and then it was again pointed out that by considering phase characteristics of the controller in conjunctions with the polarity of the piezoelectric films in higher order modal frequencies, multimodal control will be implemented experimentally. Finally, results of multimodal vibration control experiments using the present method were shown.

7977-32, Session 7

Semi-active magnetorheological refueling probe systems for aerial refueling events

Y. Choi, N. M. Wereley, Univ. of Maryland, College Park (United States)

No abstract available

7977-33, Session 7

Magnetorheological elastomer mount for shock and vibration isolation

B. M. Kavlicoglu, B. Wallis, H. Sahin, Y. Liu, Advanced Materials and Devices, Inc. (United States)

A novel magnetorheological elastomer (MRE) mount is designed to provide a wide controllable stiffness range for protecting a system with variable payload from external shock and vibration forces. MRE is a field-controllable material in which the stiffness properties can be altered by changing the applied magnetic field. A MRE mount is fabricated for naval submarine vertical support group applications by using 0.5 inch thick MRE layers and built-in electromagnets. The performance of the 2-layer MRE mount is characterized by compression, shear, vibration, and shock tests. The compression stiffness change is up to 100%, while the lateral stiffness change is about 20% under various magnetic fields, and the dynamic stiffness change is less than 30% for submarine missile vibration frequency range. Also the performance of MRE mount stays unchanged for various operating temperatures and pressures of sea conditions. It is demonstrated that the designed MRE mount can handle different payload weight envelopes for naval submarine missile tube vertical support group applications.

7977-34, Session 7

Dynamic behavior of thick magnetorheological elastomers

N. Johnson, X. Wang, F. Gordaninejad, Univ. of Nevada, Reno (United States)

In this study, the dynamic properties of thick magnetorheological elastomers (MREs), subjected to various magnetic fields under shear loadings for a wide range of frequencies, are investigated. A double-shear test setup is developed. A mass is attached to two MRE samples. A frequency sweep excitation at an acceleration of 0.5g which starts at 10Hz and ends at 400Hz is applied to the system. The natural frequency,

complex modulus, loss modulus and storage modulus is obtained from the measured transmissibility functions. The test samples are made with varying thicknesses and amounts of iron particles. Thicknesses of 1/4 inch, 1/2 inch, 3/4 inch and 1 inch are used for the MRE samples. The iron particle percentages of 30, 50, 60 and 70, by weight are considered for the specimens tested. In addition, the effect of dimension of the samples on the dynamic moduli of MRE materials are evaluated by examining the results as a function of the thickness of the MRE samples.

7977-35, Session 7

Electrical conductivity in magnetorheological elastomers

P. Mysore, N. Ghaforianfar, X. Wang, F. Gordaninejad, Univ. of Nevada, Reno (United States)

Application of a magnetic field at the post cure stage to magnetorheological elastomers (MREs) generates a force between the particles embedded in the elastomer. The magnetizable particles are electrically conductive. The overall electrical properties of MRE depend on the volume fraction of particles, magnetic field, as well as, mechanical deformations. There is a critical particle volume fraction (referred to as percolation threshold) at which the conductivity of the MRE composites rapidly increases by several orders of magnitudes. The percolation threshold is extremely sensitive to the structure and the volume fraction of the conductive particles. In this study, the electrical percolation behavior and conductivity of MREs are experimentally investigated. The electrical conductivity of MREs for the longitudinal direction is measured as a function of particle volume fraction to understand the percolation behavior. The percolation thresholds for different particle sizes and shapes are obtained. Moreover, the longitudinal electrical conductivity of MREs under the combined effects of magnetic field and compressive strain are also examined.

7977-36, Session 7

Thick magnetorheological elastomers

P. Mysore, X. Wang, F. Gordaninejad, Univ. of Nevada, Reno (United States)

The requirement of high magnetic field to cure or activate magnetorheological elastomers (MREs) has restricted the use of MREs to small dimensions with thicknesses less than 10mm. However there is no warrant, that measurements in MREs are not influenced by the specimen dimensions and shapes. In the present study, two types of MRE specimens of varying concentrations, with circular and rectangular shapes having thicknesses from 6.35mm to a maximum of 25.4mm are prepared. These samples are tested under quasi-static compression and quasi-static double lap shear. It is observed that the measured off-state shear modulus shows large variations with increase in the thickness of the sample. The measured shear modulus from the double lap shear tests results, as well as the Young's modulus from the compression tests at zero-field, follows a logarithmic trend. It is also observed that the induced change in modulus is independent of the thickness of MRE and only dependent on the iron particle concentration and the magnetic field strength. With the increase in applied magnetic field, it is observed that the change in modulus changed from a linear trend at lower field to a non-linear trend at higher field. The controllability of MRE is found to be more in the compression mode than in the shear mode.

7977-37, Session 7

Effects of temperature on performance of a compressible magnetorheological fluid suspension system

M. McKee, X. Wang, F. Gordaninejad, Univ. of Nevada, Reno (United States)

A compact compressible magnetorheological (MR) fluid damper-liquid spring (CMRFD-LS) suspension system is designed, developed and tested. The performances of the CMRFD-LS are investigated under room temperature. However, since MR fluids are temperature dependent. The effect of temperature is observed in both the viscosity and the compressibility of the MR fluid. This study is to experimentally determine how temperature affects the performance of a CMRFD-LS device. A test setup is developed to measure the stiffness and energy dissipated by the system under various frequency loadings, magnetic fields and temperatures. The experimental results demonstrate that both the stiffness and the energy dissipated by the CMRFD-LS are inversely related to the temperature of the MR fluid. These changes in damper characteristics show that the compressibility of MR fluid is proportional to the fluid temperature while the viscosity of the MR fluid is inversely related to the fluid temperature.

7977-38, Session 7

Design of a preview semi-active vehicle suspension with MR damper based on a PID control strategy with nonlinear differentiator

X. Huang, Z. Xie, Univ. of Macau (Macao, China)

This work sets up a half-car model for the semi-active suspension with magneto-rheological (MR) damper and wheelbase preview information. The MR damper is modeled by the modified Bouc-Wen model which can accurately describe the nonlinear relationship between the input voltage and output force. Also, a sensor placed on the front suspension can collect and feed forward the road information as an input to the rear suspension system. Then, a PID controller combined with a nonlinear differentiator is used to process the obtained road information signal from the sensor on the front suspension and the feedback signal of vehicle state. The application of PID control with nonlinear differentiator (ND) is aimed to improve system robustness against the noise, and this improvement is validated by compared with regular PID control scheme. And then, the whole suspension system is tuned by using Genetic Algorithm (GA) to obtain an optimum configuration on several design parameters. At last, numerical examples are conducted to compare performances such as sprung mass acceleration, pitch acceleration, front and rear suspension strokes, road holding and control forces between proposed optimized semi-active suspension and the regular passive suspension. Results of numerical examples show that the optimized semi-active suspension can achieve much better performances.

7977-40, Session 8A

Elimination of spades in wheeled military vehicles using MR-fluid dampers

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An armored fighting vehicle is a military vehicle, protected by armor and armed with weapons and it can be either wheeled or tracked. For years, tracked military vehicles were the choice of fighting vehicles due to their heavy fire power, better armor package distribution, better traction, and ability to fire on the move without a need for a spade.

Nowadays, more and more armies are converting to all wheeled vehicles due to a lower fuel consumption, better mine survivability, lower noise, higher vehicle speeds, and ease of repair. But one of the drawbacks is the inability to fire on the move without spades as compared to a conventional tracked vehicle.

Addition of spades to wheeled military vehicles, during mortar fire, make the vehicle stationary and a target by the enemy fire, reduce vehicle mobility, make the vehicle heavy thus increasing fuel consumption, and result in considerable time to plant the spades into the ground and retract them after firing.

The authors got inspired to do a study to investigate the possibility of removing the spades, and using MR-fluid shocks to control chassis vibration during mortar firing, without bursting the tires.

A 2D heave pitch vehicle model consisting of a chassis and a recoil system is developed. Simulation results for a HMMWV vehicle indicate that by the use of MR-fluid dampers with the skyhook control policy, it is possible to remove the spades, control chassis vibration, and prevent vehicle lift off during firing, without bursting the tires.

7977-41, Session 8A

Design and analysis of a self-powered, self-sensing magnetorheological damper

C. Chen, W. Liao, The Chinese Univ. of Hong Kong (Hong Kong, China)

Magnetorheological (MR) dampers are promising for semi-active vibration control of various dynamic systems. In the current MR damper system, separate power supply and dynamic sensor are required. In this paper, we proposed a novel self-powered, self-sensing (SPSS) MR damper, which integrates energy harvesting, sensing and MR damping technologies into one device. This MR damper has self-contained power generation and velocity sensing capabilities. It combines the advantages of energy harvesting - reusing wasted energy, MR damping - controllable damping force, and sensing - providing dynamic information for system control. This SPSS MR damper is composed of MR damping part, power generation part, sensing mechanism, and interaction components. The interaction components are designed to minimize the magnetic-field interferences among different functions. A prototype of the SPSS MR damper was fabricated. The prototype was tested to obtain the performances of three functions: power generation ability, sensing ability, and controllable damping force. The power generation part converts part of the mechanical energy from the moving damper to electricity for the usage of MR device itself, rather than just wasting it as heat. The electromagnetic linear generator is used for power generation. Analysis on the induced voltages and generated power was conducted and experimentally validated. The average generated power that could be used for load is proportional to the square of excitation velocity. The experiment results match well with the theoretical analysis. A novel velocity-sensing method is used to obtain the relative velocity between the damper piston rod and cylinder.

7977-42, Session 8A

Optimal design of a disc-type MR brake for motorcycle application

Q. Nguyen, Ho Chi Minh City Univ. of Technology (Viet Nam); J. Jeon, S. Choi, Inha Univ. (Korea, Republic of)

This research work focuses on optimal design of a MR brake that can replace the conventional hydraulic brake (CHB) for commercial motorcycle. Firstly, a new MR brake configuration is proposed considering the available space and the simplicity and availability to replace the CHB by the proposed MR brake. An optimal design of the proposed MR brake is then performed considering the required braking torque, operating temperature, mass and size of the brake. In order to perform the optimization of the brake, the braking torque of the brake is analyzed based on Bingham rheological model of the MR fluid. The

operating temperature of the MR brake is estimated by considering the steady temperature of the brake when the motorcycle is cruising and the temperature increase during a braking process. A multi-objective function considering the mass and size of the MR brake structure is proposed and an optimization procedure based on the finite element analysis integrated with an optimization tool is developed to obtain optimal geometric dimensions of the MR brake.

Based on the developed optimization procedure, optimal solutions of the proposed MR brake featuring different types of MR fluid are achieved. From the results, the most effective MR brake for the motorcycle is identified and some discussions on the performance improvement of the optimized MR brake are described.

7977-43, Session 8A

Optimal design of a hybrid MR brake for haptic wrist application

Q. H. Nguyen, Ho Chi Minh City Univ. of Technology (Viet Nam);
P. Nguyen, S. Choi, Inha Univ. (Korea, Republic of)

In this work, a new configuration of a magnetorheological (MR) brake is proposed and an optimal design of the proposed MR brake for haptic wrist application is performed considering the required braking torque, the zero-field friction torque, the size and mass of the brake. The proposed MR brake configuration is a combination of disk-type and drum-type which is referred as a hybrid configuration in this study. After the MR brake with the hybrid configuration is proposed, braking torque of the brake is analyzed based on Bingham rheological model of the MR fluid. The zero-field friction torque of the MR brake is also obtained. An optimization procedure based on finite element analysis integrated with an optimization tool is developed for the MR brake. The purposes of the optimal design is to find the optimal geometric dimensions of the MR brake structure that can produce the required braking torque and minimize the mass of the brake. Furthermore, the zero-field friction torque is constrained to be smaller than a critical value.

Based on the optimization procedure, optimal solutions of the proposed MR brake featuring different types of MR fluid are achieved. From the results, the most effective MR brake for the haptic MR wrist is identified and some discussions on the performance improvement of the optimized MR brake are described.

7977-98, Session 8A

MRF-actuator concepts for HMI and industrial applications

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Actuators based on magnetorheological fluids as brakes and clutches offer a high dynamical and almost linear force generation combined with fast response times and a high force density. In this paper, concepts of MRF based actuator with radial and axial shear gaps for realizing braking and coupling functions in HMI devices and industrial applications are presented. Designing well defined shear gaps and appropriate electromagnetically driven excitation systems, combined brake and clutch functionalities can be realized even by providing current less bias torques. While actuators using radial shear gaps meet often the requirements for applications with low rotational speeds, e.g. HMI applications, designs with axial shear gaps are predestinated for applications for higher rotational speeds due to their robustness against centrifugation impacts. In this paper developed MR actuators for both, integrated in HMI and industrial system applications, are presented in detail that are using the multiple advantages of MR fluids as e.g. the smooth adjustable torque, fast response time and noiseless operation.

7977-44, Session 8B

Design of a controllable shape-memory-actuator with mechanical lock function

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Machine tools for small work pieces are characterized by an extensive disproportion between workspace and cross section. This is mainly caused by limitations in the miniaturization of drives and guidance elements. Due to their high specific workloads and relatively small spatial requirements, Shape-Memory-Alloys (SMA) possess an outstanding potential to serve as miniaturized positioning devices in small machines. However, a disadvantage of known actuator configurations, such as an SMA wire working against a mechanical spring, is that energy is steadily consumed to hold defined positions.

In this paper we present a novel SMA actuator design, which, due to an antagonistic arrangement of two SMA elements does not require energy whilst holding position. The two SMA actuators are applied in a differential setup and were designed regarding material, geometrical parameters, applied load, and control aspects. Furthermore, closed loop control concepts for positioning applications are implemented. These not only cover approaches using sensors, but also sensor-less concepts which utilize the distinctive length - resistance - correlation of SMAs for position controlling. Furthermore, a model/sample actuator has been used to demonstrate the designs capabilities to serve as miniaturized positioning device in small machines.

7977-45, Session 8B

Design of an antagonistic shape memory alloy actuator for flap type control surfaces

B. Donmez, B. Ozkan, TÜBITAK SAGE (Turkey)

In accordance with the technological advancements there is an increasing interest in unmanned aerial vehicles. UAVs has found diverse applications for both civil and military applications such as search, rescue and observation missions and also UAVs provide excellent low-cost test beds for navigation system experiments, their design and control facilitate the exploration of many new research areas in control theory. This paper presents flap control of Unmanned Aerial Vehicles (UAVs) using Shape Memory Alloy (SMA) actuators in an antagonistic configuration. The use of SMA actuators has the advantage of significant weight and cost reduction over the conventional actuation of the UAV flaps by electric motors or hydraulic actuators. In antagonistic configuration, two SMA actuators are used: one to rotate the flap clockwise and the other to rotate the flap counterclockwise. In this content mathematical modeling of strain and power dissipation of SMA wire is obtained through characterization tests then model of the antagonistic flap mechanism is derived. Later, based on these models both flap angle and power dissipation of the SMA wire are controlled in two different loops employing proportional-integral type and neural network based control schemes. In this study, power consumption of the wire is introduced as a new internal feedback variable and the error in the flap angle induced because of the indirect control is suppressed by the second control loop updating the power command of the wire. Constructed simulation models are run and performance specifications of the proposed control systems are investigated and it can be concluded that proposed controllers perform well in terms of achieving small tracking errors.

7977-47, Session 8B

Seismic retrofit of structures using super elastic behavior of shape memory alloys

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In the past two decades, shape memory alloys have been used by many researchers in different fields of engineering with innovative applications. Shape memory alloys can also be employed in the existing frames for the retrofitting purposes. Shape memory alloys can exploit the super-elastic behavior which can function as an appropriate passive seismic control device and also provides the desirable recentering behavior in the structure. This paper presents the result of a numerical study in which the improvement of the existing structural frame, designed with previous specifications, is attained by implementing the shape memory alloy bracing system in order to enhance the lateral behavior of the frame; particularly when subjected to seismic loadings. The nonlinear analysis of existing structures by the finite element method of analysis with and without shape memory alloy bracing system subjected to different mechanical loading conditions are presented and compared. The results show the effectiveness of the implementation of the shape memory alloy bracing system to the existing structure, the overall seismic behavior of the system improves considerably; while the main advantage is shown to be the drastic mitigation of the permanent deformations remained on the structure when using the proposed system.

7977-48, Session 9A

Electromechanical response of aligned carbon nanotube arrays

G. J. Ehlert, Arizona State Univ. (United States); M. R. Maschmann, Universal Technology Corp. (United States); J. W. Baur, Air Force Research Lab. (United States)

Gusts can destabilize the current generation of micro aerial vehicles (MAVs); however the addition of flow sensors on the control surfaces can enable control strategies to counteract the large forces. Hierarchical carbon fibers show potential as a biomimetic hair flow sensor for use on MAVs for gust alleviation. The sensor is inspired from bat wings, which have thousands of micro-scale hairs that deflect due to the flow and feedback flow information through force sensitive cells. Radially aligned carbon nanotube arrays on carbon fiber could function as the transducer in a similar device by decreasing resistance with increasing compressive strain on the nanotubes. Preliminary testing of radially aligned carbon nanotube arrays on carbon fiber has shown that the arrays exhibit a large change in resistance during deformation. The electromechanical response of aligned carbon nanotube arrays on flat substrates will be examined to predict the behavior for a radially aligned case.

Electromechanical testing will be performed in a dynamic mechanical analyzer instrumented with ITO coated glass platens and conductivity measurement capability. A transfer process is developed to move the carbon nanotubes from insulating Si to conductive substrates. The carbon nanotube arrays exhibit mechanical properties that agree with previously published results. Although instrumentation limits input frequency to 2 Hz, the electromechanical response is repeatable under cyclic loading for up to 240 cycles at 2 Hz. Measured gauge factors range from 20-120, indicating that aligned carbon nanotube arrays offer significantly higher sensitivity than a gauge factor of 2 for typical constantan foil strain gauges.

7977-49, Session 9A

Acoustic metamaterial with controllable directivity and dispersion characteristics

A. M. Baz, Univ. of Maryland, College Park (United States); W. N. Akl, Ain Shams Univ. (Egypt)

Current acoustic metamaterials are developed only with controllable directivity characteristics of wave propagation. The wave speed usually remains unaffected. This limits considerably the potential use of acoustic metamaterials in many critical military and civilian applications.

In the present work, an attempt is presented for developing a new class of acoustic metamaterials that have controllable directivity and dispersion characteristics. Such metamaterials are developed using a linear coordinate transformation of the acoustic domain to achieve the directivity control capabilities. The transformation is augmented with an additional degree of freedom to simultaneously control the dispersion characteristics. With such capabilities, the proposed acoustic metamaterials will be capable of controlling the wave propagation both in the spatial and spectral domains. The proposed control approach affects the density tensor of the acoustic metamaterials.

The theory governing the design of this class of acoustic metamaterials is introduced and the parameters that control the tuning of the directivity and dispersion characteristics are presented in details. Several numerical examples are presented to illustrate the potential capabilities of this class of metamaterials.

The proposed design approach of acoustic metamaterials with tunable wave propagation characteristics can be invaluable means for the design of many critical military and civilian applications.

7977-50, Session 9A

Variable-focal lens using electroactive polymer actuator

V. Vunder, A. Punning, A. Aabloo, Univ. of Tartu (Estonia)

We present a simple and cost-effective design and fabrication process of a liquid-filled variable-focal lens using electroactive polymer as an actuator. The lens is made of soft polymer material, its shape and curvature can be controlled by pneumatic pressure. As an actuator, we used a carbon-polymer composite (CPC); likewise it is possible to use any other ionic EAP. The device is composed of elastic membrane upon a circular lens chamber, a reservoir of liquid, and a channel between them. It is made of three layers of polydimethylsiloxane (PDMS), bonded using the technics of partial curing. The channels and reservoir are filled with incompressible liquid after curing process. A CPC actuator is mechanically attached to reservoir to compress or decompress the liquid. Squeezing the liquid between the reservoir and the lens chamber will push the membrane inward or outward resulting in the change of the shape of the lens and alteration of its focal length. Depending on the pressure the lens can be plano-convex or plano-concave or even switch between the two configurations. With only a few minor modifications it is possible to fabricate bi-convex and bi-concave lenses. We report on a 1 mm diameter lens that can be converging or diverging with the focal length from infinity to 17 mm. The 5x15mm CPC actuator with the working voltage of only up to $\pm 2.5V$ was capable to alter within the full range of the focal length in 10 seconds.

7977-51, Session 9A

Design, fabrication, and testing of contact-aided compliant cellular mechanisms with curved walls

S. A. Cirone, G. R. Hayes, B. L. Babcox, M. I. Frecker, J. H. Adair, G. A. Lesieutre, The Pennsylvania State Univ. (United States)

Contact-Aided Compliant Cellular Mechanisms (C3M) are compliant cellular structures with integrated contact mechanisms. The focus of the paper is on the design, fabrication, and testing of C3M with curved walls for high strain applications. It is shown that global strains were increased by replacing straight walls with curved walls in the traditional honeycomb structure, while the addition of contact mechanisms increased cell performance via stress relief. Furthermore, curved walls are beneficial for fabrication at the meso-scale. The basic curved honeycomb cell geometry are defined by a set of variables. These variables were optimized using Matlab and finite element analysis to find the best non-contact and contact-aided curved cell geometries as well as the cell geometry that provides the greatest stress relief. Currently, the most effective contact-aided curved honeycomb cell can withstand global strains approximately 160% greater than the most effective contact-aided, non-curved cell. Ongoing work includes quantifying the effect of different contact mechanism locations and geometries to design curved, contact-aided cells with maximum stress relief and even higher contact-aided global strains. The different designs will then be fabricated via the Lost Mold-Rapid Infiltration Forming (LM-RIF) process. C3M mechanisms, fabricated from both metal and ceramic, with curved and non-curved walls, will then be mechanically evaluated using a custom test fixture. Finally, the measured performance of the curved and non-curved C3M parts will be compared to that predicted by finite element analysis.

7977-52, Session 9A

Damping behavior of polymer composites with high volume fraction of NiMnGa powders

X. Sun, J. Song, H. Jiang, X. Zhang, C. Xie, Shanghai Jiao Tong Univ. (China)

Polymer composites inserted with high volume fraction of NiMnGa powders was fabricated and their damping behavior was investigated by dynamic mechanical analysis. It is found that the polymer matrix has little influence on the transformation temperatures of NiMnGa powders. A damping peak appears for NiMnGa/epoxy resin composites accompanying with the martensitic transformation or reverse martensitic transformation of NiMnGa powders. The damping capacity of NiMnGa/epoxy composites increases with the increase of volume fraction of NiMnGa powders and, decreases dramatically as the test frequency increases to 5Hz.

7977-53, Session 9B

Performance modeling of unmanned aerial vehicles with on board energy harvesting

S. R. Anton, D. J. Inman, Virginia Polytechnic Institute and State Univ. (United States)

The concept of energy harvesting in unmanned aerial vehicles (UAVs) has received much attention in recent years. Currently, research has begun to investigate harvesting ambient vibration energy during the flight of UAVs. A critical aspect of integrating any energy harvesting system into a UAV, however, is the potential effect that the additional system has on the performance of the aircraft. Added mass and increased drag can significantly degrade the flight performance of any aircraft, therefore, it is important to ensure that the addition of an energy harvesting system does not adversely affect the efficiency a host aircraft. In this work, a

system level approach is taken to examine the effects of adding both solar and piezoelectric vibration harvesting to a UAV test platform. A formulation recently presented in the literature by Thomas and Qidwai is applied to describe the changes to the flight endurance of a UAV based on the power available from added harvesters and the mass of the harvesters. Details of the derivation of the flight endurance model are reviewed in this work, and the formulation is applied to an EasyGlider remote control foam hobbyist airplane, which is selected as the test platform for this study. Both a theoretical case study and an experimental analysis are performed on the EasyGlider aircraft in which the normalized change in flight endurance is calculated based on the addition of flexible thin-film solar panels to the wings as well as flexible piezoelectric patches to the wing spar of the aircraft.

7977-54, Session 9B

Equivalent models of corrugated laminates for morphing skins

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Morphing aircraft wings have attracted much attention in recent years and in many cases the design of the skins has been identified as a major issue. Corrugated laminates offer a solution due to their extremely anisotropic behaviour: compliance in the chordwise (corrugation) direction allows shape changes and increases in surface area; stiffness in the spanwise (transverse to the corrugation) direction enables the aerodynamic and inertial loads to be carried. Currently the design of the morphing wing and the specification of the skin are performed independently. This approach is adequate for simple wing geometries (such as morphing trailing edges), but inadequate for more complex three-dimensional geometries (such as the morphing winglet). This paper investigates equivalent material models that reduce the size of the finite element models, so that the skin may be incorporated into the system level model. The skin model must retain dependence on the geometric parameters of the corrugations so that it may be used for optimization at the conceptual design stage. Both the elastic linear deformation and the nonlinear behaviour due to transverse displacements in the corrugation direction are investigated. The analytical homogenization model is obtained from a simplified geometry for a unit-cell and the validity of this model is compared to a detailed finite element analysis. Parametric studies are used to investigate the effects of corrugation geometry, ply angles, laminate thickness, fibre volume fraction, and so on. The equivalent material model is also integrated into a conceptual design model with a view to optimizing morphing wing systems.

7977-55, Session 9B

Topology optimization of pressure adaptive honeycomb for a morphing flap

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Pressure adaptive honeycomb is a highly-deformable structure that relies on a pressure-differential for actuation. In previous work, it has been demonstrated that strains in excess of 50% can be achieved without plastically deforming the honeycomb structure. In addition, at a pressure differential of 0.9 MPa (which can be generated by the HP compressor of a modern jet engine), the mass-specific energy density is on the par with shape memory alloy, while the transfer efficiency is an order of magnitude higher. Proof-of-concept tests successfully demonstrated the application of pressure adaptive honeycomb in the aft 30% of a wing section. Camber variations in excess of 5% could be generated at a pressure differential of 40kPa. Results of subsequent wind tunnel test show an increase in lift coefficient of 0.3. These results sparked the motivation for subsequent research into the optimal topology of the pressure adaptive honeycomb within a morphing Fowler flap. As an input for the optimization two known shapes are required: a desired shape in cruise configuration and a desired shape in landing configuration. In

In addition, the boundary conditions and load cases (including aerodynamic loads and internal pressure loads) are specified for each condition. A finite-element analysis is run for each topology configuration in Nastran. The optimization process finds the internal flap topology that minimizes the error between the acquired shape and the desired shape in each configuration. A response-surface technique is employed to find the optimal topology in the design space. The optimization tool can be used to determine the honeycomb topology that best meets the constraints and requirements of a pressure-adaptive morphing flap.

7977-56, Session 9B

A composite structure aiming for its first large scale ground test in a smart and gapless wing leading edge

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At the Institute of Composite Structures and Adaptive Systems (FA, Prof. Wiedemann) of the DLR the structure of a flexible and gapless wing leading edge has been developed for testing in large scale structure-system ground tests. High lift systems for commercial aircraft of nowadays design are highly efficient systems consisting of rigid and movable structures supported by complex kinematics. Technologies for future aircraft generations have to enable the reduction of flow resistance, emissions and noise. Within this context, the absence of gaps in a flexible wing leading edge allows for a significant noise reduction and provides an additional key technology for realizing wings with a fully natural laminar flow. In the years 2009 and 2010 the work in the national project SmartLED within the 4th German Aviation Research Program (LuFo) was focused on the preparation and realization of the first ground test of the in the project developed overall system. The test program considers several load cases including wing bending. The overall smart droop nose concept arose from the cooperation of Airbus and EADS, whereas the DLR Institute FA dealt with the structural design, the test of the material systems, the simulation of the overall system, and the development of manufacturing technologies for the composite structures to be employed in the planned tests. Fulfilling this project work required the thorough application of the process chain in the Institute FA and spanned in the ground test preparation phase the arc from the design and simulation of the overall system according to the test and to manufacturing conditions, over the safeguarding of the design and the selection of material systems through substructure tests and damage analysis, the preparation of detailed design documents to the optimization of manufacturing processes. The detailed presentation of this work forms the content of this paper. First, the overall system will be discussed and the planned verification model as well as its test condition described. This motivation of the presented project work is followed by a discourse of the material system and substructure tests, the simulation of the damage behavior on substructure level and the design of a test apparatus for local tests of load introductions implemented as hat stringers. The closure is formed by presenting the structural simulation of the large scale test stand for the smart droop nose device and the description of the manufacturing concept for the flexible composite structure.

7977-57, Session 9B

Controller design for a morphing, perching aircraft

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An aircraft's range of maneuvers is limited by the ability of its actuators. For instance, the range of elevator deflection and maximum thrust output help determine how demanding a maneuver the aircraft can perform. Expansion of the controller ranges enables the aircraft to perform more challenging maneuvers. The aircraft is also limited by its aerodynamic profile in maintaining the attached airflow necessary to provide sufficient

lift for flight. New techniques may also be applied to improve the profile of the aircraft for a wider range of flight conditions.

A morphing aircraft is developed by implementing new controlled degrees of freedom. The new degrees of freedom, wing incidence and tail angles, are selected to provide the aircraft with the most utility to perform new maneuvers through the active control of their orientation with respect to their conventional, fixed-frame positions. This morphing aspect also allows the aircraft to reorient these structures to help maintain attached airflow over a wider range of conditions in order to perform some complex maneuvers more easily than a conventional aircraft. The range of trim conditions is also enlarged, allowing the possibility that the aircraft could also use its new degrees of freedom to adapt to more severe conditions than could a conventional aircraft.

The maneuver of interest in this paper is to land by using a perching maneuver. This maneuver is similar to the method used by some large birds and would allow the aircraft to perform short, planted landings primarily through the control of aerodynamic surfaces instead of the utilization of powered or vectored thrust. This type of maneuver is suggested for small UAVs, and an application of which is to extend the duration of an ISR mission, for instance by enabling the aircraft to land more easily in order to conserve fuel while continuing to perform measurements and communication. These new degrees of freedom require a suitable controller to leverage the morphing capabilities to their fullest potential.

This paper discusses the development of a feedback controller for the morphing aircraft. Various controller methods and designs are explained and their simulation data are compared to determine those that offer the best performance. The proposed controller incorporates both the conventional and morphing inputs in order to control the aircraft to allow it to perform the desired tasks, in this case the perching maneuver.

7977-58, Session 9B

Static aeroelastic deformation of flexible skin for continuous variable trailing-edge camber wing

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The method for analyzing the static aeroelastic deformation of flexible skin under the air loads was developed. The effect of static aeroelastic deformation of flexible skin on the aerodynamic characteristics of aerofoil and the design parameters of skin was discussed. Numerical results show that the flexible skin on the upper surface of trailing-edge will bubble under the air loads and the bubble has a powerful effect on the aerodynamic pressure near the surface of local deformation. The static aeroelastic deformation of flexible skin significantly affects the aerodynamic characteristics of aerofoil. At small angle of attack, the drag coefficient increases and the lift coefficient decreases. With the increasing angle of attack, the effect of flexible skin on the aerodynamic characteristics of aerofoil is smaller and smaller. The deformation of flexible skin becomes larger and larger with the free-stream velocity increasing. When the free-stream velocity is greater than a value, the deformation of flexible skin and the drag coefficient of aerofoil increase rapidly. The maximum tensile strain of flexible skin is increased with consideration of the static aeroelastic deformation.

7977-59, Session 10A

A computational inverse problem approach for the design of morphing processes in thermally activated smart structural materials (SMP SESSION)

S. Wang, J. C. Brigham, Univ. of Pittsburgh (United States)

Shape memory polymers (SMPs) are attracting increasing attention as a class of smart structural materials due to their light weight, ability

to exhibit variable stiffness and undergo large deformations without damage, and, of course, their shape memory effect. Furthermore, SMPs have the clear potential to be used to develop new technologies for sensors and actuators, and of particular interest to this work, to create a variety of structures that are entirely and intrinsically morphable. In theory, a structure composed completely of SMP could have limitless shape-changing functionality, provided sufficient activation (whether thermal, electric, or light) and mechanical actuation. Towards the utilization of this potential functionality, this work presents a computational inverse mechanics framework to design the optimal activation and actuation patterns to morph a structure fully composed of a smart material into a predefined shape or set of shapes. More specifically, a numerical study is shown for the example of thermally activated smart materials in which the objective is to identify the applied boundary heat and traction to deform and lock a structure into a predefined shape with minimal total energy and without damaging the material. The finite element method is used to analyze the coupled thermo-mechanical response of the structure given a set of design parameters, and constrained nonlinear optimization is applied to identify the ideal activation and actuation to achieve the desired deformation. Through example problems based on thermally activated SMPs, the approach is shown to provide a generalized means to optimally design and/or control smart material structures.

7977-60, Session 10A

Energy-based comparison of various controllers for vibration suppression using piezoceramics

Y. Wang, A. Erturk, D. J. Inman, Virginia Polytechnic Institute and State Univ. (United States)

Suppression of undesired vibrations in flexible structures with limited energy is becoming an important design problem to develop energy-autonomous controllers powered using the harvested ambient energy. The objective of this paper is to compare different control laws to suppress low-frequency vibrations using the minimum control energy for the same system and under the same design constraint (identical settling time for free vibrations). The vibration suppression performance of four active control systems as well as their hybrid versions employing a switching technique are compared. The compared control systems are a Positive Position Feedback (PPF) controller, a Proportional Integral Derivative (PID) controller, a nonlinear controller (with a second-order nonlinear term multiplying the position and velocity feedback to create variable damping), a Linear Quadratic Regulator (LQR) controller and their hybrid versions integrating a bang-bang control law with each of these controllers. Experimental results are presented for a thin cantilevered beam with a piezoceramic transducer controlled by these eight controllers with a focus on the fundamental vibration mode under transverse free vibrations and the control energy requirements are compared. Experimental results reveal that all the controllers reduce the vibration settling time to 0.85s as a design constraint (which is 92.3% of the open-loop settling time: 10.9s). The average power input provided to the piezoceramic transducer in each case is obtained for the time current and voltage measurements until the settling time. The hybrid bang-bang-PPF requires 66 % less power than the active PID control system. More experiments will be conducted for the nonlinear, hybrid bang-bang-nonlinear, LQR and hybrid bang-bang-LQR controllers.

7977-61, Session 10A

Degradation of embedded systems in multifunctional composites

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The multifunctional composite structures have enabled great weight savings, efficiency and performance for advance structures such as aerospace vehicles. The goal of such multifunctional structures (MFS) is

to incorporate various tasks and functions such as structural, electrical and thermal within a structural housing. The performance and behavior characteristics of the multifunctional structures can be affected by degradation of any of the sub-components such as sensor, actuator, structure, battery etc. (Kessler et al 2002) However, there are some uncertainties about using an embedded system (sensor) in multifunctional composites in terms of functionality, durability and reliability.

In order to solve these uncertainties; Firstly, it requires very effective use of available resources. Secondly, it requires formal methods to quantify the current integrity of a specific structure/component and subsequent reliable evaluation of its future integrity. The first case includes uncertainties associated with lack of sufficient data of multifunctional composites. The second case is full of uncertainties from: (1) unknown assumptions and conditions to characterize structural responses, (2) effect of various loading conditions, and (3) material and sensor degradation of various factors, etc. (Wikie et al.2000)

These uncertainties determine the gap exists in certifying the SHM system in terms of reliability, durability and longevity of the embedded system (sensor) for the life-time of the host structure. In this paper, the behavior of the PFC/MFC sensors and the structure are investigated while they are in-service and the electrical/mechanical parameters of the embedded system (sensor) which can be used to characterize the structural responses are determined. The PFC sensors offer many advantages over conventional monolithic piezo-ceramic devices.

7977-62, Session 10A

Sheet metal hydroforming of functional composite structures

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This paper studies the formability of functional composite structures, consisting of a metal substrate, insulating plastic foils, flat copper conductors and printable conductive polymers. The objective is to produce smart components in a sheet metal hydroforming process.

In order to integrate actuator and sensor elements into sheet metal hydroformed components, some significant constraints must be considered. Both a reliable energy and a save data supply have to be ensured. Nowadays this is realized through a subsequent wiring of the actuator and sensor elements. The cross-section and the mass of the electrical conductors do not improve the mechanical properties of the components.

Synergetic effects resulting from the aggregation of these elements, mentioned in the first section, can be used profitably. The cross-section of the conductors can influence the stiffness of the smart components positively. At the same time the insulating plastic foils can reduce the vibrations. Thus, the developed smart components can accomplish many tasks at the same time. The borderline between mechanical and electrical elements is partially lifted, in order to achieve a higher functional integration and better product quality.

The challenge is the design of the forming process, so that all elements of the functional composite structure will withstand the process conditions. Occurring strains may not destroy the elements of the functional composite structure and must be controlled. The process design and, above all, the sensor positioning are of great importance. In this context, an analytical method for estimating the formability of these smart components is presented and discussed.

7977-63, Session 10A

Adverse event detection (AED) integrated system for continuously monitoring and evaluating structural health status

J. Yun, D. S. Ha, D. J. Inman, Virginia Polytechnic Institute and State Univ. (United States)

To establish AED integrated system, we added Acoustic Emission (AE) functionality to an integrated system for both impedance-based and wave propagation SHM. With these three health-monitoring methods, we can determine the presence, location, and severity of damage. AE detects impacts. Impedance techniques are used to detect the presence of damage. Incipient damage has been shown to be detectable with the impedance technique. When damage is found with the impedance method, the Lamb wave portion of the device is activated. The pitch-catch method for Lamb waves looks for changes in waves propagated between two piezoelectric patches. Changes in the waveform can be used to determine the severity of any damage present. In addition to the damage severity, the pulse-echo technique can pinpoint the location of any damage. The use of AE considerably expands the structural volume that can be monitored. Furthermore, in suitable structures such as sandwich composites sensor coverage can be further increased through Lamb wave propagation methods.

According to experimental results of AED system, the hardware realization combining these three SHM method proved to be a seamless transition from the conventional approach in which only one method has been exploited. Our hardware validation tests clearly demonstrated integrated SHM capability and verified AED system operation. Furthermore, our combined hardware modifications turned out to be a power efficient system, since our system is capable of removing unnecessary repetitions of power hungry Wave propagation method owing to the introduction of AE method.

7977-64, Session 10A

Piezoelectric actuation of a flapping wing accounting for nonlinear damping

K. R. Olympio, G. Poulin-Vittrant, Univ. de Tours (France)

The proposed paper summarizes recent results as part of a French multiple-partner research project where the objective is to design a fully automated flapping wing entomopter with as few discrete parts as possible. The MAV is made of a control system, piezoelectric unimorph actuators, a thorax that amplifies the actuators' stroke and wings attached to the thorax. The paper will focus on the stroke, mechanical power generated and efficiency of piezoelectric actuators when the drag on the wing, transmitted to the actuator via a thorax, is modeled as a nonlinear damping. The objective is to test, simulate and model the actuators' behavior in conditions as close as possible to what would happen on a flapping wing MAV, without having to build the entire MAV which is still in its development stage.

The loading applied to the actuator is created using a push-pull actuator piloted with a feedback loop to simulate a load varying with the tip displacement of the actuator (hence simulating a stiffness) and with the tip velocity (hence simulating linear and nonlinear damping). Measurements of velocities, forces and absorbed current have been used to calculate consumed electric power and mechanical power generated in steady state regime.

The full-length paper will present the experimental setup, the experimental measurements of the mechanical and electric power of PZT unimorph benders under loads similar to those seen by the actuator if mounted on the MAV. This will allow implementing a strategy to evaluate in a simple manner an actuator's performance for flapping wing MAV applications. Parametric studies will help understand how to increase the actuation efficiency for a given excitation and damping.

7977-65, Session 10B

Piezoelectric driven thermo-acoustic refrigerator

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Thermoacoustic refrigeration is an emerging refrigeration technology which does not rely for in its operation on the use of any moving parts or harmful refrigerants. This technology uses acoustic waves to pump heat across a temperature gradient. The vast majority of thermoacoustic refrigerators to date have used electromagnetic loudspeakers to generate the acoustic input. In this paper, the design, construction, operation, and modeling of a piezoelectric-driven thermoacoustic refrigerator are detailed. This refrigerator demonstrates the effectiveness of piezoelectric actuation in moving 0.3 W of heat across an 18 degree C temperature difference with an input power of 7.6 W.

The performance characteristics of this class of thermoacoustic-piezoelectric refrigerator are modeled using DeltaEC software and the predictions are validated experimentally. The obtained results confirm the validity of the developed model. Furthermore, the potential of piezoelectric actuation as effective means for driving thermoacoustic refrigerators is demonstrated as compared to the conventional electromagnetic loudspeakers which are heavy and require high actuation energy.

The developed theoretical and experimental tools can serve as invaluable means for the design and testing of other piezoelectric driven thermoacoustic refrigerator configurations.

7977-66, Session 10B

A honeycomb-based piezoelectric actuator for a flapping wing MAV

K. R. Olympio, G. Poulin-Vittrant, Univ. de Tours (France)

With the development of better manufacturing techniques and new materials systems, engineers and researchers are increasingly trying to design new structures and systems with integrated components for sensing and actuation. This is increasingly done in combination with a bio-mimicry approach where one takes inspiration from nature to develop more efficient, versatile or multifunctional systems.

One such research area concerns the development of flapping wing micro air vehicles (MAVs) for monitoring and sensing or assisting in search and rescue operations. These MAVs are designed to mimic the flight of insects because it is thought that at small scale and low Reynolds numbers, such type of flying provides greater agility and efficiency than fixed-wing and rotary-wing MAV. Many research teams are currently developing flapping wing MAVs. So far, successful attempts have led to MAVs actuated with a brushless motor and a fragile gear system that is expensive to manufacture, or an articulated system connected to actuators.

The proposed paper will summarize recent results as part of a multiple-partner research project where the objective is to design a fully automated flapping wing entomopter with as few discrete parts as possible. As such, a monolithic actuation system is sought and the piezoelectric actuation is one of the few approaches considered.

The full-length paper will present a simple analytical model for the static and dynamic behavior of honeycomb-based amplified actuators. Validation of the model with experimental data will also be presented. It will focus on the experimental and analytical data for the actuator's stroke, and on the measured and calculated electrical impedance. A parametric study will illustrate the effect of the geometric parameters on the free displacement, the blocking force and the electrical impedance in both static and dynamic regimes.

The model will finally be used to find optimal actuator configurations for a flapping wing MAV for which we seek to minimize (1) the mass and (2)

the energy absorbed, and maximize (3) the free displacement and (4) the blocking force. An approach using a multi-objective hybrid genetic algorithm will help select a posteriori the most appropriate configurations for EVA's MAV and help compare these amplified actuators to more commonly used unimorph actuators.

This paper will put emphasis on using this type of actuator for flapping wing MAVs. Furthermore, it will also give the necessary tools to use active honeycomb structures for actuation purposes, energy harvesting and sensing applications, which will be the focus of future studies.

7977-67, Session 10B

Pressure tracking control of vehicle ABS using piezo valve modulator

J. Jeon, S. Choi, Inha Univ. (Korea, Republic of)

This paper presents a wheel slip control for the ABS(anti-lock brake system) of a passenger vehicle using a controllable piezo valve modulator. The ABS is designed to optimize braking effectiveness and maintain steerability. In order to achieve this goal, a new type of ABS using a piezo valve modulator is proposed for passenger vehicles

As a first step, the principal design parameters of the piezo valve and pressure modulator are appropriately determined by considering the braking pressure variation during the ABS operation. The proposed piezo valve consists of a flapper, pneumatic circuit and a piezostack actuator. In order to get wide control range of the pressure, the pressure modulator is proposed. The modulator consists of a dual-type cylinder filled with different substances (fluid and gas) and a piston rod moving vertical axis to transmit the force.

Subsequently, a quarter-car wheel slip model is formulated and integrated with the governing equation of the piezo valve modulator. A sliding mode controller to achieve the desired slip rate is then designed and implemented via the simulation. Braking control performances such as brake pressure and slip rate are evaluated via computer simulations.

7977-68, Session 10B

Modeling of a piezostack actuator considering dynamic hysteresis

P. Nguyen, Inha Univ. (Korea, Republic of); Q. Nguyen, Ho Chi Minh City Univ. of Technology (Viet Nam); S. Choi, Inha Univ. (Korea, Republic of)

This paper proposes a novel model for dynamic hysteresis of a piezostack. It is developed based on mathematical Prandtl-Ishlinskii model. In the classical Prandtl-Ishlinskii model, the hysteresis is obtained to be a weighted sum of ideal backlashes that are independent of dynamics or rate-independent. In our work, these backlashes are considered not to be ideal but rate-dependent. Each of them consists of two components: a phase-lag component cascaded with an ideal backlash. The lag components of the proposed model are considered to be the linear systems whose coefficients are tuned based on a suitable adaptive identification method. In the other hand, to determine the ideal backlashes in the model, an approach to identify their bandwidths and weights under static condition is introduced. In order to demonstrate the efficiency of the proposed model, performances of output displacement are experimentally evaluated in time domain with different input voltage waveforms: constant-frequency, varying-frequency sinusoidal and random waveforms. Moreover, a comparison between the proposed and classical Prandtl-Ishlinskii models is undertaken. It is shown that the proposed model can provide a much better accuracy than the classical Prandtl-Ishlinskii one.

7977-70, Session 10B

Effect of equivalent constant and output power of concentric disk-type piezoelectric transformer on temperature

I. Chou, Y. Lai, W. Wu, National Taiwan Univ. (Taiwan); C. Lee, National Taiwan Univ. (Taiwan) and Institute for Information Industry (Taiwan)

This paper presents the effect of equivalent constant and output power of concentric disk-type piezoelectric transformer on temperature. In order to analyze the energy loss in the piezoelectric transformer, the equivalent circuit model is built. Loss in the piezoelectric transformer is considered generally as two different parts: dielectric loss and mechanical loss. First of all, in order to measure the energy loss, a circuit for measurement is built. Also, an impedance analyzer is used for measuring. Then, PSIM, a kind of circuit simulation software, is employed to verify the measurements. Secondly, according to the experimental results, we know that temperature and input voltage are the two factors which influence the energy loss in a piezoelectric transformer. As the input voltage and temperature increased, the energy loss raises, too. In addition, when the input voltage is low, the temperature becomes the main factor for energy loss of the piezoelectric transformer. On the contrary, when the input voltage is high, the main factor for energy loss of the piezoelectric transformer is the input voltage other than the temperature. Furthermore, the control loop of the energy loss inside the piezoelectric transformer is proposed. At different temperatures, the variations inside the piezoelectric transformer are presented in this paper. Finally, the dielectric loss and mechanical loss are combined into the piezoelectric transformer. Then, the relationship between the output power of the piezoelectric transformer and the temperature is revealed. The result shows that as the temperature increased, the output power decreased as well.

7977-71, Session 10C

Combining network models and FE-models for the simulation of electromechanical systems

U. Marschner, E. Starke, G. Pfeifer, W. Fischer, Technische Univ. Dresden (Germany); A. B. Flatau, Univ. of Maryland, College Park (United States)

The combination of Network Methods and Finite Element Methods on user level is an efficient simulation method for the time-efficient simulation of dynamic behavior of electromechanical systems. Combined simulation can be structured into five areas of application: (1) Determining network structures with FE-simulations, (2) Determining network parameters with FE-simulations, (3) Including network elements in FE-models, (4) Including equivalent network structures in FE-models and (5) Simulation of models incorporating different model levels. The capabilities of the combined simulation are demonstrated by sample applications. Combined Simulation is suited for a better system insight and fast simulation-based optimization.

7977-72, Session 10C

Applying network models to improve FE-models

E. Starke, G. Pfeifer, W. Fischer, Technische Univ. Dresden (Germany)

To achieve an efficient simulation of the dynamic behaviour of electromechanical devices it is often necessary to use more than one simulation method or program. The main reason for this is that electromechanical Systems contain different physical domains and transduction principles. In many cases a smart solution is the

combination of Finite-Element-Methods with Network Methods on user level. As one application Network Methods can be used to achieve efficient and problem oriented Finite-Element-Models. The method will be clarified by simple examples. For instance the embedding of Network Models in FE-Models is shown at the simulation of an active noise reduction system in a duct.

7977-73, Session 10C

Magnetic transducer design using a combination of ODE and FEA modelling techniques

S. C. Thompson, The Pennsylvania State Univ. (United States)

The analysis of electromechanical transducers using magnetic drive requires multidomain analysis that includes at least the electrical, magnetic, mechanical domains. Such a system results in a set of differential and algebraic equations (DAE) that can be solved by analogy using modern electrical circuit analysis codes, or with codes written specifically for multidomain DAE modelling. Often, some components in the system require partial differential equations for their analysis, and FEA methods are required. This is especially true in magnetic systems where the flux path including leakage defies simple a priori estimation. Examples of magnetostrictive and variable reluctance devices will be shown.

7977-74, Session 10C

Optimization of an electromagnetic linear actuator using a network and a finite element model

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Model based design optimization leads to non-robust solutions when neglecting the statistical deviations of design, load and ambient parameters from nominal values. We describe an optimization methodology that involves these deviations as stochastic variables for an exemplary electromagnetic actuator. A combined model simulates the actuator and its non-linear load. It consists of a dynamic network model and a stationary magnetic FEA model. After a sensitivity analysis using DoE methods and a nominal optimization based on evolutionary and gradient methods, a robust design optimization is performed. Selected design variables were involved in form of their density functions. In order to reduce the computational effort we used response surfaces instead of the combined system model obtained in all stochastic analysis steps. This allows Monte-Carlo simulations to be applied. As a result we found an optimum system design meeting our requirements with regard to function and reliability as well.

7977-75, Session 10C

Fast and efficient multidomain system simulation based on coupled heterogeneous model structures

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When accurate and reliable system design optimization analysis is the driving factor of the entire electromechanical design flow the usage of a system simulator with multi-physics capabilities is required. To achieve fast and efficient simulation design point analysis or considering the wide system optimization analysis multi-scaling capabilities need to be accounted. In the light of the multi-physics system design concept, this paper describes a mechatronics system design analysis by employing both a reduced order technique to account for a flexible dynamic model into an analog system simulator and the state-of-the-art technique that couples the implicit system analog solver with an explicit rigid dynamics solver. Based on this coupling architecture the engineers can develop a control strategy into the system simulator and drive complex assembly dynamics and kinematic systems.

7977-76, Session 11A

Preliminary design of a smart composite telescope for space laser communication on a satellite for the Geosynchronous orbit

M. N. Ghasemi-Nejhad, N. Antin, Univ. of Hawai'i (United States)

This paper presents a preliminary design of a smart composite telescope for space laser communication. The smart composite telescope will be mounted on a smart composite platform with Simultaneous Precision Positioning and Vibration Suppression (SPPVS), and then mounted on a satellite. The laser communication is intended for the Geosynchronous orbit. The high degree of directionality increases the security of the laser communication signal (as opposed to a diffused RF signal), but also requires sophisticated subsystems for transmission and acquisition. The shorter wavelength of the optical spectrum increases the data transmission rates, but laser systems require large amounts of power, which increases the mass and complexity of the supporting systems. In addition, the laser communication on the Geosynchronous orbit requires an accurate platform with SPPVS capabilities. Therefore, this work also addresses the design of an active composite platform to be used to simultaneously point and stabilize an intersatellite laser communication telescope with micro-radian pointing resolution. The telescope is a Cassegrain receiver that employs two mirrors, one convex (primary) and the other concave (secondary). The distance, as well as the horizontal and axial alignment of the mirrors, must be precisely maintained or else the optical properties of the system will be severely degraded. The alignment will also have to be maintained during thruster firings, which will require vibration suppression capabilities of the system as well. The innovative platform has been designed to have tip-tilt pointing and simultaneous multi-degree-of-freedom vibration isolation capability for pointing stabilization.

7977-77, Session 11A

Integration of pseudo negative stiffness control and structural health monitoring for large scale structural system

Y. Ding, S. Law, The Hong Kong Polytechnic Univ. (Hong Kong, China)

The structural control and structural health monitoring are two important parts for modern large scale structural system. The integration system of structural control and health monitoring can be implemented in large structures with multi-purpose sensor system. However, the online implementation of structural control and health monitoring of a large structure are difficult due to the large mass, damping and stiffness matrices calculation. Moreover, the reliability of the structural control and health monitoring will also reduce in a large scale structural system during harsh environmental loading, including the severe earthquake and strong wind. In this paper, a new combination system of adaptive structural control and structural health monitoring is proposed. The structural control system is implemented by the Pseudo Negative Stiffness (PNS) control which is an effective control method proposed for the vibration mitigation of structures. The PNS control is adaptive with the updating of the structural parameters which is conducted with the structural health monitoring system. The combination of the structural control and health monitoring system is designed as autonomous-decentralized to guarantee the reliability in large scale structural system during the harsh environmental excitation. Each adaptive autonomous-decentralized control system explores substructure method which is more efficient in calculation with smaller mass, damping and stiffness matrices especially for the inverse problem. The proposed integrated system is implemented and verified through numerical simulation. And the effectiveness of performance of the proposed system is also compared with a structural system with passive dampers.

7977-78, Session 11A

Actuator grouping optimization on flexible space reflectors

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Large arrays of actuators are becoming more common for surface control in smart structures, such as large flexible space reflectors. A major constraint in many of these structures is the high cost of having enough power supplies to individually power each actuator. One solution is to group multiple actuators together and power each group with a single power supply. Currently, heuristic algorithms are used to optimize this grouping, but a global optimum is never guaranteed. To guarantee the global optimum, we have developed a new optimization method - the En Masse Elimination (EME) technique. This new optimization algorithm is used to determine the grouping of actuators when there are more actuators than power supplies present. The first step in this method is to find an acceptable solution that satisfies the power supply constraint and determine the required control authority. Then, some actuators are grouped while the power supply constraint is temporarily relaxed for all the other actuators. If the control authority for this solution is no better than the control authority of the acceptable solution, then large areas of the design space can be eliminated. This continues until the entire design space has been searched, and the global optimum is found. To examine the performance of the EME algorithm, a model of a 2.4 m diameter reflector with multiple actuators is developed. The EME algorithm is applied to the model to demonstrate the efficacy of the algorithm.

7977-79, Session 11A

A genetic algorithms based optimization on active constrained layer damped rotating plate

Z. Xie, P. K. Wong, I. I. Chong, Univ. of Macau (Macao, China)

Rotating structures are widely used in machines like wind turbines, helicopters, ships, while vibration on the rotating parts cause a huge problem. Most existing research models the structures as beams that are not the case many times. It is meaningful to model the rotating part as plates because of improvements on both the accuracy and the versatility. At the same time, existing research shows that the active constrained layer damping provides a more effective vibration control approach than the passive constrained layer damping. Thus, in this work, a single layer finite element is adopted to model a three-layer active constrained layer damped rotating plate. Unlike previous ones, all types of damping are taken into account in this finite element model. Also, the constraining layer is made of piezoelectric material to work as both the self-sensing sensor and actuator, and a proportional control strategy is implemented to effectively control the displacement of the tip end of the rotating plate. Then, due to the large number of design variables that can be present in complex systems incorporating visco-elastic damping, this work examines the application of genetic algorithms in optimizing the response of these structures. A genetic algorithm is applied to simultaneously determine several design parameters that provide the best response under an objective function. The numerical example shows that the optimum configuration can achieve a satisfactory response level. By demonstrating the applicability of GA for a flat rotating plate structure, the approach can be extended to more complex damped rotating structures in the future.

7977-80, Session 11A

Modified approach for optimum position and sizing of piezoelectric actuator for steering of parabolic antenna

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Researchers are trying to identify various applications of piezoelectric actuators for shape control of structures. One of the applications currently being explored is shape control of antennas. It has been demonstrated that piezoelectric actuators can deform the antenna shell to obtain beam steering and shaping. Gupta et al obtained steering and shaping of radiation of a cylindrical parabolic antenna by generating nearly linear phase variation at the aperture plane, using piezoactuators. In optimal shape control, typically the number of sensors/actuators, their sizes, location and voltage to be applied on piezoelectric actuators etc are considered as the variables. Gupta, et al [2007] used genetic algorithm for optimization of paraboloid antenna. In this paper a modified approach for the optimization is presented for better results. It is proposed to modify objective function using penalty approach to include some constraints on beam steering, side lobe ratio and directivity. The new approach gives better result than the previous. A sample result is presented here.

7977-81, Session 11B

A friction damper with continuously variable post-sliding stiffness

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Proposed in this study is a kind of friction damper characterized a continuously variable post-sliding stiffness. It is able to provide an increased post-sliding force with the accretion of the deformation. Users could adjust the output force according to the performance target under the different level of earthquakes, thus enlightening a practical approach to the explicit structure control to satisfy all of the required performance objectives.

The proposed friction damper consists of a tube jacket, a piston, a rubber spring and a set of sliders. The inside surface of the jacket and the outside surfaces of sliders constitute the contact pairs. Wearable material shall be adopted for these contact interfaces. The rubber spring is used to provide the normal forces at the contact surfaces, which is constrained by the piston and the sliders. Because of its incompressibility, the rubber stiffness could be very high, and the stiffness is also adjustable by changing the area of the non-constrained surface of the rubber spring. The variable post-sliding stiffness of the damper is designed by curving the inside surface of the jacket along the piston movement path. Theoretically, a quadratic polynomial curve could result in a cubically increased post-sliding force-displacement relationship. Both numerical studies and experiments demonstrated a more desirable performance to prevent structural collapse than the conventional fiction dampers.

7977-82, Session 11B

Nonlinear semi passive vibration control based on synchronized switch damping with energy transfer between two modes

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Synchronized switch damping (SSD) technique has been widely developed due to their simplicity, low power consumption and good performance. This paper deals with a newly proposed SSD technique which is named synchronized switch damping with energy transfer (SSDET). The purpose of this research is to verify SSDET on one structure which is excited under both two modes. Two groups of piezoelectric patches were bonded on the structure in order to extract the energy from one mode and damp another mode respectively. Combining with a shared inductor and a resistor, they formed two LCR oscillators. The energy from source mode was firstly stored in the inductors and then transferred to the piezoelectric patches which aimed to damp the target mode. Such energy increased the inversion factor which is closely related to the damping in the SSD techniques so as to reach a better control. The experiment was carried out on a one edge clamped plate and the energy is transferred from its bending mode to torsion mode in order to control the latter. Experimental results showed the SSDET could perform an effective control on the torsion mode while the energy source mode was also suppressed. The test revealed that the threshold setting of the control strategy could increase the control performance which exhibits a good agreement with the simulation. The relationship between the attenuation of the target mode and vibration level of energy source mode also considered with the experiment. The stability was researched with the consideration of the vibration level and threshold value as well. Thus, such SSDET technique could provide a multimode structure control with an energy transfer between the different vibrating modes.

7977-84, Session 11B

Experiment research and nonlinear analysis to visco-elastic damping structure for whole-spacecraft passive vibration isolation system

L. Tan, B. Fang, W. Huang, Harbin Institute of Technology (China)

Visco-elastic damping material is applied to a new disc type of isolator for the whole-spacecraft passive vibration isolation system, which can be used to improve the dynamic environment during its ascent into orbit. The dynamic simulation analysis of the isolator is fulfilled by the PATRAN / NASTRAN. The isolation experiments are carried out to verify correctness of simulation scale model. The results of the simulation and the experiment show that the vibration transmissibility of the mass center decreases more than 40%. The accuracy of the Visco-elastic damping material applied in the new type of isolator is illustrated by combination of the theory analysis, simulation by FEM and experiment. In order to ascertain the optimal vibration isolation effect of the visco-elastic dampers, the experiments of the isolator with different damping area are performed. The results suggest that the resonance frequency increases simultaneously with the increase of the damping area. However, the decrease percent of transmissibility does not increase in accordance with the increase of the damping area. It can be seen that the damping rate manifests a saturation value. The issues of natural frequency drifts and the transmissibility decreases as excitation level raises are discussed by comparing vibration experimental datum. It is deduced that the nonlinear of visco-elastic damping material and structure in the vibration experiment is the main influence factors by the calculation of equivalent linear model and nonlinear model. Some solutions are put forward to improve the nonlinear issue.

7977-85, Session 11B

Performance analysis for a new whole-spacecraft isolation using viscoelastic damping material

B. Fang, S. Li, W. Huang, Harbin Institute of Technology (China)

There are several parts in this paper. First, the background of the application of viscoelastic material and structure vibration control is presented. Second, model of viscoelastic damping material is obtained, and the parameter of the fractional order derivative is used. Then, By a simple simulation experimentation we designed, the influencing factors of the damping in viscoelastic material was verified through comparing the theory and test results. In this part, we test serials of the the influencing factors, e.g. structure stiffness, the area of damping layer, different Geometry of damping layer, etc. Finally, simulation experiments are conducted to evaluate the performance of this structure by varying operational modes. It is more than 50 percent reduce in first order amplitude on both vertical and horizontal mode vibration by using the new Whole-spacecraft isolation. Results show that viscoelastic material applied in the new whole-spacecraft isolation is reasonable, and the vibration environment of satellite is improved.

Conference 7978: Behavior and Mechanics of Multifunctional Materials and Composites V

Monday-Wednesday 7-9 March 2011

Part of Proceedings of SPIE Vol. 7978 Behavior and Mechanics of Multifunctional Materials and Composites 2011

7978-01, Session 1

Progress on 3D finite element analysis with ferroelectric constitutive laws

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Linear piezoelectric finite elements have been deeply investigated and are readily available for use. The linear constitutive laws do not exhibit hysteresis loops in response to stress and electric field which are inherent in ferroelectric materials. A 3D finite element program has been developed to include ferroelectric and ferroelastic switching behavior. Currently, it is capable of handling full anisotropic material response for a multi-material system. The micromechanical model allows for switching between tetragonal, rhombohedral and orthorhombic phases using a generalized energy barrier criterion. This allows for analysis of problems where current experimental techniques would either be costly or unable to obtain a solution. This includes the optimization of macro-fiber composite geometry to maximize piezoelectric coupling, 3D crack tip analysis, simulations of phase changes, and failure analysis. This paper will discuss the techniques used in developing the FEM code along with the micromechanical switching criterion and their coupling. Supplementing this discussion will be preliminary results from running the code for different mesh geometries and material models.

7978-02, Session 1

Phase field models of ferroelectric materials as part of a multiscale modeling chain

B. Voelker, M. Kamlah, Karlsruher Institut für Technologie (Germany)

The phasefield theory of ferroelectrics introduces the polarization of domains as continuous order parameter. The heart of this theory is free energy density, which encodes all properties of the material.

In this talk, we discuss first the parameter identification in the free energy density. In contrast to conventional phenomenological methods, we identify the coefficients in the free energy density from ab initio and molecular dynamics results.

A procedure was established giving unique parameter values based on physical properties. Based on the theory obtained in this way, representative volume elements with typical domain configurations are constructed to derive effective elastic, piezoelectric, and dielectric small signal properties including extrinsic contributions stemming from reversible domain wall processes.

7978-03, Session 1

Phase transformations of ferroelectric rhombohedral to antiferroelectric orthorhombic in phase-field model of 95/5 PZT

W. Dong, C. S. Lynch, Univ. of California, Los Angeles (United States)

Ferroelectric materials are widely employed in many modern devices ranging from transducers and sonar to sensors and micromechanical devices. One of the most utilized ferroelectric materials is the ceramic

solid state solution Lead Zirconate Titanate, PZT. There is considerable interest in PZT that has a 95/5 ratio of Lead Zirconate / Lead Titanate. At this composition, PZT is ferroelectric-rhombohedral, FR, phase but the PZT is very close to the antiferroelectric-orthorhombic, AFO, morphotropic phase boundary. Experimentally, it has been shown that hydrostatic stress can be used to induce the 95/5 PZT to undergo a phase transformation from FR to AFO. The paper discusses the thermodynamics and constitutive behavior of this phase transformation. This leads to the creation of a 3D multiscale phase-field model based on the Time Dependent Ginzburg-Landau equation, TDGL, that can model the phase transformation behavior of 95/5 PZT. The TDGL evolves the system in the direction of thermodynamic driving forces to minimize the free energy of the system. These driving forces are from the structural, electrostatic, and mechanical energy terms. Experimental data are used to calibrate the constitutive equations and are used to verify the accuracy of the final model.

7978-04, Session 1

Constitutive model for rate dependent behavior of ferroelectric materials

T. Ikeda, K. Yoshida, T. Ueda, Nagoya Univ. (Japan)

A constitutive model for rate dependent behavior of ferroelectric materials was developed from the one-dimensional switching model [Ikeda et al., Proc. of SPIE, 7289 (2009), 728905]. The one-dimensional switching model has the following three features. (i) Four ferroelectric variants; the 0-degree variant, the 90-degree variant, the 180-degree variant, and the initial mixed variant, are considered. (ii) The required switching energy is approximated as a sum of two exponential functions of the volume fraction. (iii) A specimen is assumed to be comprised of grains with infinitesimal size, and the relationship between two grains with respect to the required switching energy is unchanged independently of the switching directions. Accordingly, the switching proceeds one-dimensionally. To take into account the effect of the loading rate, a function of the volume fraction rate was added to the required switching energy function. That made the energy wall higher at higher rates. To verify the validity of the present model, electro-mechanical behavior of a thin PZT plate was measured for various loading rates and simulated using the present model. The result showed the present model could capture the influence of the loading rate on the electric field - electric displacement diagram and the electric field - strain diagram, such that the coercive field increases with the loading rate.

7978-18, Session 2

Modeling the nonlinear behavior of macro fiber composite actuators

Z. Hu, R. C. Smith, North Carolina State Univ. (United States); M. Hays, W. S. Oates, The Florida State Univ. (United States)

Macro Fiber Composites (MFC) are planar actuators comprised of PZT fibers embedded in an epoxy matrix that is sandwiched between electrodes. Due to their construction, they exhibit significant durability and flexibility in addition to being lightweight and providing broadband inputs. They are presently being considered for a range of applications including positioning and control of membrane mirrors and configurable aerospace structures. However, they also exhibit hysteresis and constitutive nonlinearities that must be incorporated in models and model-based control designs to achieve the full potential of the devices. In this talk, we discuss the development of models that quantify the

hysteresis and constitutive nonlinearities in a manner that promotes subsequent control design. The constitutive models are constructed using the homogenized energy model for ferroelectric hysteresis and used to develop resulting system models. The performance of the models is illustrated validated with experimental data.

7978-19, Session 2

Time-dependent response of active composites with thermal, electrical, and mechanical coupling effect

A. Muliiana, H. Ben Atitallah, Z. Ounaies, Texas A&M Univ. (United States)

The mechanical and physical properties of materials change with time. This change can be due to the dissipative characteristic of materials like in viscoelastic bodies and/or due to hostile environmental conditions and electromagnetic fields. An experimental study on active fiber composite (AFC) having PZT5A fibers dispersed in epoxy shows that the mechanical response and electro-mechanical coupling behavior of AFC depend on time and temperature. The piezoelectric constants of the AFC also vary with the magnitude of applied electric field. We study time-dependent response of active fiber reinforced polymer composites, where the polymer constituent undergoes different viscoelastic deformations at different temperatures, and the electro-mechanical and piezoelectric properties of the active fiber can also vary with temperatures. A micromechanical model is formulated for predicting effective time-dependent response in active fiber composites with thermal, electrical, and mechanical coupling effects. In this micromechanical model limited information on the local field variables in the fiber and matrix constituents can be incorporated in predicting overall performance of active composites. We compare the time-dependent response of active composites determined from the micromechanical model with those obtained by analyzing the composites with microstructural details and available experimental data.

7978-20, Session 2

Estimating mechanical properties of bi-continuous two-phase composites for optimised multi-functionality

Y. Xia, E. I. Saavedra Flores, Swansea Univ. (United Kingdom); H. Peng, Univ. of Bristol (United Kingdom); M. I. Friswell, Swansea Univ. (United Kingdom)

High performance composite materials, including multi-functional and smart materials, require good design of the microstructure of the matrix and reinforcement. In bi-continuous composites the two phases are interpenetrating and continuous throughout the microstructure. This leads to improved mechanical properties over traditional discontinuous two-phase composites, such as increased elastic modulus and strength. In this paper, the effect of the phase volume fraction and phase contiguity on the mechanical properties of bi-continuous two-phase composites is investigated. The microstructure of the material is modeled using representative volume elements (RVEs). A microstructure with triply periodic minimal P interfaces between the two phases is considered and homogenization methods are used. A group of 'P-like' interface RVE models with different volume fractions were created and simulated using finite element analysis. A functional material with piezoceramic (PZT) and polymeric phases is chosen to demonstrate the modeling approach. The PZT phase is treated as elastic material, and the polymeric phase as an isotropic elasto-plastic material. The mechanical properties of the composite are highly sensitive to the overall volume fraction of the reinforcement; increasing fraction of PZT produces a stiffer composite, and increasing the fraction of polymer gives an effective plastic trend in the composite mechanical behavior. Finally, a group of RVEs with different contiguities and the same volume fraction is generated and their properties investigated using homogenization theory and finite element

analysis. The mechanical properties are significantly affected by the contiguity of the PZT phase when the volume fraction is fixed. The phase contiguity is optimised for such composite structures.

7978-21, Session 2

Micromechanical analysis of constitutive properties of active piezoelectric structural fiber (PSF) composites

K. Ng, Q. Dai, Michigan Technological Univ. (United States)

Recent studies showed that the active piezoelectric structural fiber (PSF) composites may achieve significant and simultaneous improvements in sensing/actuating, stiffness, fracture toughness and vibration damping. These characteristics can be of particular importance in various civil, mechanical and aerospace structures. The PSF is fabricated by coating the piezoelectric shell to the silicon carbide core fiber with Electrophoretic Deposition (EPD) process to overcome the fragile piezo-ceramic nature. The PSF composite laminates are made of longitudinally poled PSFs that are unidirectionally deployed in the polymer binding matrix. The PSF laminate transducer has electrical inputs/outputs that are delivered through a separate etched interdigital electrode layer. This study analyzed the electromechanical properties with the generalized dilute scheme for active PSF composite laminate with multi-inclusions. The well-known Mori-Tanaka approach was used to evaluate the Eshelby's tensor. To accurately predict the transverse properties, the role of mixtures were applied by considering the inclusions' geometry and shape. The micromechanical finite element modeling was also conducted with representative volume element (RVE) to compare with the micromechanics analysis on the electromechanical properties. The micromechanics analysis and finite element micromechanical modeling were conducted with varied fiber geometry dimensions and volume fractions. These comparison studies indicate the developed micromechanics models with generalized dilute scheme can effectively predict the properties of multi-inclusion PSF composites.

7978-22, Session 2

Functionally-modified bimorph PZT actuator for cm-scale flapping wing

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Army combat operations have placed a high premium on reconnaissance missions for Unmanned Aerial Vehicles (UAVs) and Micro Air Vehicles (MAVs). One approach for accomplishing this mission is to develop a biologically inspired flapping wing insect that can maneuver into confined areas and possess hovering capabilities. Analysis of insect flight indicates that in addition to the bending excitation (flapping), simultaneous excitation of the twisting degree-of-freedom (pitching) is required to manipulate the control surface of the wing adequately. Traditionally, bimorph actuators have been used in many applications to excite the bending degree-of-freedom. The pitching motion is introduced by adding a bend-twist coupling that arises from anisotropic material symmetry. In laminated or layered structures, bend-twist coupling is governed by the existence of at least one anisotropic layer not aligned with the primary plate axes. By adding a layer of off-axis piezoelectric segments to a PZT bimorph actuator, thereby producing a layered structure to be referred to as a functionally-modified bimorph, bend-twist coupling may be introduced to the flexural response of the layered PZT. Furthermore, by selectively charging off-axis layers in specific combinations with the bimorph, the response of the functionally-modified bimorph may be tailored yielding a biaxial actuator to actively control the flapping wing response. This current study presents analytical and experimental investigation of functionally-modified bimorph PZT designs intended for active bend-twist actuation of cm-scale flapping wing devices.

7978-23, Session 3

Dynamics of ion transport in a bio-derived ionic transistor

V. B. Sundaresan, H. Zhang, N. Kitchen, Virginia Commonwealth Univ. (United States)

Biological processes and electromechanical function in ionic polymers share ion transport as the fundamental processes for sensing, actuation and energy harvesting. Inspired by the similarity in protein-bound cell membranes and polypyrrole membrane (an ionic polymer), our group is developing a hybrid device that provides the template for integrating biology and electronics. The integrated device, referred to as a bio-derived ionic transistor (BIT), consists of a bilayer lipid membrane (BLM) formed on a polypyrrole membrane and has two inputs that regulates the output of the device. A chemoelectrical, chemical or mechanical input to the protein in the BLM serves as the gate signal; the ionic gradient across the thin-film transistor serves as the source and the polypyrrole membrane serves as the drain in the proposed device. The integrated device is an assembly of BLM with proteins, a gel layer and a protein-bound BLM formed in the pores of an insulating material and the assembly in each pore is treated as a fundamental transistor unit. The array of pores on a 2-D sheet is proposed for sensing and energy harvesting applications and a NEMS linkage of these transistor devices is proposed as artificial muscles. This proceedings article will discuss the constructional features of proposed actuator, fabrication procedure of a prototype actuator and present a molecular dynamics simulation of the ion transport processes in a unit transistor device. The Monte-Carlo based simulation will analyze the open-loop amplification properties of the ionic transistor and relate the inputs to experimentally measured outputs of this device.

7978-24, Session 3

Nonlinear mechanics and structural dynamics of azobenzene photoelastomer films

L. Cheng, Y. Torres, W. S. Oates, The Florida State Univ. (United States)

A nonlinear photomechanical shell model is developed to understand polarized light induced bending deformation and structural dynamics of photoelastomer films. The model is compared with data in the literature on azobenzene photoelastomers that undergo large bending rotation from polarized light. Model comparisons to static and dynamic free displacement experiments are given and predictions of static bending forces and power efficiencies for a known laser input power are computed. Insight on the internal microstructure evolution are discussed in comparison with the photomechanical finite element 1shell model to illustrate polarized light dependence on bending. In addition, the size of the film is shown to have a strong effect on photomechanical efficiency. As the area of the film is reduced, significant increases in efficiency for a fixed laser power input is predicted. This has important implications on developing efficient MEMS scale actuators that can be remotely actuated by light.

7978-25, Session 3

Finite element modeling of electromechanical behavior of a dielectric electroactive polymer actuator

A. Deodhar, S. S. Seelecke, North Carolina State Univ. (United States)

Dielectric Electroactive Polymers (DEAP) will undergo large deformations when subject to an electric field making them an attractive material for use in novel actuator systems. There are many challenges with DEAP actuators resulting from their inherent electromechanical coupling and

non-linear material behavior. FE modeling of the material behavior is a useful tool to better understand such systems and aid in the optimal design of prototypes. These modeling efforts must account for the electromechanical coupling in order to accurately predict their response to multiple loading conditions expected during real operating conditions. Some work in this regard has been presented by Zhao et al (2009)[1] and Wissler et al (2004)[2].

This paper presents a Finite Element model of a dielectric elastomer undergoing out-of-plane, axisymmetric deformation. The response of the elastomer was investigated while it was subjected to mechanical and electric fields and combined electro-mechanical actuation. The model was developed using the commercial Finite Element Modeling software COMSOL and the results are validated against experiments conducted by York et. A.I (2009) [3].

7978-26, Session 3

A novel hp-FEM model for IPMC actuation

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The system of Poisson and Nernst-Planck equations is generally used to describe the charge transport - which includes the ionic migration and diffusion - in ionic polymer-metal composite (IPMC) materials. This process is a key mechanism for the electromechanical transduction of the material. As the system coupled with elastostatic equations is nonlinear and for a domain with two electrodes, the charge concentration differences occur in a very narrow region near the boundaries, the required computing power for a full scale finite element (FE) model is, especially in 3D, rather significant. Furthermore, it is challenging to find a mesh that would be optimal in terms of calculation time, required computing resources, and calculation accuracy. Most of the commercially available FE software for multi-physics problems has rather strict restrictions in terms of element types, mesh types, and choice of polynomial degrees. For instance, in many cases irregular meshes are not supported and the solution error estimate is unknown. In this paper, we explore the option of using hp-FE modeling to solve the Nernst-Planck, Poisson, and elastostatic equation system. We demonstrate how the multi-meshing and the time dependent adaptivity help to control the error of the solution and also how the problem size is reduced. Both 2D and 3D versions of the model are implemented in Hermes which is a space- and space-time adaptive hp-FEM solver. Full mathematical derivation of the weak formulation of the system of equations and the solution comparison with a non-adaptive conventional FEM is presented. The model is validated with experimental results. Furthermore, we discuss how using the Hermes as a modeling tool, can help in studying and improving the IPMC materials.

7978-27, Session 3

Unusual light-induced viscoelasticity of azobenzene liquid crystal elastomers

H. Wang, W. S. Oates, The Florida State Univ. (United States)

Liquid crystal elastomers exhibit a large number of field-coupled mechanical characteristics including light induced deformation, flexoelectricity, thermal shape memory, electrostriction, and chemically induced deformation. Light induced deformation has received considerable attention recently due to its unique functionality for morphing structure applications. These elastomers are typically doped with liquid crystal azobenzene chromophores which undergo a photoisomerization from a rod shape (trans phase) to kinked shape (cis phase).

When these chromophores are synthesized within an elastomer, the azobenzene liquid crystals act as molecular motors and do work on the host elastomer film. This process depends on the wavelength and polarization of light. Recently, it has been reported that the kinked cis phase may revert back to the original trans phase while rotating 90 from polarized light with a wavelength of 440 nm. It is shown here that liquid

crystal kinetics and viscoelasticity of the host elastomer network play an important role in understanding this unusual constitutive behavior. In this study, a new scheme is developed to describe viscoelastic behavior and coupling with liquid crystal microstructure evolution. Nonlinear continuum mechanics coupled with liquid crystal microstructure is implemented in a finite element model and correlated with recent temperature dependent experimental results to understand this behavior.

7978-28, Session 3

Efficient electro-chemo-mechanical finite element model for the simulation of patterned high surface area electrode in ionic polymer transducers

J. Najem, Virginia Polytechnic Institute and State Univ. (United States); B. J. Akle, W. Habchi, Lebanese American Univ. (Lebanon); T. Wallmersperger, Technische Univ. Dresden (Germany); D. J. Leo, Virginia Polytechnic Institute and State Univ. (United States)

An IPT is made of an ion saturated polymer usually Nafion, sandwiched between two electrodes made of a mixture of Nafion and electrically conductive particles usually RuO₂ or platinum. Nafion is an acid membrane in which the cations are mobile while the anions are covalently fixed to the polymer structure. Upon the application of an electric potential on the order of 2V at the electrodes the mobile positive ions migrate towards the cathode leading to bending strains in the order of 5%. Our earlier studies demonstrate that the cations develop thin boundary layers around the particles in the electrode. These studies were supported by the results of several finite element models. Previously we used these models to demonstrate the importance of adding particles in the electrode. The electro-chemical model is based on the Nernst-Planck and the Poisson's equations, while the chemo-mechanical model is based on previous studies (Akle and Leo) in which the authors experimentally showed that the mechanical strain in IPTs is proportional to a linear term and a quadratic term of the charge accumulated at the electrode. These models were limited to simulate few particles (approximately 200 particles) due to the computational limitations. In this study we use the original model and build a efficient finite element model, in which the particles in the electrode area are replaced by special elements with increased permittivity and mobility; that are capable of precisely predicting the charge accumulation. The results from model simulations are compared to experimental results of patterned IPT actuators.

7978-29, Session 3

Optomechanical behavior of photochromic liquid crystal polymer film composites

Y. You, C. Xu, B. Wang, Y. Huo, Fudan Univ. (China)

Liquid crystal polymer networks (LCNs) are cross-linked polymeric networks with liquid crystal messogens. LCNs can be actuated by thermal, electrical and opto stimulus upon suitable design of the network molecules and structures. Photochromic molecules such as Azobenzene can be added to utilize the opto-mechanical actuation. To further enhance the strength of the material, multilayered structures with LCN thin films sandwiched with some stronger transparent polymer substrates are designed as well. Such photochromic LCN composites can be applied as actuators and sensors in Micro-Opto-Mechanical Systems (MOMS).

Both beam and plate models are studied for such film composites in this work. Analytical solutions are obtained under suitable simplifications. Their study show that the bending moment of the composite has two contributions, the opto moment due to the decay of the light intensity and the bi-film moment because of the light induced contraction of LCNs. The opto moment and its effect on the bending of LCN films have been

studied recently by our group and many others. The results indicated that very large deflections can be produced by UV light irradiations and the bending moment, named opto moment, is due to the inhomogeneous distribution of the light induced contraction. The inhomogeneity is a result of the light absorption of the materials. Both Beer's and non Beer's decay laws are considered. In any case, the magnitude of the opto moment and the resulted bending curvature are relatively small compare to the light induced contractions. The direction of the opto moment is uniquely determined by the directions of the liquid crystal directors and the incident light. However, for film composites, the contraction itself can be utilized in the bi-film moment similar to the well known bi-metal bending model. Thus, the magnitude of the total moment and the bending curvature can be enhanced largely. Moreover, the bending direction, i.e. the direction of the total moment, can be well controlled by suitable design of the multilayered structures.

Various boundary conditions such as, free edged, simple supported and clamped boundaries are studied and their effects on the light induced bending behavior are analyzed by using finite element simulations. Some interesting bending patterns of the film composites are shown to be possibly produced either by patterned layer structures or by patterned incident light.

7978-30, Session 3

Self-sensing of DEAP actuators: capacitive and resistive experimental analysis

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Dielectric Electro-Active Polymers (DEAP's) have become attractive material for various actuation and sensing applications such as light weight and energy efficient valve and pumping systems. The materials ability to act as both actuator and sensor enable DEAP actuators to have "self-sensing" capabilities. This advancement provides low cost actuator systems that do not require external sensors for feedback control. This paper explores the resistive and capacitive sensing capabilities of a DEAP actuator under loading conditions typical for pumping and valve applications. The capacitive sensing capabilities of the actuator are tested using a method similar to that used by Jung et al. (2008)1 which uses the DEAP actuator as a variable capacitor in a high pass filter circuit. The resistive sensing capabilities of the DEAP actuator are tested using a full Wheatstone bridge configuration with the DEAP serving as one of the variable bridge resistors. Both of these sensing circuits produce a direct voltage output when the actuator is displaced. This response is studied under a variety of excitation schemes and displacement rates.

7978-31, Session 3

Mechanics of light-activated network polymers

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Mechanically responsive, environmentally activated polymers can undergo large, complex deformation in response to external stimuli such as temperature, light, and chemical changes. Light as a stimulus provides unique application potential because it allows for remote, rapid, and isothermal activation of the material with precise spatial control via existing optical technologies.

In this work we develop a multi-physics constitutive modeling framework to simulate the continuum scale, photo mechanical behavior of light-activated polymers and implement it into a finite element analysis setting. This framework is independent of specific underlying photo-stimulation mechanisms and is discussed in the context of photo-activated shape memory polymers and network rearranging polymers. We then employ the framework to model a light-activated network rearranging polymer system, which is relaxed of stress upon irradiation with UV light. A suite of characterization and application-oriented experiments are carried

out to calibrate and validate the predictive capability of the model. The calibrated model is used to study several applications such as photo-activated stress relaxation of notched specimens, bending actuation, the buckling of equi-biaxially deformed and irradiated patterned films, and photomechanically-formed channels and ridges in a substrate. In all cases, good agreement is obtained between theory/simulation and experiments.

7978-32, Session 4

Adaptive control design for hysteretic smart systems

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Ferroelectric and ferromagnetic actuators are being considered for a range of industrial, aerospace, aeronautic and biomedical applications due to their unique transduction capabilities. However, they also exhibit hysteretic and nonlinear behavior that must be accommodated in models and control designs. If uncompensated, these effects can yield reduced system performance and, in the worst case, can produce unpredictable behavior of the control system. In this presentation, we address the development of adaptive control designs for hysteretic systems. The resulting algorithms permit the adaptive estimation of certain model parameters as well as control gains for vibration attenuation or tracking. Properties of the control design are illustrated through numerical examples.

7978-33, Session 4

Some new aspects of electroelastic tractions at crack faces in pieoelectrics

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Cracks in piezoelectric solids have been subject to fracture mechanical investigations for more than 30 years. All essential concepts of linear elastic fracture mechanics have nowadays been generalized towards coupled electromechanical boundary value problems. In the early years of research, boundary conditions at crack faces have been adopted from pure mechanical systems assuming traction free boundaries. From the electrostatic point of view, cracks have been assumed to be either free of surface charge or fully permeable, i.e. "invisible" to the electric field. Later, limited permeable crack boundary conditions have become popular among the community, however still assuming traction free crack faces. Recently, the theoretical framework has been extended including electrostatically induced mechanical tractions into crack models yielding a significant crack closure effect. However, these models are still simple neglecting e.g. piezoelectric field coupling. As a consequence, the tractions do not depend on the direction of the electric field with respect to the direction of material polarization. In this paper, an extended model is presented, accounting for the full piezoelectric coupling. The electroelastic crack closure now depends on the electric field direction. Second, the new model yields an effect coupling a mechanical load parallel to the crack faces with the Mode-I stress intensity factor (SIF). Finally, the model shows a new shear effect, i.e. the Mode-I SIF is influenced by an in-plane shear load. However, these nonlinear features, which are unique in fracture mechanics, do only appear for specific electromechanical loading configurations.

7978-34, Session 4

Effects of polarization switching and dielectric breakdown on the mode I energy release rate in rectangular piezoelectric ceramics with a single-edge crack

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Piezoelectric lead zirconate titanate (PZT) ceramics have become very popular in sensor and actuator components of smart materials and structures. To be successful in such device applications, piezoelectric ceramics must provide adequate reliability and durability under severe electromechanical loading conditions. Successful designs require comprehensive evaluation of crack behavior in piezoelectric ceramics, and fully understanding of the piezoelectric fracture mechanics parameters such as energy release rate is of great importance. Over the past two decades, there has been controversy about the electrical boundary conditions across the piezoelectric crack face. On the other hand, it is well known that under a high negative electric field, the nonlinear effect due to the polarization switching affects the piezoelectric crack behavior. It is also expected that the fracture behavior of piezoelectric ceramics is influenced by the dielectric breakdown under a high positive electric field.

This work examines the mode I energy release rate for a single-edge crack in rectangular piezoelectric ceramics under electromechanical loading. A crack was created normal or parallel to the poling direction, and electric fields were applied parallel/antiparallel to the poling. A nonlinear finite element analysis was employed to calculate the energy release rate for the permeable, impermeable, open and discharging crack models. The effect of applied electric field on the energy release rate was then discussed under various crack face boundary conditions. The effects of localized polarization switching and dielectric breakdown on the energy release rate were also examined.

7978-35, Session 5

Correlation between the thermal and mechanical responses and the percolation threshold in an epoxy SMP/nanotube system

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In this study the epoxy resin is Veriflex E2, a two-part thermoset shape memory polymer (SMP) supplied by CRG Industries. This resin is modified by the addition of differing contents, 0.1, 0.2, 0.3, 0.4 and 0.5 wt%, of NC-7000 multi-walled carbon nanotubes supplied by Nanocyl. A sequence of high shear mixing and horn sonication was used to achieve a satisfactory dispersion of the nanotubes in the resin. The final mixtures were cured in a closed mould with the following thermal cycle: temperature ramped up to 120°C at 2°C/min, held at 120°C for 4 hours, ramped up to 150°C at 2°C/min followed by a further dwell period of 4 hours at 150°C.

The addition of the carbon nanotubes to the base SMP resin produces an electrically conductive composite. Compared to the neat SMP control, the addition of 0.3 wt% of carbon nanotubes produced a sharp increase in conductivity to the order of 10⁻³ S/m. However, at the highest nanotube content of 0.5 wt% the conductivity did not change substantially from that of the 0.3 wt% sample. Scanning electron microscope (SEM) observation of the 0.3 wt% nanocomposite showed that carbon nanotube aggregates were localised in the thermosetting blend. It is believed that the selective localisation of the conductive nanoparticles resulted in the formation of conductive percolation pathways.

The glass transition temperature (T_g) of all the nanocomposite blends produced was determined by modulated differential scanning calorimetry (MDSC). The T_g of the control SMP was 93°C. The addition of 0.1 and 0.5 wt% of nanotubes produced a slight T_g reduction of 1-2°C. At the percolation threshold of 0.3 wt% of CNTs the T_g reached a

minimum value, approximately 9°C below the control. A similar T_g trend for conducting filler - insulating polymer systems has been reported previously [1].

Flexural strength test data showed a similar reduction-recovery trend around the 0.3 wt% percolation threshold concentration. The SMP control, 0.1 wt% and 0.5 wt% samples displayed similar flexural strength and ductile failure. The flexural strength of the 0.2 wt% and 0.3 wt% samples showed a sharp decrease and displayed brittle failure. The flexural modulus remained constant for all samples at approximately 3.8 GPa.

Simple shape fixing ability tests showed similar and consistent responses from all the nanocomposite blends produced.

The current message is that the presence of carbon nanotubes in this epoxy shape memory polymer can influence the thermal and mechanical properties of the cured blends. The evolution of these properties can be correlated to the percolation threshold concentration where a transition occurs from a local to an infinite conductive state.

[1] "Glass transition temperature depression at the percolation threshold in carbon nanotube-epoxy resin and polypyrrole-epoxy resin composites", S. Barrau, P. Demont, C. Maraval, A. Bernes and C. Lacabanne, *Macromolecular Rapid Communications*, 2005, Vol. 26, Issue 5, p.p. 390-394.

7978-36, Session 5

Fundamental investigations of carbon nanotubes working as actuators

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Carbon Nanotubes (CNTs) have some extraordinary properties like their low density, high Young's modulus and excellent electrical conductivity. Therefore they seem to be one of the most interesting materials of the 21st century to solve the great challenges for the development of new high tech materials.

One special feature is their ability to strain within a matrix of free-movable ions and an electrical field. Recent publications show a divergent behaviour of CNT-actuation. There is a discussion about the actuation-character, if it is either an electrostatic or a quantum-mechanical effect or a combination of both. That's the motivation to investigate the stretching-process more in detail. Within this paper we give an overview about our investigations about the electrical, mechanical and morphological studies of CNT-structures. Furthermore several in-plain and out-of-plain experiments and their corresponding results are shown. Within these experiments several kinds of CNT-dominated structures (randomly oriented Bucky-Papers, aligned Bucky-Papers and CNT-Arrays) are tested with the aim to determine the most efficient and usable structure as well as the key-mechanism of CNT-actuators.

It was found that the structural composition can change dramatically by switching the manufacturing process, but the composition itself has a great impact on most of the electro-mechanical properties.

It will be discussed how to optimize the CNT-based structure for their requirements as actuator.

7978-37, Session 5

Damping of multi-scale fiber reinforced polymer-based composites

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Multi-scale fiber reinforced polymer-based composites (MFPC) were fabricated by incorporating multi-wall carbon nanotube (MWNT) with traditional continuous fiber reinforced composites. Firstly, MWNT was

dispersed in polymer with help of sonicator, and then a vacuum assitant method was applied to infiltrate continuous fiber with this MWNT solution. A sinusoidal excitation was applied on the prepared MFPC specimens with a Materials Testing Systems. From the response under sinusoidal excitation, the storage modulus, loss modulus and loss factor of MFPC were obtained. The experimental results showed that compared with traditional continuous fiber reinforced composites, the damping of MFPC was significantly improved. This damping improvement was dependent on the concentration and aspect ratio of MWNT, and was also dependent on the amplitude and frequency of excitation.

Theoretical model was derived based on micromechanics to reveal the interfacial energy dissipation and the corresponding effect on damping of MFPC. The interfacial friction dissipation depends on the interfacial sliding length and interfacial friction force. Loss factor then will be calculated as a ratio of the friction dissipation to the strain energy. In this paper, one cell containing a nanofiber and the around matrix was taken out for calculating the energy dissipation and strain energy. Dynamic tribology theory indicated that the interfacial friction during vibration was a dynamic process and the friction coefficient was dependent on the vibration frequency and the experimental results showed that friction coefficient decreased upon frequency. Also, the more longer of nanofiber, the more higher of relativity between damping and vibration frequency. The theoretical and experimental results showed a same relationship of damping and vibration amplitude and frequency.

7978-38, Session 6

Strain dependent visco-elastic response of CNFs reinforced epoxy composites

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Recent advances in the production and availability of nanoscale materials has led to a significant interest in the use of nanoscale fillers in order to augment and tailor material performance in nanostructured composites. A specific area of interest is the use of high aspect ratio fillers, such as carbon nanotubes (CNT) and carbon nanofibers (CNF) to augment the damping capacity of nanostructured composites. Previous work has show the use of high aspect ratio fillers to significantly enhance the damping capacity at low frequency by more than 100%; however, the enhancement achieved has been predicated on strain levels in the composite. Our previous studies have indicated a strong strain dependent response in the nanostructured composites utilizing CNF to augment damping capacity. This is due, in part, to the random distribution of fiber orientations seen in the nanostructured composites. The random distribution of filler orientations is thereby relative to the load applied to the composite that results in a critical shear stress thresholds being surpassed at the nano scale, allowing the filler to slip relative to the matrix, resulting in frictional energy dissipation as heat and thereby inducing damping to the high aspect ratio filler nanostructured composite. In light of the promise this technology holds for use in engineered applications requiring specific damping performance, there remains a fundamental lack in understanding of the precise mechanisms and thereby a lack of ability to accurately predict material performance, which is limiting application of the technology. This study looks at the effect of the random filler orientation of CNF included composites and examines the viscoelastic response of the composite relative to the strain applied. Furthermore, this study looks at the strain dependent nature of the viscoelastic response and develops analytical modeling tools to look at the effect of the strain dependent viscoelastic response seen in previous studies with the aim of achieving a better fundamental understanding of the strain dependent nature of the viscoelastic response seen in high aspect ratio nano filled composites.

7978-39, Session 6

Study of the graphene/nanofiber nanopaper composite

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With the development of modern aviation industry and materials science, the structural components of aircraft platforms are being transitioned from metals to polymeric matrix composites. Nanocomposites are also lighter at the same time, each component can promote the others, it compensates for the shortcomings of traditional materials fully and makes the materials have multiple functions, so this become research focus.

In this paper, we used the improved Hummer method to oxidize graphites for the synthesis of graphene oxide (GO). The GO was exfoliated by ultrasonication and chemical reduction carried out by hydrazine hydrate to get graphene. Then admixture graphene and nanofiber with capability of high conductivity in a certain ratio to making of fabricate nanopaper, and then form composite materials by incorporating nanopaper with epoxy resin.

The morphology, structure and electrical properties of nanopaper were characterized by scanning electron microscope (SEM) and four-point probe measurement. Measurement of the electromagnetic interference (EMI) shielding of the material is done by vector analyzer. The experimental result proves that the conductivity of the nanocomposite with graphene added is better than composite materials with pure nanofiber, and with the added quantity growing, the conductivity grows more excellent. The electromagnetic interference (EMI) shielding experiment prove that it can achieve the request of EMI which the max shielding rates of the composite materials entirely approach or exceed 99.9%, it show that the materials take on the multifunction in combination of electrical properties and EMI shielding capability.

7978-40, Session 6

Improved electromechanical property of nanocomposites with aligned PZT nanowires

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The piezoelectric materials have become quite common in a wide range of applications, including structural health monitoring and power harvesting. However, bulk piezoelectric materials are often brittle and difficult to apply. The 0-3 piezoelectric composites can not only overcome the brittle nature of monolithic piezoceramics but also increase flexibility but in turn significantly reduce the composites electromechanical coupling. In order to enhance the electromechanical performance of 0-3 active composite, previous research have demonstrated that using Lead Zirconate Titanate (PZT) nanowires as active reinforcement could significantly increase the piezoelectric coupling coefficient (d_{33}) and energy storage density compared with the samples with nanorods or nanoparticles. However, the d_{33} is still low and limit its application. Therefore, this paper will create a nanowires alignment technique to increase the electromechanical property compared to composites with randomly dispersed fillers. PZT nanowires are used for the nanocomposites and synthesized with a hydrothermal method. A high frequency alternating electric field is used to align the nanowires in the direction of the electric field. SEM analysis will show the success of the alignment. The LCR meter, Sawyer-Tower circuit and laser interferometer are used to characterize the nanocomposites of dielectric permittivity, energy density and d_{33} , respectively. This work will demonstrate that a significant increase energy density and piezoelectric properties of 0-3 nanocomposite can be achieved by alignment of the PZT nanowires. The findings of this novel research will lead to broad interest due to the ability to use reinforcement orientation control to enhance the performance of nanocomposites.

7978-41, Session 6

Solid and porous melt blended polylactide-chitin composites

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This study details the fabrication and foaming of melt blended polylactide (PLA) and chitin composites. The chitin used for compounding was as-received, in nano-whisker form and in nano-whisker form with a compatibilizing agent. The chitin nano-whiskers were produced by an acid-hydrolysis technique and their morphology was examined with transmission electron microscopy. Composites of chitin and PLA were prepared by a micro-melt mixer with varying amounts and types of chitin added to the PLA. The composites were characterized for their thermal, rheological and mechanical behavior. Chitin was found to decrease the thermal stability but increase the crystallinity of PLA. Addition of chitin was also found to reduce the viscosity of the composites even though chitin is a stiffer phase. The reason for this observation is believed to be due to the hydrolysis of PLA during melt blending of chitin in suspension. The stiffness of the composites was found to increase with increasing chitin content while the strength was found to decrease. Porous PLA-chitin composites were produced by a two step batch foaming technique and the expansion behavior was correlated with the visco-elastic observations.

7978-42, Session 6

Spherically shaped micron-size particles reinforced PC and PMMA composites for improving energy absorption capability

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The focus of this study is to experimentally investigate spherically shaped micron-size particles reinforced PC and PMMA polymer composites for improving energy absorbing capability such as toughness and low-velocity impact resistance. In this study, a solution mixing method was developed to fabricate both PC and PMMA polymer composites with spherically shaped micron-size particles inclusions. The morphology of the fracture surfaces of polymer composites was examined by using Scanning Electron Microscopy. Strain-rate dependent response of both PC and PMMA polymer composites was investigated in tension. Low-velocity penetration testing was performed for both polymer composites and the key mechanisms responsible for the observed energy absorption capability were discussed in this study.

7978-43, Session 7

Enhanced thermal conductivity of novel multifunctional polyphenylene sulfide composites embedded with heat transfer networks of hybrid fillers

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Today's smaller, more powerful electronic devices, communications equipment, and lighting apparatus required optimum solutions for heat dissipation. Traditionally, metals are widely known for their superior thermal conductivity; however, their good electrical conductivity has limited their applications in heat management components for microelectronic applications. In this context, the next generation heat management materials are expected to possess high thermal

conductivity and superior electrical insulating ability. This prompts the requirement to develop novel plastic composites that satisfy multifunctional requirements thermally, electrically, and mechanically. Furthermore, the moldability of polymer composites would make them ideal for manufacturing three-dimensional, net-shape enclosures and/or heat management assembly. Using polyphenylene sulfide (PPS) as the matrix, heat transfer networks were developed and structured by embedding hexagonal Boron Nitride (BN) alone, blending BN fillers of different sizes and shapes, as well as hybridizing BN fillers with carbonaceous nano- and micro-fillers. A series of parametric studies were conducted to elucidate the effects of types, shapes, sizes, and hybridization of fillers on the composite's thermal, electrical, and mechanical properties. The use of hybrid fillers, with optimized material formulations, was found to effectively promote a composite's thermal conductivity. This was achieved by optimizing the development of an interconnected thermal conductive network through structuring hybrid fillers with appropriate shapes and sizes. The thermal conductive composite affords unique opportunities to injection mold three-dimensional, net-shape microelectronic enclosures with superior heat dissipation performance.

7978-44, Session 7

Elastomeric composite materials for shock mitigation

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The primary objective of this research effort is to create an elastomeric composite material for blast-induced shock-wave management through material design by both small-scale heterogeneity and anisotropy. The initial material of interest is a polyurea system that is lightly cross-linked and a two-phase polymer which consists of the diamine component Versalink P-1000 as the soft block and the diisocyanate component Isonate 143L as the hard block. Commercially available analogs to this polyurea system are also being investigated. Furthermore, polyurethanes with alcohols analogous to the current diamine component are being explored in order to provide a comparison to the polyurea systems. Lastly, we are evaluating the impact of additives, both those that are covalently bonded and those that are simply mechanically bound. The additives of interest include both untreated and surface treated milled glass fibers, dendritic polyamines, and silica micro- and nano- particles with both unmodified and modified surfaces. In this work, the properties of the resultant elastomeric materials are mechanically and thermally characterized using durometer testing, dynamic mechanical analysis (DMA) testing, and differential scanning calorimetry (DSC) testing in order to determine the hardness, storage and loss moduli, and glass transition temperature of the composites, respectively. Preliminary results indicate that the mechanical and thermal properties of the material can be significantly altered through such modifications. The work described here is part of an ongoing effort to understand the impact of both chemistry modifications and additives on the ultimate properties and performance of the host elastomeric material.

7978-45, Session 7

Development of a nonlinear acoustic metamaterial for impact mitigation

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We constructed a nonlinear acoustic metamaterial by forging a highly nonlinear granular chain for efficient energy transmission and a dispersive and deformable linear medium for shock mitigation. Leveraging the extremely distinctive natures of linear and nonlinear media, we can

efficiently manipulate and redirect wave propagation in the acoustic metamaterial with an added degree of freedom. Based on the newly created nonlinear metamaterial, we built a prototype of a regenerative acoustic filter, which transmits or rejects external excitations in a selected range of frequencies and amplitudes without active modulation. This is an improvement over the current frequency-tunable bandgap structures. In experiments the prototype demonstrated that nearly 95% of impact energy was transmitted under the low amplitudes, whereas only 15% of the energy was relayed to the protected medium for the high impact situation by exhibiting efficient shock absorption mechanism. We modeled the wave propagation and impact mitigation in the nonlinear acoustic metamaterial using combined discrete particle simulator and finite element method. As a result, we found that the numerical results are in excellent agreement with the experimental results. Such a nonlinear acoustic metamaterial can be used to build an intelligent shock absorption device for selectively transmitting signals, at the same time protecting from unwanted disturbances. For example, it could make it possible to develop a head-mounted system for soldier protection against blast, while largely retaining situational awareness in battle fields.

7978-46, Session 7

Semi-active optimization of 2D wave's dispersion into mechanical systems by the mean of periodically distributed shunted piezoelectric patches: a new class of adaptive metamaterials

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Research activities in smart materials and structures are very important today and represent a significant potential for technological innovation in mechanics and electronics. The growing interest of our society in the problem of sustainable development motivates a broad research effort for optimizing mechanical structures in order to obtain new functional properties such as noise reduction, comfort enhancement, durability, decreased ecologic impact, etc. In order to realize such a multi-objective design, new methods are now available which allow active transducers and their driving electronics to be directly integrated into otherwise passive structures. The number of potential applications of these approaches is growing in many industrial fields such as civil engineering, aerospace, aeronautics, ground transportation, etc. The main research challenge today deals with the development of new multi-functional structures integrating electro-mechanical systems in order to optimize their intrinsic mechanical behavior to achieve desired goals.

In the past few years, a technological revolution has occurred in the fields of integrated Micro Electro Mechanical Systems that offers new opportunities for smart structures design and optimization. We know today that the mechanical integration of active smart materials, electronics, chip sets and power supply systems is possible for the next generation of smart "composite" structures that can be considered as a new class of adaptive metamaterials. By using such an integrated active or hybrid distributed set of electromechanical transducers, one can attain new desired functionalities. In this sense, one can speak of "integrated distributed smart structures".

In this paper, we present an application of the Floquet-Bloch theorem in the context of electrodynamics for vibroacoustique power flow optimization by mean of distributed and shunted piezoelectric material. The main purpose of this work is first to propose a dedicated numerical approach able to compute the multi-modal wave dispersions curves into the whole first Brillouin zone for periodically distributed damped 2D mechanical systems. By using a specific indicator evaluating the evanescent part Bloch's waves, we optimize, in a second time, the piezoelectric shunting electrical impedance for controlling energy diffusion into the proposed semi-active distributed set of cells.

7978-47, Session 7

Optimization of magnetoimpedance and stress-impedance effects in single-microwire polymer composites for stress monitoring

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Considerable interest has been aroused by the discovery of a so-called giant magnetoimpedance effect (GMI) and stress-impedance (GSI) in soft ferromagnetic materials for sensing applications [1-3]. Most recently, a new kind of multifunctional microwire composite with outstanding MI properties and microwave tunable properties has been developed [4, 5]. With a multiscale structure that allows for a significant coupling of internal and external stresses, the microwire composite is expected to show a sensitive response to the applied stress in a wide range. The aim of this work is to study the influence of both applied stress and the internal stress on the GMI and GSI behaviors in the microwire composites.

We found that the application of external tensile stress ranging from 150 to 600 MPa along the microwire axis decreased the GMI ratio and increased the circular anisotropy field. The increase of composite layers enhanced the internal residual stress and hence reduced the GMI ratio, while the annealing treatment was found to have the opposite effect. The calculated matrix-wire interfacial residual stress via the GMI profiles is in good agreement with the value of the applied effective tensile stress to yield a similar GMI profile. The GSI effect was enhanced in the composite compared to its single microwire counterpart, and it increased with increasing number of composite layers. These observations indicate that the prepared composites are promising for sensing applications and this opens up a new route to probing the stress conditions of such composites.

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7978-48, Session 7

Damping identification of viscoelastic composites using micromechanical approaches

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In this paper micromechanical methods combined with the correspondence principle of viscoelasticity are used to obtain the effective damping properties of viscoelastic composites. It is important to be able to predict the behavior of the material in different situations. For example viscoelastic material properties vary with temperature which results the effective damping of the composite to be a function of temperature. When dynamic loads are applied it is always of great interest to investigate the behavior of the material subjected to harmonic loads with different frequencies. Damping properties of viscoelastic materials are highly frequency dependent. When different materials with different frequency dependent properties combine to form a composite, the properties of the resulted composite is a new function of frequency.

The correspondence principle helps to consider all the frequency dependent properties of the constituent materials and conclude the effective damping vs. frequency.

The other main factor contributing to the effective damping of the composite is the volume fraction of the inhomogeneities. Whether elastic or viscoelastic, the inhomogeneities can increase or decrease the effective damping of the composite material depending on their volume fraction. In this study it is shown that for a specific composite there is always a value of volume fraction that the damping becomes maximum.

Two types of inhomogeneity shapes are investigated in this paper. At first micro spherical particles are uniformly dispersed within the viscoelastic composite. Secondly, micro fibers are used instead of particles. The micro fibers are investigated in both unidirectionally or randomly oriented. In all cases the Prony series representation is used to give an analytical expression of the experimentally obtained relaxation modulus of the constituent materials.

7978-49, Session 7

Design of phononic band gaps in functionally graded piezocomposite materials by using topology optimization

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One of the properties of composite materials is the possibility of having phononic band gaps, within which sound and vibrations at certain frequencies do not propagate. These materials are called Phononic Crystals (PCs). PCs with large band gaps are of great interest for many applications, such as transducers, elastic/acoustic filters, noise control, and vibration shields. Most of previous works concentrates on PCs made of elastic isotropic materials; however, band gaps can be enlarged by using non-isotropic materials, such as piezoelectric materials. Since the main property of PCs is the presence of band gaps, one possible way to design structures which have a desired band gap is through Topology Optimization Method (TOM). TOM is a computational technique that determines the layout of a material such that a prescribed objective is maximized. Functionally Graded Materials (FGM) are composite materials whose properties vary gradually and continuously along a specific direction within the domain of the material. One of the advantages of applying the FGM concept to TOM is that it is not necessary a discrete 0-1 result, once the material gradation is part of the solution. Therefore, the interpretation step becomes easier and the dispersion diagram obtained from the optimization is not significantly modified. In this work, the main objective is to optimize the position and width of piezocomposite materials band gaps. Finite element analysis is implemented to solve the dynamic behavior of two-dimensional functionally graded unit cells and through Bloch-Floquet theory the model is extended to infinite periodical structure. The results demonstrate that phononic band gaps can be designed by using this methodology.

7978-50, Session 7

Chiral braided and woven composites: design, fabrication, and electromagnetic characterization

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This work presents a new chiral composite composed of copper wires braided with Kevlar and nylon to form conductive coils integrated among structural fiber. To create a fabric, these braids were woven with plain Kevlar fiber. This yielded a composite with all coils possessing the same handedness, producing a chiral material. The electromagnetic response of this fabric was first simulated using a finite element full-wave simulation. For the electromagnetic measurement, the sample was placed between two lens-horn antennas connected to a Vector

Network Analyzer. The frequency response of the sample was scanned between 5.5 and 8 GHz. The measured scattering parameters were then compared to those of the simulated model. The measured parameters agreed well with the simulation results, showing a considerable chirality within the measured frequency band. The new composite combines the strength and durability of traditional composites with an electromagnetic design to create a multifunctional material.

7978-69, Session 7

Functionally graded smart materials by ultrasonic consolidation

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Ultrasonic Consolidation (UC) is a solid state additive manufacturing process which fabricates three-dimensional objects by ultrasonically joining metal foils together, layer-by-layer, to form a solid part. In UC the weld surface of the sonotrode is textured to generate adequate mechanical coupling between the foil substrate and sonotrode to achieve bonding. This study investigates the effect of sonotrode surface texture on bond strength, interlaminar microstructure and sample surface texture of parts fabricated by UC.

White light interferometry was used to examine and characterise the surface of two different sonotrodes, textured by Electro-Discharge Machining (EDM). Under identical processing conditions aluminium 3003-H18 UC samples were fabricated using both sonotrodes. The surface texture of these UC samples was measured and compared to the original sonotrode surface textures. Peel testing was used to evaluate the failure mode and bond strength of the samples. The interlaminar microstructure of the UC fabricated parts was examined and linear weld density was measured. As a result of the analysis differences in the sample surface texture, bond strength and interlaminar microstructure were observed in samples produced by the two different sonotrodes.

This paper aims to examine the influence of sonotrode texture on interlaminar bonding in UC and how this could be exploited to produce functionally graded smart materials. Through controlled variation of the UC process parameters, including sonotrode texture, as the layers of the component are consolidated, parts with deliberately nonlinear physical properties may be produced with significant degrees of control.

7978-76, Session 7

Self-actuating and self-diagnosing plastically deforming piezo-composite flapping wing MAV

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Flapping wing MAV's do not have an engine to directly produce the required lift and thrust for the flight. Hence harnessing energy for both thrust and lift from flapping is of utmost important. Usually the flapping wing MAV's are driven by mounted actuating mechanisms (powered by a servo motor) that facilitates the flapping action. The main shortcoming of such a system is increased weight owing to the presence of an actuating mechanism. One of the latest novel solutions to reduce weight of MAV's is self-actuation of piezoelectric flapping wings. Generally most of the piezoelectric materials, used as actuators, are ceramics which are heavy and brittle and thus unsuitable for dynamic applications like flapping wings. Recent developments in smart material technology like embedding piezoelectric fibers in highly-flexible polymer materials has resulted in many favorable properties. The Piezoelectric Fiber Reinforced Composites (PFRC) further enhance most of the favorable properties of the piezoelectric materials like high energy density and directional actuation. In addition they provide longer fatigue life, additional multifunctionality like sensing, health monitoring, energy harvesting, etc. Thus development of MAV's with actively deformable wings to produce

the combined flapping, twisting and feathering actions is evolving as an attractive way to reduce the weight of the MAV.

The known models for PFRC materials in the literature use linear piezoelectric constitutive equations, based on simple elastic micro-mechanical Voigt models to determine the effective elastic properties of the composite. In all these models, nonlinear electro-mechanical couplings, hysteresis effects and inelastic properties of constituents are neglected and effective moduli of perfectly electro-elastic composite are obtained. However, in reality, plastic deformation occurs, but when the maximum strain(s) and strain rate(s) are negligibly small, then the material behavior is considered essentially elastic. When PFRC is used in flapping wings in MAV's, it is subject to dynamic conditions at high mechanical and electrical strain rates. MAV wings are also highly susceptible to winds and impact loading due to particles present in the atmosphere. All the above conditions induce residual plastic strains in the PFRC wings. The resulting residual plastic strain leads to degradation in flapping frequency. Some of the recent works have also shown that cyclic plasticity can induce fatigue failure. Thus constituting an elasto-plastic model for PFRC composites is of significance. This work is motivated by the lack of analytical closed-form solutions to describe the elasto-plastic behavior of PFRC.

The developed analytical elasto-plastic model is implemented using computer program modules to enable tailoring of PFRC composites for MAV applications. This is also extended to provide SHM based on plasticity induced degradation of flapping frequency of PFRC. The developed modules can be coded into electronic chips and directly used in MAV to provide online SHM on chip.

Overall this work provides an effective mathematical tool that can be used for structural self-health monitoring of plasticity induced flapping degradation of PFRC flapping wing MAV's. The developed tool can be re-calibrated to also provide SHM for other forms of failures like fatigue, matrix cracking etc.

7978-59, Poster Session

Experimental, analytical, and computational analysis of fatigue crack growth of HPDC-AM60B magnesium alloy

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The present study corresponds to the crack growth of HPDCAM60B magnesium alloy, which has been increasingly being used in automotive industries due to its outstanding ductility and energy absorbing properties, combined with good strength, less weight and castability. The fatigue crack growth tests were conducted at room temperature with stress ratio($R=0.1$) and frequency of 30 Hz. The objective is to ascertain the fatigue response of the alloy and to determine the FCGR (Fatigue Crack Growth Rate) experimentally followed by a comparison with analytical and finite element analysis on the basis of Paris and Walker model.

7978-60, Poster Session

Sliding wear map for Al-Si alloy

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Al - Si alloys are widely used in a variety of automotive components due to their excellent strength to weight ratio. The reduction in weight of components such as pistons, clutch housings and liners leads to significant impact on fuel economy in dynamic systems. Dry sliding wear behavior was investigated in the load range 6 -20 N against AISI 52100 bearing steel ball using a reciprocating ball-on-flat configuration at a frequency range of 4 - 20 Hz. Microstructures of worn surfaces and wear debris were characterized by scanning electron microscope (SEM), energy dispersive X - ray spectrometer (EDS) and X - ray diffractometer (XRD). A wear mapping approach, consisting of identification of each mechanism as a function of load and speed, has been adopted.

7978-61, Poster Session

Electromechanical field concentrations and polarization switching due to interdigitated electrodes in piezoelectric macro-fiber composites

F. Narita, Y. Shindo, K. Sato, T. Takeda, Tohoku Univ. (Japan)

Piezoelectric macro-fiber composite (MFC) elements are gaining increasing interest for structural health monitoring and energy harvesting systems. In some MFC applications, high values of stress and electric field arise in the neighborhood of electrode tips in PZT fibers, and the field concentrations can result in electromechanical degradation. There is also another problem related to the manufacturing process. PZT wafer is first diced in rectangular fibers. This fiber arrangement is infiltrated with the resin and cured together with the interdigitated Kapton electrode sheets in a high precision lamination pressing machine. After this the MFC is polarized in a final step with high voltages at room temperature. For these fabrication techniques, the resulting polarization of the PZT fibers would inevitably be partial. Due to the presence of interdigitated electrode (IDE) edges and the resulting inhomogeneity of its constituents, the piezoelectric MFCs can suffer damage prematurely during service. It is therefore important to understand the electromechanical field concentrations near IDEs in the piezoelectric MFCs.

This work investigates the electromechanical response of piezoelectric macro-fiber composites (MFCs). Nonlinear three dimensional finite element model incorporating the polarization switching mechanism was used to predict the electromechanical fields near interdigitated electrode (IDEs) in the piezoelectric MFCs. The lead zirconate titanate (PZT) fibers in the MFC are partially or fully poled. The electric field-induced strain was then measured, and test results were presented to validate the predictions.

7978-62, Poster Session

Electromechanical field concentrations near electrodes in piezoelectric thick film mirror devices

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Microelectromechanical systems (MEMS) technology is creating micro-mirrors for applications such as scanning and adaptive optics. Unimorph structures with one piezoelectric lead zirconate titanate (PZT) film and one elastic layer are commonly adapted to control the mirror. In some MEMS mirror applications, high values of stress and electric field arise in the neighborhood of an electrode tip in PZT unimorphs, and the field concentrations can result in electromechanical degradation. It is therefore important to understand the electromechanical field concentrations near electrodes in PZT unimorphs for MEMS mirrors. Prediction of the intensified electromechanical fields would require detailed finite element calculations. To run the simulations, material properties must be known. Accurate measurement of the elastic and piezoelectric constants for the PZT thin or thick films, however, is by no means straightforward. In order to aid in the design of MEMS mirrors, extensive work for evaluating the required material parameters and predicting the PZT film performance is necessary.

The main aim of this work is to evaluate the electromechanical response of piezoelectric mirror devices driven by PZT thick films. Material properties of the PZT thick films on elastic layers were first characterized by a combined electromechanical tests and finite element simulations. Next, a finite element method was used to predict the mirror tilt angle and electromechanical field concentrations ahead of electrodes in piezoelectric mirrors under electric fields. The mirrors consisted of four fully or partially poled PZT unimorphs. The mirror tilt angle was then measured, and test results were presented to validate the predictions.

7978-63, Poster Session

Study on the graphene-based actuator

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Bilayer actuators comprising of MWCNT (Multi-walled carbon nanotubes) and Graphene oxide (GO) were studied for their actuation performance by using induction heating system. A simple fabrication method namely, filtration of the colloidal suspensions of MWCNT and GO through an Anodisc membrane was used to fabricate the actuators. In case of bilayer actuators, sequential filtration of MWCNTs and Graphene oxide dispersions through a membrane filter membrane was used. Morphological studies by SEM showed that the bilayer paper did not delaminate at the macro-scale and a certain degree of adhesion between MWCNT and GO can be achieved even without any functionalization of either of the constituents of bilayer actuators. Actuation was tested by using the induction heating system, operated at different current densities. Substantial degree of deformation, as much as 0.128 mm⁻¹ at 300 A was measured. The degree of actuation was defined in terms of bending curvature, because the deformation was too large to be detected by conventional displacement laser sensors. An attempt has been made to explain the basic mechanism of bilayer actuator in terms of the differential thermal expansion rates and eddy current which was confirmed from images obtained from thermal camera wherein the variation in bilayer actuator's surface temperature were monitored. Finally the deformation trend under different pulses is also examined.

7978-64, Poster Session

Electrical and mechanical properties of multi-phase systems under external impacts

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The recent progress in creation of materials with negative refractive index inaccessible for natural substances show all-important role of the multi-phase materials in modern technology. The problem of multi-phase materials has also significant application in the correct determination of the phase transition points and also in the revealing of the true intrinsic parameters of different phases of multi-phase systems.

In the present work the approach for calculating of effective properties is considered for multi-component composite materials with variable configurations and concentration of inclusions [1]. The approach is based on interpolation formulas obtained between the rigorously calculated limiting borders. [2] The examples of application of the above model are given for the analysis of multi-phase states in the vicinity of pressure-induced phase transition. The model was used for a set of semiconductor compounds like PbX, SmX (X - Te, Se, S), iron ore, etc. [3]. The program for calculation of different electrical, thermal, mechanical etc. properties of n-phase systems with variety of configuration and concentration of phase inclusions has been created, which may be applicable for real multi-phase systems.

The research is supported by the Russian Foundation for Basic Research (RFBR) and the Presidium of the RAS Scientific Programme.

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7978-65, Poster Session

Overview on the feasibility of micro-rotors driven by momentum transfer, spin angular momentum transfer, and orbital angular momentum transfer from photons

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Since the invention of the optical tweezers in 1986 various ideas for optically driven micro-rotors have been suggested and brought to life. There are essentially three basic techniques to drive the rotation of small, micrometer sized objects: The transfer of linear momentum from photons to asymmetrically shaped particles [1,2] and the transfer of spin [3,4] or orbital angular momentum [5] of the tweezing laser beam to particles. Each technique has distinct advantages and disadvantages when used to drive the rotation of a micro-rotor. No beam shaping is necessary to transfer linear momentum, but this technique usually requires the fabrication of complicated micrometer sized structures. Recently, bacteria, which can be grown easily, have been used successfully [2]. In order to transfer spin angular momentum the beam needs to be polarized and the tweezed particle has to be birefringent. Orbital angular momentum transfer requires a more sophisticated beam shaping, but has no restrictions on the form or dielectric properties of the particle. We will present our own experiments on each of the three techniques and discuss their advantages and disadvantages. We will also suggest two other possible applications for the spin transfer of light to matter.

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7978-66, Poster Session

Experimental investigation on mechanical behavior of filament-wound CFRP tubes

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Firstly, two types of CFRP tubes are designed using the filament-wound forming technology. These tubes are wound by carbon fibers with a filament winding pattern of $[(900/00)2]_S$. The compression and tensile test are also carried out to investigate the stress-strain relationship, ultimate strength and macroscopic failure mode of the CFRP tube. The results demonstrate that the CFRP tube has a much larger ultimate tensile stress and strain than compressive stress and strain. However, the elastic modulus of CFRP tubes under tension and compression are similar and the final failure modes for CFRP tubes under compression and tension are both brittle. The ultimate failure of CFRP tubes under compression attributes to the break of fibers and epoxy. While the failure of tubes under tension can be ascribed to break of the carbon fibers. Secondly, the stress and strain analysis method of filament-wound CFRP tube is investigated according to anisotropic elasticity theory and lamination theory of composite material. Then, the strength of carbon-fiber-reinforced plastic tubes is obtained. In addition, the comparison of theoretical analysis results and experimental results shows that the theoretical analysis results are reliable. The strength calculated by the anisotropic elastic mechanics method is higher than that of the real CFRP tube because it is unavoidable for the CFRP tubes to have deficiency during their construction.

7978-67, Poster Session

Buckling control of morphing composite airfoil structure using multi-stable laminate by piezoelectric sensors/actuators

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In the present work, an unsymmetric laminated plate with surface bonded piezoelectric sensors, and actuators has been considered. Piezoelectric sensor were used to monitor the load and deformation bifurcation occurs.

Monitoring the shape and load of a morphing structure is essential to ascertain that the structure is properly deployed and it is not loaded excessively, thus, preventing structural failure. A piezoceramic actuator is used to provide activation load and to force the structure to change its stability state from one to another. A non-linear finite element model based on the layerwise displacement theory considering the electro-mechanical coupling effects of piezoelectric elements has been developed for simulation purposes. A control mechanism is also employed to actively control the shape of the structure. It is observed that, utilizing multistable composite to design a morphing structure may significantly reduce the energy required for changing the shape. Further controlling the buckling phenomena using piezoelectric sensor and actuator along with an ON/OFF controller can effectively and efficiency enhance the performance of the morphing structure during maneuver.

7978-68, Poster Session

Electromagnetic radiation of polaritons in piezoelectric superlattices

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There are five kinds of plane waves in a general piezoelectric solid, three of them are quasi-acoustic waves and the other two are quasi-electromagnetic waves. When these plane waves propagate from interior of a half space to the solid-vacuum interface, electromagnetic waves in vacuum are induced. For the same input power, the power of EM waves in the free space induced by quasi-acoustic waves is much smaller than that induced by quasi-electromagnetic waves. That is, the EM waves are hardly to be generated mechanically in piezoelectric materials.

Periodic structures can be formed in a piezoelectric plate by intervallic polarizing oppositely along one direction. The polariton behavior in the plate is observed by solving Newton's equations of motion and Maxwell's equations simultaneously. Significant coupling between phonon and photon occurs in the vicinity of the center of the first Brillouin zone. Adjusting the periodicity and thickness of the plate, the polariton behavior can exist in the frequency range of RF band. Since the polariton in the piezoelectric superlattice can be excited by either electromagnetic waves or acoustic waves, it can be applied to both transducers and filters.

LiNbO₃ is adopted as an example. The radiated EM waves caused by incident acoustic waves are analyzed for homogeneous polarized single crystal. The calculated results show that the power ratio between the EM wave transmitted into the free space and the incident acoustic waves is smaller than the order of $1e^{-4}$. Once the LiNbO₃ is polarized intervallic oppositely, the power ratio increases significantly.

7978-70, Poster Session

Phase-field simulation and design of a ferroceramic nano-generator

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We study the behavior of ferroceramic material (BaTiO₃) intended to design a nano-generator converting mechanical into electrical energy. The investigations consider an electro-mechanical phase-field model with

polarization as state variable. This widely accepted model has its origins in the work of [Fried&Gurtin 1993, Fried & Gurtin 1994, Gurtin 1996] and is fully developed by Landis [Su & Landis 2007, Kotsos & Landis 2009].

We use a finite element model to simulate tetragonal regions of ferroceramic material sputtered on substrate. Different aspect ratios as well as various mechanical and electrical boundary conditions are considered. The model is normalized, inter alia with an internal length scale to achieve better computational conditions within the stiffness matrix of ferroceramics on the nano-scale.

The major objective of this contribution is the fundamental understanding of domain switching caused by a cyclic electrical field. The corresponding hysteresis loops of overall polarization cannot be achieved by using a two-dimensional model because domain topologies evolve really three-dimensional. This is even true for flat regions or thin films [Zhang et al. 2008]. We show some examples of three-dimensional domain topologies, which are able to break energetically unfavorable symmetric situations.

Finally, the computational model of a cubic nano-generator with dimensions 20 x 20 x 6 nm is presented. The specific ratio of height to width (6/20) and the mounting on substrate is essential for its performance and principle of energy harvesting. We discuss the challenges and scopes of such a system. Further, we take environmental considerations into account.

7978-72, Poster Session

Fabrication and properties of multiple oriented carbon nano tube paper

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A novel approach has been developed to fabricate oriented carbon nano tube (CNT) paper, which is composed of carbon nano tube solution spraying, high electric field and negative pressure filtration. The electric field in the solution spraying area can align the CNT in air, and finally fall on the filtration membrane under negative pressure oriented in electric field direction. With the applying electric field direction changing, multiple orientation CNT paper can be formed. In this study, the air pressure for solution spraying, solution concentration, electric field intensity, negative filtering pressure and other fabrication parameters were discussed. The mechanical, electrical conductivity experiment results show that the CNT paper had high mechanical properties, low electrical resistivity and electric conductivity performance. And the SEM results indicated that the CNTs in the CNT paper are highly oriented and can be aligned in multiple directions according to the electric field exerting time and direction in the fabrication process. This approach can be used to fabricate large scale and continuous CNT paper, which can be applied in composite stealth and anti lightning striking in plane and wind blade.

7978-73, Poster Session

Fracture toughness characterization of nanoreinforced carbon-fiber composite materials for damage mitigation

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Nanoscale constituents can have a wide variety of effects on composite material behavior due to morphology, volume fraction, and fabrication methods. In this study, continuous polyacrylonitrile (PAN) nanofibers fabricated via the electrospinning process and silica nanoparticles were individually studied and compared for their representative impact mitigating effects when incorporated into conventional composite materials. Due to their low volume fraction in the composite part, the

nanofibers and nanoparticles are thought to reduce the effects of delamination and matrix cracking caused by low velocity impact events when incorporated at internal ply interfaces or mixed into the matrix material, respectively. This behavior was experimentally characterized by determining the fracture toughness of flat polymer matrix carbon-fiber composite coupons using the double cantilever beam (DCB) test according to ASTM D5528. The nanofibers were introduced to the composite coupons by directly electrospinning the fibers onto the carbon-fiber ply surfaces or transferring the electrospun fibers from an interim substrate, while the nanosilica particles were mixed into the resin system during conventional vacuum bagging hand layup. Testing allowed the calculation of Mode I strain energy release rates and results were compared with baseline coupons to compare the relative improvement in properties versus the different nano-reinforcements. Fabrication techniques and composite consolidation were analyzed for their contribution to the quality of each sample.

7978-74, Poster Session

A micropolar continuum model for large deformation caused by magnetic or electric fields

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The central point of this contribution is an appropriate continuum theory to predict the behavior of flexible magnetic or electrically polarized materials undergoing large deformation caused by applied magnetic or electric fields. As in shell theories, this continuum theory treats angular momentum as an explicit complementary principle. The loading of remanent magnetized materials in magnetic fields respectively of remanent polarized materials in electric fields can be modeled. Thus, net-couples appear in the balance of angular momentum and require possibly non-symmetric Cauchy stresses for equilibrium. This is unlike in classical shell theories. However, the micropolar model is in accordance with classical phenomenological modeling parameters but with the feature to cover large deformations and non-classical types of loading.

The formulation considers rotational degrees of freedom to appear in the kinematical equations as exact rotations in SO(3). This is a source of nonlinearity in the model but allows easily for large deformation as well as for net-couples.

The torque of a compass needle is a simple example to explain the effect of materials with remanent magnetization within a magnetic field. The twisting moment becomes a maximum for remanent magnetization being perpendicular to an outer magnetic field. It vanishes if both fields are parallel.

Applications for both, thin magnetic and thin ferroelectric structures are investigated by finite element simulations, e.g. a cone shell as magnetic valve. Additionally, the development of active materials on the micro- and nano-level is in the focus. Simulations are used to design microstructures with engineered performance.

7978-75, Poster Session

Experimental investigation of road snow-melting based on CNFP self-heating concrete

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The road snow-melting system consisted of CNFP thermal source, AIN/Epoxy-based insulated-encapsulated layer and MWCNT/cement-based thermal conductive layer, was fabricated in this study. The carbon nano-fiber paper (CNFP) with excellent thermal and electrical properties was integrated into snow-melting system as the high-efficient thermal source. The remarkable electro-thermal and resistive properties of CNFP with the thickness of 0.38mm were investigated, which were verified much higher efficiency and more stable electro-thermal property than other papery materials. The resistivity exhibits linearly temperature-dependent characteristics in certain temperature scope and met the three line model as a function of temperature. Carbon nanotubes (CNT) attracted

many researches interesting based on its unique thermal conduction as a strong thermal-transferring candidate, the MWCNT/cement-based composites, fabricated by electric repulsion/high-frequency oscillatory dispersing method and filled with 3% MWCNT, presents the best thermal conductive property in contrast with other fillers and dispersing methods, which was integrated into snow-melting system with other parts as the thermal conductive layer material. The AlN/Epoxy-based composite, filled with 20% micron-AlN by the weight of mixture exhibited favorable insulating, thermo-conductive and mechanical properties, was used to guarantee the insulation and high-efficient operation of CNFP as the insulated-capsulation material. Due to the field test, the snow-melting characteristics of integrated snow-melting system, dependent on the ambient temperature, wind speed, heat flux density and snow thickness, was investigated. The results verified the high-efficient, stable, feasible and economic properties of CNFP& MWCNT/cement-based snow-melting system in practical application.

7978-77, Poster Session

Equivalent properties of 1-3 piezocomposites made of PMN-PT single crystals for underwater SONAR transducers

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The design of a piezocomposite transducer is accomplished by such advanced modeling technique as finite element method (FEM). However, accurate analysis of a 1-3 piezocomposite transducer enforces three dimensional (3D) modeling that requires a very fine meshing of the transducer structure, which is frequently over affordable calculation resource capacity. In order to simplify the FEM model for complicated underwater transducers, the 1-3 piezocomposite needs to be simulated with a single phase material of equivalent properties. The 1-3 piezocomposite material in this study is made of the PMN-PT single crystal as the active material and urethane as the matrix material. Theoretical models for the calculation of new material parameters of 1-3 composites having fine lateral periodicity have been derived. For the validation of the equivalent properties, TE (thickness extensional), LE (length extensional), LTE (length thickness extensional), and TS (thickness shear) FEM models have been built to compare the impedance-frequency spectra of the 1-3 composite material and an equivalent material. Through the simulation with the models, all the equivalent elastic, dielectric and piezoelectric constants of the single phase material are determined. Further, 3D and axis-symmetric 2D FEM models of a multi-mode Tonpilz transducer have been constructed with the equivalent material properties. The equivalent material provided a very good correlation between the 2D and 3D transducer models, which is unattainable with the full 1-3 piezocomposite model. This result confirms the efficacy of the equivalent material properties of the 1-3 piezocomposites.

7978-78, Poster Session

Fabrication of fibrous composites with re-mendable polymer matrices

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Integrating reinforcing fibers with a re-mendable polymer creates a healable composite. The re-mendable polymer 2MEP4FS could be an ideal matrix material; it has previously been shown to completely heal damage in neat specimens, and a related polymer was shown to have mechanical properties similar to epoxy, a traditional matrix material. There are challenges to using 2MEP4FS in composite fabrication. At ambient conditions, one constituent monomer is a solid powder (2MEP) and one is a viscous liquid (4FS). Heating the monomers until they are both low viscosity liquids will enable effective mixing, but fast polymerization

leaves little time for fiber integration. Resin transfer molding techniques have been previously used with some success, but a more flexible method is desired. Here, several pre-preg fabrication approaches are investigated. One approach is the use of a solvent to mix and distribute the monomers in a thin layer of unidirectional fibers. The thin nature of the pre-preg is exploited to remove the solvent. Another approach is mixing the heated monomers, but subsequently lowering the temperature to slow the polymerization rate. Fibers are integrated with the prepolymer to create a pre-preg. The pre-preg layers can be stacked and laminated into multilayered composites. The pre-pregs and composites are characterized using optical microscopy, differential scanning calorimetry (DSC), and dynamic mechanical analysis (DMA). The advantages and disadvantages of each pre-preg approach are explored.

7978-79, Poster Session

Overall dynamic constitutive relations for layered elastic composites

A. Srivastava, S. Nemat-Nasser, Univ. of California, San Diego (United States)

A method for homogenization of a layered elastic composite is presented. It allows direct, consistent, and accurate evaluation of the averaged overall frequency-dependent dynamic material constitutive relations. It is shown that, when the spatial variation of the field variables is restricted by a Bloch form periodicity, then these relations together with the overall conservation and kinematical equations accurately yield the displacement or stress mode-shapes and dispersion relations. It also gives, as a matter of course, point-wise solution of the elasto-dynamic field equations, to any desired degree of accuracy. The formulation is based on micro-mechanical modeling of a representative unit cell of the composite. We show that, for a layered elastic composite, the overall effective mass density and compliance (stiffness) are always real-valued and positive, whether or not the corresponding unit cell is geometrically and/or materially symmetric. The average strain and linear momentum are however coupled and the coupling constitutive parameters are always each others complex conjugates for any heterogeneous elastic unit cell, such that the overall energy-density is always real and positive.

7978-80, Poster Session

Controlling wave propagation in solids using layered anisotropic materials

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Stress wave propagation in solids can be managed at the interface of highly anisotropic materials. The interface between two elastic media causes reflection and transmission of an incident stress wave as pressure or shear waves. In strongly anisotropic media, the maximum stiffness direction is the preferred direction for the group velocity and wave-energy flow. Layered media designed with the proper anisotropic orientations can control the reflected and transmitted longitudinal and/or shear waves. A program is developed to examine the directions and amplitudes of reflected and transmitted plane waves with various modes of vibration.

It is established that a bi-layered structure can be designed to trap the pressure component of reflected and refracted acoustic waves and transfer it into shear components. We show that, while the transmitted and reflected shear waves are still present, the transmitted quasi-longitudinal wave can be rendered to be evanescent (non-propagating) and travel as a surface wave along the interface. The reflected quasi-longitudinal wave would also propagate toward the interface. This traps the energy of the longitudinal component of the transmitted and reflected plane wave in the two-layer anisotropic material. Furthermore, multilayered structures with oriented anisotropies in each layer provide an extra degree of freedom for managing the stress-waves.

7978-81, Poster Session

Magnetic performance of Fe₃O₄/epoxy nanocomposites

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In nanocomposites, the size of the matrix or reinforcement falls within the nanoscale. The physical properties and performance of the nanocomposite will differ from that of the component materials greatly. In this manuscript, we reported the preparation and characterization of Fe₃O₄/Epoxy nanocomposites. Structural characterizations were given by powder X-ray diffraction (XRD) and thermogravimetric analysis (TGA) proved the interaction between Fe₃O₄ and Epoxy chains. The magnetic performance of the resulting composites was investigated by vibrating sample magnetometer (VSM). The coercivity of Fe₃O₄ nanoparticles in the composites has no obvious change. The saturation magnetization of Fe₃O₄ in the composites was affected and increased from 42 emu/g to 60 emu/g with its content increasing, but its value was always smaller than that of its bulk value.

7978-82, Poster Session

Fabrication of TiNi shape memory alloy thin films by current activated tip-based sintering (CATS)

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The focus of this paper is the development of a novel powder-based rapid manufacturing process that will allow the controlled sintering of micro-scale TiNi shape memory alloys (SMAs) thin films from layered powders. The process, named "Current Activated Tip-based Sintering (CATS)", uses an ultra precision manipulator with conductive and/or patterned tip to simultaneously apply electric current (pulsed, direct or alternating) and controlled contacting pressure to the surface of a powder bed. The position and path of the tip is controlled to sinter different locations or geometries; the approach allows 1D, 2D and 3D (with layering) micro-scale powder-based fabrication, with far reaching applications. Advantages of the process also include ultra-rapid heating and sintering rates un-attainable by conventional sintering, and a process zone that can be maintained even on the nano-scale, unlike other rapid proto-typing processes such as laser sintering.

In recent years, TiNi SMA based devices have received a high level of attentions nationally and found a variety of applications due to their properties of thermal actuation and super elasticity. TiNi materials in thin film form are especially attractive for use in micro-actuation devices due to their high force, long stroke, light weight, etc. Although numerous traditional manufacturing processes have been used to produce TiNi such as casting and thermomechanical processing, powder-based processing has emerged as an approach that can yield significant benefits which include net shape processing, reduced material waste and microstructural and compositional control. Titanium nickelides can be produced cost effectively from elemental powders of Ti and Ni which can react exothermically to form and simultaneously reactively sinter the intermetallic, or from pre-alloyed powder obtained for example via the mechanical alloying (MA) process, or atomization. The paper aims at taking CATS technology to the "rapid"-manufacturing of TiNi micro thin films. The technology provides a scalable, cost-effective manufacturing of thin films.

Spark plasma sintering has the advantage of achieving sintering at considerably reduced temperatures and times than conventionally possible, leading to further advantages in terms of grain size retention which is especially relevant for nanostructured materials. The tip can be in macro, micro or even nano-scale, and is precision controlled in terms of displacement, speed and applied pressure. Advantages of this recently patented process include the ability to apply extremely high current densities due to the small tip size (while using minimal input energy), which in turn facilitate exceedingly rapid sintering rates. Initial work was conducted on nickel powder proving the feasibility of this

approach in localizing the spark plasma sintering process in small regions of a powder compact. The effect of CATS processing parameters on the developed microstructure and properties are also discussed.

The following experimental results have been drawn:

The process zone size was found to increase with increased number of cycles (i.e. cumulative current exposure time)

The resulting microstructures consisted of multiple phases, and not a single NiTi phase, primarily due to in-homogeneity arising from the mechanical milling stage.

The effect of increasing current was to decrease the residual porosity, and increase hardness.

7978-83, Poster Session

Multi-scale modeling and optimization of coupled thermo-electro-magneto-mechanical behavior of load-bearing antenna structures

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Load-bearing antennas are multi-functional sensing (actuating) and receiving (detecting) devices that are integrated with a load-bearing structure. These antennas are appealing for military applications, importantly Unmanned Aerial Vehicles (UAV). The antenna structure is subjected to mechanical forces, temperature gradients, and electromagnetic fields, giving rise to highly-coupled nonlinear thermo-electro-magneto-mechanical (TEMM) behavior. In the present work, we have developed analytical techniques and computational tools for multi-scale, multi-physics modeling of composite load-bearing antennas, specific to UAV applications. Our mathematical model, based predominantly on first principles, employs the thermomechanical governing equations (i.e., conservation of mass, momentum, angular momentum, energy and second law of thermodynamics) coupled with Maxwell's equations. Our modeling has identified 92 nondimensional numbers which quantify the competition between physical effects in the operation of load-bearing antenna. Depending on the design of the structure and nature of the excitation, only a subset of physical effects are dominant, which dictates the appropriate computational model. A fixed relative ordering of all competing effects as quantified by nondimensional numbers determines a "regime" of antenna/environment interaction. Regimes and the corresponding leading-order equations are deduced for a particular design of load-bearing antenna structure. The mathematical structure of leading-order equations for these physical regimes is presented and solved for some special cases.

7978-84, Poster Session

An explicit formulation for the analysis of functionally graded plates subjected to mechanical and thermal loads

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Plates and shells made of functionally graded materials (FGMs) often find application in a high-temperature environment. In the literature, considerable effort has been directed towards the analysis of functionally graded plates using two-dimensional theories. Many of these analysis techniques are extensions to approaches used for fibre-reinforced plastic (FRP) laminates. They consider the effects of through-thickness strains since these can be significant in FRPs. Functionally graded materials (FGMs) are often made from metals and ceramics, however. The through-thickness moduli are of the same order as the inplane moduli and therefore errors introduced by neglecting the effects of throughthickness strains are far smaller. Classical lamination theory (CLT) can consequently provide useful estimates of deflection and stresses in all but the thickest plates. CLT does not accommodate material properties that progressively change through. As a consequence, the usual approach is to discretize each layer of FGM into a large number

of sub-layers and then use a constant set of material properties appropriate to each sublayer. It is more convenient, however, to use a method that directly considers variation in material properties. This paper presents such an approach, formulated as an extension to classical lamination theory. The resulting equations accommodate any through-thickness variation in material properties and loading. The true variation in these parameters is approximated by polynomial series of sufficiently high order that good accuracy is ensured. The resulting mathematical problem can be explicitly formulated irrespective of the actual variation in material properties and loading. Comparisons against results available in the literature demonstrate the accuracy of the method.

7978-51, Session 8

Compressive response of epoxy-based shape memory polymers

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Smart materials can sense and react to environmental conditions or stimuli. As a new class of smart materials, Shape Memory Polymers (SMPs) are attracting considerable interest due to their ability to recover very large deformations upon heating and their low fabrication cost compared to their metallic counterparts; Shape Memory Alloys. They offer many promising applications in biomedical and aerospace industry due to their unique properties.

In this study, characterization results on thermo-mechanical properties of the epoxy based SMPs will be presented. The effects of level of applied load, strain rate and test temperature on compressive response and shape recovery of several epoxy-based shape memory polymer compounds and some preliminary results on non-contact actuation of SMP composites by magnetic and electrical fields will be reported. In the light of our findings, feasibility of SMP composites utilization for many applications including aerospace and automotive industries will be discussed.

7978-52, Session 8

On a novel self regulating shape memory polymer composite

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Polyurethane shape memory polymers (PU-SMPs: 30MPa of Tensile strength below $T_g=45^\circ\text{C}$) are active material that can be transformed into complicated shapes with the ability to recover their original shape even after undergoing large deformations. Because of their light weight, large recoverability, low cost, and high compliance, SMPs can be potentially employed as actuators, MEMS devices, temperature sensors, and damping elements to name a few. One of the key challenges in implementing SMPs is the effective method of heating and cooling. Unlike shape memory alloys, SMPs can be activated by multiple stimuli including lasers, resistive heating, electric fields, and magnetic fields. While these methods provide an efficient way of heating the SMPs, they rely on the slow process of conduction for cooling, which is required to stabilize the SMP's secondary shape. In this paper, a self regulating SMP composite is introduced, whereby a novel heating and cooling system consisting of embedded silica micro-channels in the SMP (MP-4510: SMP Technologies, Inc.) has been developed. The microchannels are used to pump hot/cold fluid through the SMP membrane. In order to show the effectiveness of the mechanism, the thermomechanical response of the self regulating SMP is compared experimentally to a SMP

with "conventional" heating and cooling mechanisms. It is shown that the self-regulating SMP has a faster thermomechanical response. MP-4510 (PU-SMP) consists of resin (Diphenylmethane-4, 4'-diisocyanate) and hardener (1,4-Butanediol). Thermomechanical characterization of PU-SMP composites is described by varying the weight percentages of resin and hardener. These results show how the material properties of the SMP can be tuned for specific applications.

7978-53, Session 8

Three-dimensional numerical implementation of a thermoelastic, finite deformation constitutive model for shape memory polymers

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Shape memory polymers (SMPs) are a class of active materials that, under an appropriate thermomechanical cycle, will recover a thermodynamically stable applied strain. SMPs have been the focus of many recent experimental and theoretical investigations, many of which consider the SMP response due to infinitesimal deformations. This paper focuses on the three-dimensional implementation of a finite deformation constitutive model. This model is based on the theory of nonlinear thermoelasticity, and accounts for the coexisting active and frozen phases of the SMPs as well as the transition between the two phases. The model is implemented as a user material subroutine (UMAT) in ABAQUS.

Upon implementing the model, the material properties in the model are calibrated from finite deformation experimental data of a polyurethane (PU) SMP. Tensile tests are performed on the PU specimens for both constant strain and constant stress recovery scenarios. After calibrating from a subset of the experimental results, the model is used to predict the material response for additional thermomechanical loading paths. Furthermore, the three-dimensional implementation allows for the modeling of complex geometries under various loading paths. Geometries of interest that have been analyzed and presented in this work are based on biomedical and aerospace applications.

7978-54, Session 9

Giant electrical tuning of magnetic properties in magnetoelectric heterostructures using (110) PMN-PT single crystal

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We report giant electric tunable in-plane magnetic anisotropy in Ni/PMN-PT heterostructures characterized by Magnetic-Optical Kerr Effect (MOKE) measurement. 35nm polycrystalline Ni thin film with 5 nm Ti as adhesive layer is evaporated on (110) single crystal PMN-PT ferroelectric substrate. The poled PMN-PT substrate has anisotropic biaxial piezoelectric response. The positive electric field produces tensile strain along the M-H measurement direction as well as compressive strain in the perpendicular direction, creating a negative effective magnetic anisotropy since the magnetostriction of Ni is negative. Therefore the Ni thin film becomes harder to magnetize and the coercivity increases. In contrast, rotating the sample 90° exhibits the opposite trend. By utilizing the large piezoelectric coefficient of (110) PMN-PT, over 100 % tunability of coercivity H_c has been achieved. During the poling process, large remnant strain can also alter the magnetic properties of the Ni thin film.

7978-55, Session 9

Rate-dependent deformation of magneto active polymer

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Magneto Active Polymer (MAP) is a smart material comprised of magnetic particles dispersed in the polymer matrix. The basic characteristics such as large deformation and quick and quiet response to magnetic fields, make MAP promising for applications such as actuators and sensors. Due to the viscoelasticity of polymer matrix, the properties of MAP are usually dependent on the frequency or rate of change of the applied field. However, very few models of coupled magnetic field and viscoelasticity exist in the literature, and even fewer are capable of reliable predictions. Based on the principles of nonequilibrium thermodynamics, a field theory is developed to fully couple the finite-deformation viscoelasticity and magnetostatics of a MAP. The theory provides a guideline for experimental characterization of a MAP, and most material laws are readily applicable in this theoretical framework. A specific material model is then selected and the theory is applied to describe the deformation of a MAP in response to uniform and non-uniform magnetic fields. The dynamic response of a MAP to cyclic magnetic fields is studied, and the predictions agree with existing experimental results. In the non-viscous limit, our theory recovers existing models for elastic MAP, and is capable of capturing some instability phenomena.

7978-56, Session 9

Design and fabrication of a micro-scale magnetoelectric surgical tool

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We propose to use a magnetoelectric material as the basis for a micro-scale tool designed to perform common tasks in minimally invasive surgery. This tool is inserted and removed via catheter and is remotely actuated, allowing for improved patient outcomes in a variety of surgical procedures. The actuator is excited by the application of a cyclic external magnetic field, and the electrical output of the piezoelectric layer is used to provide closed-loop control of the actuator as well as haptic feedback. The closed-loop control provides improved positioning accuracy in the tool. In this paper, the behavior of the actuator is predicted using a force-deflection-sensing model developed in our previous work. This force-deflection-sensing model is based on variational principles and has been shown previously to accurately predict the quasi-static and dynamic behavior of a magnetoelectric laminate bimorph. In addition, micro-scale fabrication techniques for the actuator are examined, and a laminated bimorph cantilever actuator consisting of an Iron-Gallium(Galfenol) magnetostrictive layer and a Lead Zirconate Titanate (PZT) piezoelectric layer is fabricated at a scale that is physiologically appropriate for application in minimally invasive surgery. The mechanical behavior of the actuator is experimentally measured as the free displacement and blocked force at the actuator tip. The electrical behavior of the actuator is experimentally measured as the electrical current output by the piezoelectric layer. Both the mechanical and electrical behavior of the actuator are characterized and compared to the behavior predicted by the model.

7978-57, Session 9

Preliminary model of a 3D dynamically loaded Galfenol based stress sensor using rate equations

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The Villari effect of magnetostrictive materials, a change in magnetization due to an external stress, is used for sensing applications. For a dynamically loaded sensor, one measures the time-varying magnetization on the material. The question is, from these measurements, could information be extracted about all the applied stresses (the three axial and the three shear) on the material? In a previously developed rate-equation model [P. Weetman and G. Akhras, SPIE Proceedings Vol. 7644, 76440R], essentially the inverse of this problem was discussed where the input was a set of known stresses and the output was the calculated resulting magnetizations.

A preliminary conceptual design of a Galfenol based 3D dynamical sensor is presented. In the proposed prototype sensing device, one can measure the time-varying magnetization and its derivative in all three directions. Incorporating the previously developed 3D rate equation model, a new model is developed pertaining to this sensor. It will be shown that, under certain conditions, all stresses can be found from the magnetization measurements. The required calculations are presented and then performed on a sample set of magnetization data for validation. From this model, the implications to future sensing devices are discussed as well as suggestions on improvements to the model and the prototype.

7978-58, Session 9

3D dynamic finite element model for magnetostrictive Galfenol-based devices

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Magnetostrictive iron-gallium (Galfenol) alloys possess structural-grade mechanical properties in addition to exhibiting moderate magnetostriction. Galfenol sensors and actuators are uniquely well suited for integration within three-dimensional (3D) active structures. Modeling the behavior of these devices is challenging due to nonlinear Galfenol behavior and coupling between the electrical, magnetic, thermal and mechanical domains. This work addresses the development of an advanced modeling tool which describes this full nonlinear coupling in 3D Galfenol structures thereby providing complete transducer input-output relationships. Maxwell's equations for electromagnetics and Navier's equations for mechanical systems are formulated in weak form. The constitutive behavior of Galfenol is modeled by solving the linear piezomagnetic equations in piecewise increments. At the end of each step the piezomagnetic coefficients are updated using analytical differentiation of a discrete energy-averaged model formulated through thermodynamic principles. To account for the spatial dependence of the boundary value problem, the piezomagnetic coefficients are declared as interpolated data functions of global coordinates. The resulting model equations are coded into the finite element software COMSOL, which is used for meshing, global assembly of matrices, and post-processing. The model is applied to a unimorph actuator consisting of a Galfenol beam bonded to a brass substrate and a U-shaped magnetic circuit. Voltage-current and voltage-deflection curves are computed and compared with measurements. The example illustrates the effects of eddy currents, structural dynamics, flux leakage, and nonlinear Galfenol behavior on the dynamic response of the beam.

7978-05, Session 10

FE modeling of multiple SMA wire actuated adaptive structures

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Shape Memory Alloy (SMA) wires are attractive materials for use in adaptive structures due to their unique dual actuating and sensing capabilities. The complexity of such coupled structures incorporating multiple SMA wires and materials makes prototyping both a time consuming and expensive process. Thus, there is an inherent need for modeling efforts that encompass SMA materials assisting in the development of composite smart structures, especially using finite element tools.

This paper presents finite element analyses of adaptive structures that use multiple SMA wires for dual actuation and sensing. The commercially available FEA program ABAQUS was chosen as the simulation tool for its effectiveness in modeling materials with non-linear behavior and for its unique user material (UMAT) feature. The SMA wires were modeled within UMAT using a mesoscopic free energy model [1] to accurately describe their thermomechanically coupled actuator behavior. For each adaptive structure analyzed, the required heat input, resulting strains, electric resistance change, and the mechanical interactions with the structure were determined for each SMA wire. The second order effects of multiple-wire-structure coupling were also analyzed. The results from each simulation were compared with measurements taken with adaptive lab prototypes using a video camera system and LabVIEW Machine Vision software by National Instruments. Finite element analysis of SMA wire actuated adaptive structures using a thermomechanically coupled actuator SMA wire model will help in the development and optimization of future adaptive structures controlled by SMA wires.

7978-06, Session 10

The accumulation of retained martensite during thermomechanical cycling of NiTi shape memory alloys

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The shape memory and pseudoelastic behavior of Shape Memory Alloys have been investigated for a wide variety of cyclic behavior applications. In most applications, to obtain repeatable behavior the alloy is trained which leads to the accumulation of residual strain that stabilizes the transforming variants. To understand the training, the material stabilization and to accurately capture the cyclic behavior it is important to understand the evolution of the residual strain. However, the nature of the residual strain formed has been a matter of debate because this residual strain could be a combination inelastic strains such as transformation induced plastic strain, Two Way Shape Memory Effect (TWSME), creep strain (in the case of HTSMAs) or retained martensite. While the contributions from TWSME and the total residual strain can be readily obtained from the thermomechanical test data, decoupling the contribution of retained martensite has posed a challenge in recent years.

In the present effort, to study the origin of retained martensite accumulated during cyclic loading, nickel-titanium wires undergoing pseudoelastic cycles were characterized. Emphasis was placed on determining if the quantity of retained martensite is a function of test temperature and the maximum applied stress during cycling. Specimens were trained at different temperature above the austenitic finish temperature and to different applied maximum stress levels. The total residual strain was decomposed into the contributing, plastic strain, retained martensite and TWSME strain (as a consequence of the pseudoelastic cycling). To quantify the retained martensite in the specimen, a custom thermomechanical setup equipped with the

capability to flash heat was assembled on a MTS frame. The flash heating was conducted to temperatures of 200 and 300°C within the duration of heating for each within 25 seconds. The strain recovered during the course of the flash heating was recorded for each test case. Additionally, the effect of the flash heating on the TWSME as well as the cyclic stabilization was also investigated. Based on the retained martensite strain, the contribution from the plastic strain was determined. The trend in the evolution of plasticity, TWSME and retained martensite as a function of test temperature w.r.t. Austenite finish temperature as well as the maximum applied stress is presented.

7978-07, Session 10

Two-way shape memory behaviour of Ni-Ti-Hf based high-temperature shape memory alloys

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Aerospace, automotive and energy exploration industries (especially oil) have been calling for better actuator materials for their challenging applications. Ni-Ti-Hf emerged as a promising High Temperature Shape Memory Alloy (HTSMA) candidate to answer this call with its outstanding operation temperatures above 200°C and modest cost. However, its mechanical strength, ductility and unstable shape memory behavior during thermal/mechanical cyclic working conditions entailed a systematic study in order to understand and overcome these negative aspects.

In our study, we focused on enhancement of shape memory behavior related performance in Ni-Ti-Hf based HTSMAs by employment of alloying with quaternary elements, chemical composition management and thermomechanical treatments (i.e., aging under stress).

Consequently, we report that transformation temperatures of Ni-Ti-Hf alloys can be arranged with respect to the preferred operation range of the industrial application in hand. Stable and fully reversible isothermal mechanical cycling (pseudoelastic behavior) at temperatures beyond 200°C and stable isobaric thermal cycling under applied stresses beyond 1000 MPa are also successfully achieved. Succeeding the adequate thermomechanical training, a perfect two way shape memory effect (TWSME) is observed up to 2%.

7978-08, Session 10

A combined phase transformation-deformation mechanism map for Ti50.5Pd30Ni19.5 high temperature shape memory alloy

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For HTSMAs with transformation temperatures overlapping with the creep regime, a typical thermal actuation cycle could be accompanied by interaction of different inelastic mechanisms such as phase transformation, plasticity induced by the transformation, and viscoplasticity. For such SMAs, the classical stress-temperature phase diagram alone does not capture the complete behavior. The behavior of most metallic systems at high temperatures has traditionally been represented through deformation mechanism maps, which represent regions of different deformation mechanisms in stress-temperature space [1-5]. Some of these diagrams are based on the creep rates and probable mechanisms that accompany certain regimes while others resort to microstructural studies and are classified by the observed microstructural changes that occur during deformation [1, 2, 6]. Additionally these graphs can be plotted across various parameters such as normalized shear stress, normalized applied stress, shear strain rate, versus temperature or homologous temperature (i.e. test temperature normalized by the

melting temperature). For HTSMAs, to effectively capture mechanisms such as the phase transformation, plasticity and the viscoplastic behavior simultaneously, it may be necessary to generate a combined phase transformation-deformation diagram highlighting regions of overlap between transformation behavior and active deformation mechanisms as a function of stress and temperature.

To explore this challenge, the influence of inelastic phenomena (i.e. plasticity and viscoplasticity) on the transformation behavior and the cyclic actuation characteristics of a Ti50.5Pd30Ni19.5 high temperature shape memory alloy (HTSMA) was investigated using various thermomechanical loading paths. Isothermal uniaxial experiments were conducted at various temperatures in austenite and martensite to determine the mechanical response of the transforming phases. The temperatures and stress levels for the creep and thermal cycling experiments were chosen based on the uniaxial behavior. Standard creep tests were conducted on the alloy to study the viscoplastic behavior over its expected operational temperature and stress range. In addition, constant stress thermal cycling experiments were conducted, with initial loading in either the austenite or martensite phase, to study the effect of rate-independent and rate-dependent irrecoverable strains on the cyclic actuation behavior of this HTSMA. Based on the steady state creep rates and subsequent changes in the stress exponent of the power-law creep rate equation, it can be deduced that the mechanism for creep deformation changes with both stress level and temperature within the likely operating range for this Ti50.5Pd30Ni19.5 alloy. The load-biased thermal cycling tests show that the material performance can be significantly affected by rate independent irrecoverable strain (transformation induced plasticity + retained martensite) as well as creep. While the rate independent irrecoverable strain is readily apparent early in the actuators life, viscoplastic strain continues to accumulate over the life of the HTSMA. To consolidate these inelastic mechanisms, a combined phase transformation-deformation diagram was constructed to show the phase transformation along with the plastic and viscoplastic regions within the operational range of the HTSMA.

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7978-09, Session 10

A multi-block-spin-method based on statistical physics describing martensitic phase transformation

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Current strategies in modelling shape memory alloy (SMA) behaviour follow either the concept of classical irreversible thermodynamics (concept of local thermodynamic equilibrium) or the methodology of phenomenological approaches at the micro as well as at the macro space scale. Both concepts are based on the existence of external variables (e.g. stress, temperature) and the definition of internal variables (e.g. phase fraction, transformation strain). Especially the definition of internal variables and their constraints lead to a diversity of models and their results. From a physical point of view the argumentation of

external variables controlling the physical system is trivial and can be compared with experiments directly, whereas the internal variables are either hard or impossible to measure. The objective of the present study is to show a new approach in modelling SMA's by using a statistical physics concept without the requirement of internal variables. The foundation of the present method is the so called canonical ensemble which is defined locally (in space and time) by an equilibrium distribution. This does, however not require that the entire system consisting of numerous representative volume elements (RVEs) is in an equilibrium state (concept of local thermodynamic equilibrium). Fundamental thermodynamic principles in connection with the well established mathematical apparatus of statistical physics applied to the polycrystal allow deriving relevant system properties in analogy to the formalism used for paramagnetic-ferromagnetic systems. As a result we obtain the macroscopic strains as well as strain rates and the volume fractions of the martensitic variants and their rates as functions of the external variables (stress, temperature) and their time derivatives. The multi-block-spin-approach further maps under the occurrence of several variants the tension compression asymmetry of SMA's.

7978-10, Session 11

Highly anisotropic composite: shape memory alloy torsional actuator

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Shape changing or morphing structures enable optimisation of structural configuration to suit current operating conditions. Conventional actuating mechanisms and structures can incur a weight and complexity penalty to achieve an equivalent shape change. Highly anisotropic rod reinforced polymer composite materials can be tailored to resist axial loads but possess low torsional stiffness. Such materials offer scope in the design of structural components capable of providing rotational actuation. Shape Memory Alloys (SMA) are robust solid state actuators able to generate high specific actuation stresses and recover large strains. The combination of SMA actuators and highly anisotropic composite materials offer the potential for the design of compact structures able to undergo large shape change.

This work presents a torsional actuator design consisting of a highly anisotropic composite beam with surface mounted helically wound SMA wires, which is able to undergo rotation whilst retaining high axial stiffness. The composite beam consists of unidirectional fibre reinforced polymer pultruded rods within a low stiffness elastomer matrix. The matrix provides sufficient support to prevent compressive buckling of the stiff rods, but allows the rods to move relative to one another. The helically wound SMA wires apply both a rotational and axial compression load to the composite beam when activated. High axial stiffness of the composite beam minimises compressive strain but the low torsional stiffness enables rotation. The elastic behaviour of the composite beam recovers the residual strain of the SMA wires during cooling, returning the whole beam assembly to near its original configuration.

The highly anisotropic composite beam comprises 1.7mm diameter CFRP pultruded rods within a silicone polymer matrix, with a rod volume fraction of 20%, and dimensions of 17.5mm (diameter) and 110mm (length). Two NiTi SMA wires were externally wound onto the composite beam contained within PTFE tubing to prevent damage to the soft matrix, and fixed at either end of the composite beam. Electric resistive heating of the SMA wires using a PID controller at a constant heating rate of 50C/min was used to control and characterise actuation behaviour.

The effect of winding angle between the helically wound SMA wires and composite beam were tested for both unrestrained and fully restrained actuation. Experimental testing showed both unrestrained rotation and fully restrained torque to increase with SMA winding angle. Comparison to a 1D model proposed by Brinson [1] showed good agreement with experimental results.

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7978-11, Session 11

Experimental validation of position control methods for a flexible nozzle using self-sensing SMA wire actuators

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One of the main selling points of smart materials is the potential to exploit their multi-functional capabilities. For example, a shape memory alloy (SMA) wire can be used as a positioning actuator by heating the wire to induce contraction and as a positioning sensor by measuring the resistance across the length of the wire. While SMA's have found application in many on-off type applications, their ability to 'sense' their own change in length has not been fully exploited. This is because when coupled with a compliant structure, SMA wires exhibit non-linear, hysteretic behavior that depends not only on the phase transformation within the material, but also the thermal and force interactions between the wires and structure itself. If the resistance across an SMA can be reliably mapped to wire strain, a closed-loop controller can easily vary the length of the wire by changing the amount of electrical power input to the wire. This paper analyzes the fidelity of different mapping schemes when employed in a closed-loop controller. Linear approximation is compared to model-based methods in the context of a dual-joint flexible nozzle that is designed to control both the release position and trajectory of an emitted fluid flow. The modeling methods include consideration of the force coupling that results from opposing SMA actuators. The challenges of practical implementation issues are discussed alongside the results to develop the best mapping-control scheme for this application. Results show that simple linear-mapping solutions offer 2D nozzle tip position tracking with errors of 200 μm over a range of 12 mm on both axes, with minimal investment of calibration time, while more involved model-based solutions that include force coupling and account for hysteresis can bring positioning errors to less than 50 μm .

7978-12, Session 11

Development of compressive stresses in hybrid SMA-ceramic composites via SMA transformation

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Thermomechanical loading paths have been considered for ceramic matrix composites with Shape Memory Alloy (SMA) inhomogeneities as the second phase. By selecting a new class of ceramics, MAX phases, which can undergo plastic deformation, it has been shown that it is possible to combine martensitic transformation of the SMA and elasto-plasticity of the MAX phase to generate a new ceramic reference configuration that has residual compressive stresses. To demonstrate this effect, a series of finite element analyses is performed using a representative hybrid composite mesh created from X-ray tomography. The two phases are considered to have distinct constitutive behavior. The SMA behavior is described by the 3D phenomenological model developed by Hartl and Lagoudas (2009). A methodology to describe the unique stress-strain behavior of the MAX phase ceramic is developed. Using these models, it is shown that after performing a complete loading cycle compressive stresses are generated on the ceramic phase. Both isobaric thermal cycles and pseudoelastic loadings are considered. A parametric study on several loading paths and conditions is performed. As the mesh is developed from real microstructures, the effect of local stress concentrations is studied. The effects of loading paths and properties are discussed and methodologies to maximize the benefit of this synergistic phenomenon are investigated.

7978-14, Session 11

Phase transformations in NiCoMnIn and NiCoMnAl shape memory alloy thin films

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Shape memory alloy thin films can be integrated with MEMS or NEMS device and have promising applications as sensors and actuators. Understanding the influence of microstructure and chemistry on phase transformations is critical in this context. We report on the synthesis and characterization of NiCoMnIn and NiCoMnAl thin films fabricated by magnetron sputtering technique. Phase transformations in films are investigated by differential scanning calorimetry technique. The microstructures of films are investigated systematically by transmission electron microscopy and scanning transmission electron microscopy. Annealing induced phase segregation is observed in NiCoMnIn films, and consequently the phase segregation affects the phase transformation temperature of films. In NiCoMnAl films, field induced phase transformation is revealed. Corresponding phase transformation mechanisms is discussed.

7978-13, Session 12

Model predictions of strain and magnetization responses under magneto-thermo-mechanical loading paths in magnetic shape memory alloys

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The unique characteristic of magnetic field induced phase transformation of magnetic shape memory alloys (MSMAs) lies in the generation of large transformation strains accompanied by high actuation stress. The macroscopic functionality of MSMAs originates from the coupled evolution of highly heterogeneous magnetic and elastic domain microstructures under external magnetic, mechanical, and thermal conditions. Experiments have been performed on single crystal alloys with promising results. It is observed that applied stress in combination with the applied magnetic field facilitates the release of magnetic energy of the material. This combined effect produces considerable amount of inelastic strain. In the present work, martensitic phase transformation is taken into account by introducing internal variables into a thermodynamically based constitutive model. Internal variables are needed to take account for strong effects of varying elastic and magnetic coupling, nonlinearity and irreversibility. Without explicitly considering the domain configuration and evolution, the microstructure dependence is approximated phenomenologically by certain evolution laws of the selected internal variables. Motivated by experiments in Dr. Karaman's group, a constitutive model is proposed to account for temperature, magnetic field and stress induced phase transformation from martensitic to austenitic phase. The constitutive response is derived in a consistent thermodynamic way. The model is calibrated from experiments and a 3-D phase diagram is constructed by using analytical methods. The strain versus magnetic field constitutive response is simulated and the constitutive responses of magnetization versus magnetic field is then predicted and compared with experimental results. Moreover, strain versus temperature and magnetization versus temperature responses are presented. The proposed model has the ability to predict the nonlinear, hysteretic strain and magnetization response caused by martensitic phase transformation due to temperature and magnetic field coupling. Finally, different magneto-thermo-mechanical loading paths are considered to predict the strain and magnetization response of MSMA composite structures.

7978-15, Session 12

Magneto-mechanical behavior of magnetic shape memory alloys under simultaneously variable magnetic and mechanical loading

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Magnetic shape memory alloys (MSMA) have received significant attention in recent years because of the large shape changes they produce (as large as 10% strain) when exposed to moderate magnetic fields (on the order of 1T). In addition to their high strain capability, MSMAs can operate at frequencies up to 1kHz. The material returns to its original shape when a compressive stress is applied in the appropriate direction, or the direction of the magnetic field is rotated by 90°. This shape memory effect is due to tetragonal martensite variants which reorient upon certain magnetic or mechanical loading.

The macroscopic behavior of the MSMA has been investigated through experiments performed on prismatic specimens loaded with either constant transversely applied magnetic field and variable axial compressive stress or variable transversely applied magnetic field and constant axial compressive stress. The former loading condition resembles using a MSMA as a sensor, while the latter mimics using a MSMA as an actuator. Phenomenological models have been developed to capture the macroscopic behavior under these loading conditions.

No experimental or theoretical work has been done to investigate the material response under simultaneously varied magnetic and mechanical loading. In practice, this condition mimics a MSMA that is used as an actuator to preserve the position of a load whose intensity varies in time, or an MSMA that is used as both an actuator and a sensor, the former requires changing the magnetic field and the latter requires changing stress. From a theoretical perspective, these conditions are an important step towards a 3D model.

This work presents experimental and simulated results for MSMA elements loaded with simultaneously varied magnetic and mechanical loading and discusses some of the challenges associated with true 3D modeling of the magneto-mechanical response of these materials.

7978-16, Session 12

Energy harvesting using NiMnGa martensitic reorientation process at high frequencies of excitation

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Karaman et al. proposed the application of energy harvesting using NiMnGa single crystals and proved its feasibility via a simple mathematical model which corresponded well to experimental results. Although this idea has been tested and proven, experimental results are lacking for higher frequencies of excitation. In addition, the use of magnetization equations that describe the reversible magnetic flux density upon martensitic reorientation has not been attempted. This work presents simulated and experimental results which describe the energy harvesting capabilities of NiMnGa magnetic shape memory alloy (MSMA) at high frequencies and the usage of magnetization relations developed and modified by Kiefer and Lagoudas. Simulated results are determined via COMSOL Multiphysics for different constant bias magnetic fields with varied frequencies of excitation and stress amplitudes. The simulated results are compared to experimental data, and techniques for optimization are discussed. The design of a portable energy harvesting device is also presented.

7978-17, Session 12

Investigation of Co-doped NiMnGa as a high-temperature metamagnetic shape memory alloy for actuator applications

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As actuator materials, magnetic shape memory alloys (MSMAs) are superior to magnetostrictives since they can produce one order of magnitude greater actuation strains under magnetic field. They also surpass conventional SMAs with their two orders of magnitude greater dynamic response in actuation frequency. Thanks to Villari Effect, sensing and energy harvesting applications can be cited among their most promising applications, as well.

Depending on the alloying elements and chemical composition, austenite and martensite phases (both or one) can be in ferromagnetic state in NiMn-based MSMAs. NiMnGa alloys are the most MSMAs in which magnetic actuation occurs by variant reorientation process. The main drawbacks of NiMnGa alloys are their brittleness, low actuation stress (due to limited magnetic energy) and high orientation dependence. In this study, it will be shown that Co doped NiMnGa provides a new alternative to existing MSMAs which demonstrates superelastic behavior in polycrystalline form, with transformation temperatures above 100oC and a possibility to tune the transformation and Curie temperatures and hence change ferromagnetic austenite to paramagnetic (or antiferromagnetic) martensite.

The results of a systematic characterization study of Co doped NiMnGa high temperature metamagnetic SMAs including isobaric thermal cycling (shape memory effect) and isothermal stress cycling (pseudo elasticity) tests will be presented accompanied with magnetization test results as functions of temperature and applied field. Findings on crystal structure determination of austenite and martensite phases via x-ray diffraction (in-situ heating/cooling cycles) will also be reported.

This research was supported by Research Opportunity Award by Research Corporation (RA-0357), and by the Office of Basic Energy Sciences, US DOE (contract No. DE-FG02-06ER46291).

Conference 7979: Industrial and Commercial Applications of Smart Structures Technologies V

Monday-Tuesday 7-8 March 2011

Part of Proceedings of SPIE Vol. 7979 Industrial and Commercial Applications of Smart Structures Technologies 2011

7979-01, Session 1

Temperature measurement in a turbine stator assembly using an integratable high-temperature ultrasonic sensor network

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Implementation of an integratable ultrasonic sensor network with associated cable connection for high temperature monitoring applications is demonstrated through application of a three-element ultrasonic sensor network for temperature measurement in a turbine stator assembly. The sensor network is composed of a piezoelectric composite film deposited on a titanium substrate with a sol-gel technique and three top electrodes deposited on the piezoelectric film. The sensor network is glued onto a selected area of the stator assembly in such a way that three subareas with different wall thicknesses are probed individually by each of the sensing elements. The ultrasonically instrumented stator assembly is first heated in a furnace to different temperatures. At each temperature and for each probed location the transit time of ultrasonic waves through assembly wall thickness is measured. Then a relationship between transit time and wall temperature is established. In a subsequent experiment, the stator assembly is heated up to 200 °C and then let cool down while the transit time in the assembly wall is being measured continuously. By using the transit time versus temperature relationship obtained earlier, the heating and cooling rates at the three probed locations are determined and then compared.

7979-02, Session 1

Performance and modeling of active metal-matrix composites manufactured by ultrasonic additive manufacturing

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This paper deals with the development of active metal-matrix composites manufactured by Ultrasonic Additive Manufacturing (UAM), an emerging manufacturing process that allows the embedding of materials into metals through ultrasonic consolidation. In the UAM process, successive layers of metal tapes are ultrasonically bonded together to form a metal matrix. Current methods of creating metallic composites involve methods such as sintering, forging, or casting which generally require temperatures up to 565°C (1050°F) in order to create melting or diffusion. In comparison, UAM is performed at room temperature with the bulk of the composite never exceeding 195°C. Being a low-temperature process, UAM offers unprecedented opportunities to create parts both with embedded materials (e.g., metals, fiber optics, printed circuits, polymers, and smart materials) and arbitrarily shaped internal features (e.g., internal cooling channels, designed anisotropies).

UAM operates on the principle of Ultrasonic Metal Welding (UMW). In UMW, ultrasonic vibrations created by a piezoelectric transducer are transferred to clamped work pieces by a transversely vibrating sonotrode. The vibrating sonotrode imparts a static pressure and transverse ultrasonic motion to the top piece that creates a relative, friction-like action at the interface of the two work pieces. The relative interface motion causes shear deformations of contacting surface asperities, dispersing interface oxides and bringing clean metal-to-metal contact and metallic bonding between the surfaces.

In this research, UAM is used to construct metal samples with embedded smart materials. The embedded smart materials will allow for the

composite to have sensing and actuation properties. This research focuses on the creation of active metal matrix composites by embedding NiTi, Galfenol (FeGa), and electroactive PVDF into aluminum matrices. In our work, we have shown the ability of UAM to embed large volume fractions of smart materials, over 22%, within an Al 3003-H18 matrix. These samples are constructed by placing the material, in the form of ribbons or wires, at the interface of two Al 3003-H18 tapes and then ultrasonically welding the tapes together. Embedded pieces include wire with diameters up to 381 µm and ribbons up to 381 µm thick and 9.52 mm wide. In embedding these materials, the ultrasonic vibrations cause plastic flow of the aluminum tapes around the embedded entities completely enveloping them in the matrix.

The large difference in elastic modulus, over 100%, between the low temperature martensite phase and the high temperature austenite phase of NiTi provides a mechanism for actively changing the stiffness of the composite through thermal activation. The large stiffness change can be applied in tunable vibration absorbers or for actively changing the mobility path in structure-borne noise with the goal of minimizing noise propagation. Preliminary work shows that as little as 5% NiTi can counteract the softening observed in Al 3003 by increasing the temperature and 20% NiTi creates an increase in stiffness in excess of 35%. The NiTi-Al UAM composites can also exhibit geometric stability under temperature variations. As temperature increases, the expansion of the aluminum matrix is opposed by the contraction of the NiTi wires. The counteracting strain of the matrix and NiTi reinforcement results in a partial transformation of the NiTi and a negative net strain of the composite. By carefully placing NiTi wires, an Al-based component could be made to have little change in shape over a wide range of temperatures thereby creating a dimensionally stable structure for use in environments with large temperature changes, such as an engine compartment. Modeling and experimental results on stiffness tuning and thermal invariance with UAM composites are presented.

Composites with magnetostrictive Galfenol alloys embedded into aluminum exhibit actuation and sensing properties. Magnetostrictive materials produce a strain response to a magnetic field when operating in actuation mode and generate a change in magnetization as a response to applied strain in sensing mode. Material used for our composites is rolled Galfenol which exhibits approximately 200 microstrain at magnetic saturation. Preliminary experiments have shown our FeGa-Al composite experiences 50 microstrain response at the surface of the magnetically inert Al surface. Modeling indicates that the reduced magnetostriction is due to mechanical loading of the FeGa by the Al matrix. The actuation properties may be useful for high frequency vibration cancellation. By utilizing the magnetic response of the embedded FeGa, the active composite could serve as an embedded vibration sensor to actuate other smart composites for on-demand vibration mitigation.

PVDF-Al composites allow for embedded tactile sensors within a metal component. We have demonstrated that PVDF can be successfully embedded via UAM without destroying its mechanical or sensing properties. Through strategic placement of PVDF, a stress mapping system can be developed which will allow for in situ monitoring of critical components and impact sensing body panels or structural components for selective deployment of safety systems.

Challenges being addresses include characterizing the unique properties of NiTi-Al, FeGa-Al, and PVDF-Al composites, creating constitutive models to describe their behaviors, and utilizing the models to develop multifunctional smart components. The behaviors we are focusing on include variable stiffness and thermal invariance of NiTi-Al composites, the sensing properties of FeGa-Al composites, and the frequency response and sensitivity of PVDF-Al composites. Through developing an understanding of these composites, it will be possible to create adaptive UAM components with multiple types of embedded smart materials that react to changes in their environment.

7979-03, Session 1

Embedded processing for SHM with integrated software control of a wireless impedance device

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Wireless sensor nodes with impedance measurement capabilities, often based on the Analog Devices AD5933 impedance chip and Atmel's 8-bit ATmega 1281 microcontroller, have been demonstrated to be effective in collecting data for localized damage detection (such as for loose bolt detection) and for sensor self-diagnostics. Previously-developed nodes rely on radio telemetry and off-board processing (usually via a PC) to ascertain damage presence or sensor condition. Recent firmware improvements for the wireless impedance device (WID) now allow seamless integration of the WID with SHMTools and mFUSE, an open-source function sequencer and SHM process platform for Matlab. Furthermore, SHM processes developed using mFUSE can be implemented in hardware on the WID, allowing greater autonomy among the sensor nodes to identify and report damage in real time. This paper presents the capabilities of the newly integrated hardware and software, as well as experimental validation. The ease and utility of the WID as a deployable wireless sensor node for automated and on-demand monitoring is demonstrated.

7979-04, Session 1

Hybrid energy sources for embedded sensor nodes

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In this paper, we present a series of hybrid energy configurations that are designed to provide a robust power source for embedded sensing hardware. The proper management of energy resources is a critical component in the design of any deployed sensing network. For systems that are installed in remote or inaccessible locations, or those with an operational lifespan that exceeds traditional battery technologies, energy harvesting is an attractive alternative. Unfortunately, the dependence on a single energy source (i.e. solar) can cause potential problems when environmental conditions preclude the system from operating at peak performance. In this paper we consider the use of a hybrid energy source that extracts energy from multiple sources and uses this collective energy to power sensing hardware. The sources considered in this work include: solar, vibration, thermal gradients, and RF energy capture. Methods of increasing the efficiency, energy storage medium, target applications and the integrated use of energy harvesting sources with wireless energy transmission will be discussed.

7979-05, Session 2

Direct force measurement system for assessment of aircraft/store interface loads and integrity

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Measured operational interface loads of structural systems can be invaluable as a feature for monitoring its structural integrity. However, obtaining forces and moments at critical interfaces of structural systems is not easily achieved and is often inferred from secondary system responses (e.g. strain or acceleration). These methods typically do not work in a robust fashion as, by their nature, they require a set of underlying assumptions - with varying degrees of accuracy/applicability - to be employed.

This paper addresses the development of an accurate in-situ force measurement system for directly monitoring dynamic operational loads at critical mechanical interfaces. The proposed methodology utilizes an optical strain gage-based measurement technique in which a series of sensors are calibrated with a set of known loading configurations. The sensitivity matrix relating the measured strains to the loads forms the core of the system. Unlike conventional precision load cells, a well-defined load path is not required and the method does not alter the existing connector architecture; thereby requalification/recertification of the system isn't necessary.

The specific application for which this technology is being developed includes the measurement of resultant forces and moments between an aircraft weapon store and its carriage platform. The feasibility of the proposed technique was demonstrated both analytically and experimentally on a representative store/rail interface exhibiting nonlinearity in the system with a fairly high degree of accuracy. It is suggested that the proposed technology and methods can be particularly beneficial to the structural health monitoring community by augmenting diagnostic/prognostic routines with real-time loading information.

7979-06, Session 2

Comparative analysis of shape memory alloy beam actuators for increased power output

S. Oehler, D. J. Hartl, D. C. Lagoudas, Texas A&M Univ. (United States)

The utilization of shape memory alloys (SMAs) as actuators in aerospace applications continues to show promise. However, the rate of thermally induced transformation in these materials is hindered by a low coefficient of thermal conduction and the effects of latent heat.

The relatively long cooling times observed in geometries such as beams and tubes make it difficult for such actuators to operate with sufficiently high frequency. This has motivated the effort to increase thermal actuation rates attainable in SMA active components.

This work presents a comparative analytical study of SMA beam actuators with various configurations. These components include both regions of active SMA and regions of more thermally conductive passive material.

The chosen global finite element solver is executed in conjunction with a user-defined material (UMAT) subroutine, which itself is a numerical implementation of a powerful and accurate three-dimensional constitutive model. The model considers the effects of latent heat of transformation on the energy balance and is calibrated using material parameters from SMA characterization.

The effectiveness of various secondary materials (i.e. copper, aluminum, and others) and the geometric configurations in which they are installed is compared with regard to beam actuation work output and actuation rate. Cyclic actuation power per unit mass over full transformation cycles is used as the measure of interest, and recommendations are made regarding the design of future SMA-based smart structures.

7979-08, Session 2

Chiral auxetics for shape memory polymer deployable structures

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Auxetic (negative Poisson's ratio) configurations have been used recently to build prototypes of deployable structures using classical shape memory alloys (Nickel-Titanium-Copper). The chiral configuration is a particular cellular tessellation providing non-affine deformations, leading to combined tensile-rotational mechanisms. These structures offer high deployability ratios in structural elements with load-bearing characteristics. Shape memory polymers have the potential to replace conventional shape memory alloys and other stored-energy actuators,

and have the attractive properties of low mass, high actuation strain, easy fabrication and tunable thermal properties. In this work we show how an integral Shape memory polymer (SMP) chiral core could offer enhanced deployable characteristics and increase the efficiency of the auxetic deformations in these unusual cellular structures. We present the design and development of SMP n-chiral prototypes, numerical simulations showing the auxetic behaviour and test results showing actuation motion of expanding SMP auxetic structures. Applications likely to benefit from these structures include lightweight elements for structural engineering applications, deployable structures for space applications and implantable medical devices.

7979-09, Session 2

Microfibrous metallic cloth for acoustic isolation of a MEMS gyroscope

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The response of a MEMS device that is exposed to a harsh environment may range from an increased noise floor to a completely erroneous output to temporary or even permanent device failure. One such harsh environment is high power acoustic energy possessing high frequency components. This type of environment sometimes occurs in small aerospace vehicles. In this type of operating environment, high frequency acoustic energy can be transferred to a MEMS gyroscope die through the device packaging. If the acoustic noise possesses a sufficiently strong component at the resonant frequency of the gyroscope, it will overexcite the motion of the proof mass, resulting in the deleterious effect of corrupted angular rate measurement. Therefore if the device or system packaging can be improved to sufficiently isolate the gyroscope die from environmental acoustic energy, the sensor may find new applications in this type of harsh environment. This research effort explored the use of microfibrous metallic cloth for isolating the gyroscope die from environmental acoustic excitation. Microfibrous cloth is a composite of fused, intermingled metal fibers and has a variety of typical uses involving chemical processing applications and filtering. Specifically, this research consisted of experimental evaluations of multiple layers of packed microfibrous cloth composed of sintered nickel material. The packed cloth was used to provide acoustic isolation for a test MEMS gyroscope, the Analog Devices ADXRS300. The results of this investigation revealed that the intermingling of the various fibers of the metallic cloth provided a significant contact area between the fiber strands and voids, which enhanced the acoustic damping of the material. As a result, the nickel cloth was discovered to be an effective acoustic isolation material for this particular MEMS gyroscope. Experimental results indicated that the addition of the microfibrous cloth could decrease the observed deleterious effects in the gyroscope's output signal by 6 to 10dB at acoustic noise power levels of approximately 133dB.

7979-10, Session 3

Active materials for automotive adaptive forward lighting Part I: system requirements vs. material properties

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Adaptive Frontlighting Systems (AFS in GM usage) improve visibility by automatically optimizing the beam pattern to accommodate road, driving and environmental conditions. By moving, modifying, and/or adding light during nighttime, inclement weather, or in sharp turns, the driver is presented with dynamic illumination not possible with static lighting systems.

The objective of this GM-HRL collaborative research project was to assess the potential of active materials to decrease the cost, mass, and packaging volume of current electric stepper-motor AFS designs. Solid-state active material actuators, if proved suitable for this application,

could be less expensive than electric motors and have lower part count, reduced size and weight, and lower acoustic and EMF noise.

This paper documents Part 1 of the collaborative study, assessing technically mature, commercially available active materials for use as actuators. Candidate materials should reduce cost and improve AFS capabilities, such as increased angular velocity on swivel. Additional benefits to AFS resulting from active materials actuators were to be identified as well such as lower part count. In addition, several notional approaches to AFS were documented to illustrate the potential function, which is developed more fully in Part 2.

Part 1 was successful in verifying the feasibility of using two active materials for AFS: shape memory alloys, and piezoelectrics. In particular, this demonstration showed that all application requirements including those on actuation speed, force, and cyclic stability to effect manipulation of the filament assembly and/or the reflector could be met by piezoelectrics (as ultrasonic motors) and SMA wire actuators.

7979-11, Session 3

A magnetorheological fluid locking device

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A magnetorheological fluid (MRF) device is designed to provide a static locking force caused by the operation of a controllable MRF valve. A passive magnetic field supplied by a permanent magnet provides a powerless locking resistance force. When an axial force is applied to the operational end of the device, the passively closed MRF valve provides sufficient reaction force to eliminate axial displacement up to a pre-defined force value. During unlocking operation, current is supplied to an electromagnet which neutralizes the magnetic field on the MRF valve, and allows free movement of the operational end of the device. If desired, the locking force can also be increased in certain circumstances by reversing the electromagnet coil current. Three dimensional electromagnetic finite element analyses are performed to optimize the lock valve performance. The MRF locking valve is fabricated and tested for installation on a truck fifth wheel application. The locking capacity and the neutralizing effect during the unlocking process are experimentally demonstrated.

7979-12, Session 3

Coupled axisymmetric finite element model for a magneto-hydraulic actuator for active engine mounts

S. Chakrabarti, M. J. Dapino, The Ohio State Univ. (United States)

A 2D axisymmetric finite element model is developed to describe the dynamic response of a hydraulically amplified Terfenol-D actuator for active engine mounts. Maxwell's equations for electromagnetics and Navier's equations for mechanical systems are formulated in weak form for a generalized 3D system. Axisymmetric assumptions are subsequently made to reduce the form of the model. Current densities are assumed to be only in the circumferential direction and the vector magnetic potential is reduced to a scalar form with only a circumferential component. Curl, divergence and gradient operators are expanded in cylindrical coordinates and volume integrals in the weak form are converted to area integrals for the axisymmetric system. Terfenol-D constitutive behavior is modeled using an energy-averaged hysteretic model. The resulting finite element model equations are coded into the finite element software COMSOL, which is used for meshing, global assembly of matrices, and post-processing. The FE model describes the full coupling between the electrical, magnetic, and mechanical domains in a magnetostrictive transducer and is sufficiently general to apply to any axisymmetric Terfenol-D transducer. The FE model is coupled with the LuGre friction model to describe frictional forces in the moving components and a lumped parameter driven piston model for computational efficiency. The model aims at describing the transient dynamic response of the device over the frequency range 10-500 Hz.

7979-13, Session 3

An improvement method of charge capability on a flexible electrostatic actuator and its applications

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The development of flexible electret based electrostatic actuator has become an important research topic in the smart structure field. However the uniform rate of surface charge influences on the quality of electret loudspeaker. An electret film is a piece of dielectric material that holds a quasi-permanent electrical charge. Corona charge equipment is set up to make electret charges within the electret film. The uniform discharge plays an important role in the process of electret material fabrication. The structure of the electrostatic actuator is similar to honeycomb, moreover it can be cut into any pattern for futuristic applications. The vibrating quality of the electret loudspeaker is based on the uniform rate of the discharging. Humidity is absolutely an important factor that will influence electrets' charge density. Because humid air dissipates charged ions easily than dry air, voltage of electrets' surface may decrease. In the paper, the multi-pin-grid-plate electrode system was powered from two continuously-adjustable DC high negative voltage suppliers that one for the multi-pins and the other for the grid. Then, an electret film was placed between a needle and a plate. The electrode was applied high voltage to charge the electrets film so that the electret film could hold great charges inside. The optimal multi-pins system was established, including discharging arrangement and grid voltage to achieve the uniform distribution of surface charges. The highly uniform discharge increases the efficiency and quality of the electret loudspeaker. Then the electrostatic paper-thin film actuator could be cut into any configuration and be assembled into the electret loudspeaker for many futuristic applications of the audio system such as poster, clothes, and hat etc.

7979-14, Session 3

High-frequency valve development for smart material electro-hydraulic actuators

J. P. Larson, M. J. Dapino, The Ohio State Univ. (United States)

Smart material electro-hydraulic actuators take advantage of the high blocked force and broad frequency response of smart materials such as piezoelectrics and magnetostrictives. Hydraulic rectification is used to create large motions from the relatively small, high-frequency displacements of the smart material. These actuators can be applied to develop compact power-by-wire actuators for aerospace and automotive applications where size and weight are of concern. Check valves are used to rectify high frequency pulses of hydraulic fluid to create large displacements of a cylinder. Designing check valves to perform the fluid rectification at frequencies above 1 kHz has proven difficult. This paper presents two approaches to developing improved check valves by considering both a conventional single reed-type design and an array of miniaturized valves. Design for infinite fatigue life was considered for the high frequency, high pressure environment in the pump using ANSYS for stress analysis. The expected frequency response for each valve design was calculated considering the added mass effects of the fluid. A fabrication method was developed for the miniaturized valves with micromachining processes. The multiphysics software COMSOL was used to study the 3-D fluid-structure interaction between the valve and hydraulic fluid during pump operation. The valves were specially instrumented to measure their displacement during pump operation. Their performance was evaluated with static and dynamic experiments with the results compared to the simulations.

7979-15, Session 3

Integrated piezoelectric actuators in deep drawing tools

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The production of car body panels are defective in succession of process fluctuations. Thus the produced car body panel can be precise or damaged. To reduce the error rate, an intelligent deep drawing tool was developed at the Fraunhofer Institute for Machine Tools and Forming Technology IWU in cooperation with Audi and Volkswagen. Mechatronic components in a closed-loop control is the main differentiating factor between an intelligent and a conventional deep drawing tool. In correlation with sensors for process monitoring, the intelligent tool consists of piezoelectric actuators to actuate the deep drawing process. By enabling the usage of sensors and actuators at the die, the forming tool transform to a smart structure. The interface between sensors and actuators will be realized with a closed-loop control.

The content of this research will present the experimental results with the piezoelectric actuator. For the analysis a production-oriented forming tool with all automotive requirements were used. The disposed actuators are monolithic multilayer actuators of the piezo injector system. In order to achieve required force, the actuators are combined in a cluster. The cluster is redundant and economical. In addition to the detailed assembly structures, this research will highlight intensive analysis with the intelligent deep drawing tool.

7979-16, Session 4

An evaluation of sensing technologies in a wind turbine blade

M. A. Rumsey, Sandia National Labs. (United States)

A key goal in the Department of Energy is to reduce the cost of energy from wind energy systems to make the technology a viable option for the electric utility industry. To meet this goal, there are several technology improvements that can be implemented, such as, sensors for smart rotor monitoring and control. Historically, reliability and cost have limited the use of sensor systems in the blades of a wind turbine. However, the next generation of electric utility-size wind turbines will require additional sensors in their blades to enable advanced control strategies to optimize system performance. In order for a blade sensing system to be successful the sensing system reliability has to be maintained throughout the entire life of a wind turbine. To develop an understanding of the issues in sensing system reliability a Sensor Blade Project was initiated in the Wind and Water Power Technologies Department at Sandia National Laboratories. The Sensor Blade project was highly collaborative where numerous partners had an opportunity to implement their sensing technology in a wind turbine blade at the time of blade manufacturing, assess the performance of their sensing system in a field environment, and to monitor their sensing system as the blade was fatigued to blade failure in the laboratory. These promising sensor technologies, for operational dynamics, non-destructive testing and structural health monitoring, were monitored and evaluated over the full (accelerated) life-cycle (cradle to grave) of the blade. This paper is an overview of the Sensor Blade project.

7979-17, Session 4

A shape adaptive airfoil for a wind turbine blade

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The loads on wind turbine components are primarily from the blades. It is important to control these blade loads in order to avoid damaging the

wind turbine. Rotor control technology is currently limited to controlling the rotor speed and the pitch of the blades. As the size of wind turbine blades increases the loads along the blade length can vary considerably due to a combination of turbulence, varying wind speeds, wind shear and other effects. So as blades increase in length it becomes less desirable to pitch the entire blade as a single rigid body. There is a requirement to control loads more precisely along the length of the blade. This can be achieved with aerodynamic control devices such as flaps. Morphing technologies are good candidates for wind turbine flaps because they have the potential to create structures that have the conflicting abilities of being load carrying, light-weight and shape adaptive. This paper presents the structural design, analysis and testing of a morphing airfoil flap. The flap's design enables large deflections and high strains to be achieved without a large actuation penalty. An aeroelastic analysis couples the work done by aerodynamic loads on the flap, the strain energy in the flap and the required actuation work to change shape. This aeroelastic analysis is experimentally validated with a manufactured demonstrator.

7979-18, Session 4

Metallic wear debris sensors: promising developments in failure prevention for wind turbine gearsets

J. Poley, Kittiwake Americas (United States)

This presentation includes controlled laboratory research data from tests conducted on a typical wind turbine gearbox, wherein ferrous particle measurement and particle counting were employed and monitored, and the results compared with a physical inspection of wear experienced by the gearset.

A gear test was designed and conducted by Newcastle University (U.K.), aiming to verify performance of two ANALEXrs debris sensors provided by Kittiwake Developments LTD.

Metallic debris in oil generated by surface fatigue in the form of micro-pitting and macro-pitting as well as gear scuffing were picked up by a particle sensor and a total ferrous sensor fitted in the oil return pipe of the test gearbox. Comparisons were made to see if there is agreement between sensor data and actual observation of gear damage. Vibration signal of the gearbox was also collected as an addition measure to monitor the working condition of test gears. This 18-day gear testing was completed in two phases. Phase 1 covers the first 3 test days with only particle sensor fitted. Phase 2 covers the remainder of the test with both particle and total ferrous sensor fitted.

Findings and conclusions include:

- The ANALEXrs particle sensor was able to pick up ferrous particles resulting from gear surface fatigue and scuffing damages
- The trend of cumulative ferrous particle counts correlated well with the observed progression of damage on gear flanks, indicating that the Kittiwake ANALEXrs particle sensor readings provided a very good indication of flank damage in running metallic gears

7979-19, Session 5

Structural health monitoring of wind turbine blades using fiber optic Bragg grating sensors

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Over the last few years, fiber optic sensors (FOS) have seen increased acceptance and widespread use in civil engineering, aerospace, marine, oil & gas, composites and smart structure applications. More and more, different research groups and blade manufacturers worldwide have started adopting fiber sensors and fiber Bragg gratings (FBGs) in particular, as practical sensing technology for wind turbine blade

measurements and monitoring. FOS are an attractive technology and reliable sensing solution due to the fact that are completely immune to electromagnetic interference, lightning and electric noise-unlike more conventional electronic sensors that are prone to failure given the harsh and exposed environmental conditions under which wind turbines normally operate.

Typically, FBG sensor arrays-either surface-mounted or embedded-have been used to monitor the mechanical behavior of composite rotor blades during the design and qualification stages, as well as in service, to help monitor, on-line, the blades' condition under rotating, stationary and different wind load conditions.

In this paper, will present test field results on the mechanical measurements from an experimental composite blade developed under Sandia Lab's S-Blade experimental wind turbine program, instrumented with FBG temperature and strain sensors. A discussion of the methodology, on-line monitoring electronic system, and results obtained will be presented.

7979-20, Session 5

Piezoelectric active sensing techniques for damage detection on wind turbine blades

G. Park, K. M. Farinholt, S. G. Taylor, C. R. Farrar, Los Alamos National Lab. (United States)

This paper presents the performance of a variety of structural health monitoring (SHM) techniques, based on the use of piezoelectric active sensors, to determine the structural integrity of a 9m CX-100 wind turbine blade (developed by Sandia National Laboratory (SNL)). Specifically, Lamb wave propagation, impedance based methods, frequency response functions, and a time series based method are utilized to analyze the condition of the wind turbine blade. The main focus of this research is to assess and construct a performance matrix to compare the performance of each method in identifying incipient damage, with a special consideration given to power consumption and issues related to field deployment. Experiments are conducted on a stationary, full length CX-100 wind turbine blade. This examination is a precursor for planned full-scale fatigue testing of the blade and subsequent tests to be performed on an operational CX-100 Rotor Blade to be flown in the field.

7979-22, Session 5

Full field inspection of a wind turbine blade using 3D digital image correlation

B. LeBlanc, C. Niezrecki, Univ. of Massachusetts Lowell (United States); S. Hughes, National Renewable Energy Lab. (United States); P. Avitabile, J. Chen, J. A. Sherwood, Univ. of Massachusetts Lowell (United States)

Due to increasing demand for improved wind energy harnessing technology, there has been a significant rise in the number of wind-turbine blades manufactured globally. The risk for manufacturing defects increases as the size and number of turbines erected grows. There is now a critical need for large-scale inspection and monitoring the state of structural health of these machines during normal operation. A possible method to discover manufacturing defects and allow for the in-situ measurements of the structural health of blades is by observing a wind-turbine blade's full-field state of deformation and strain. Static tests were performed on a 9-meter CX-100 composite turbine blade to extract full-field displacement and strain measurements. Measurements were taken at several angles near the blade root including the high-pressure side, low-pressure side, and trailing edge. The overall results indicate that the measurement approach is able to identify failure locations and discontinuities in the blade curvature under load. Postprocessing of the data using a stitching technique enables the shape and curvature of the entire blade to be observed for the first time for a large-scale wind-turbine blade. The experiment demonstrates the feasibility of the approach and reveals the technique can be readily scaled up to

accommodate utility-scale blades. As long as a trackable pattern is applied to the surface of the blade, measurements can be made in situ when installed on the turbine, as well as while rotating. The results demonstrate the great potential of optical measurement and its capability for large-area inspection for the wind industry.

7979-07, Poster Session

Post-microbuckling mechanics of fiber-reinforced shape-memory polymer under flexure deformation

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Employing a microbuckling, fiber-reinforced shape-memory polymer (SMP) shows high strain-to-failure capability under flexure deformation, by which the SMP composites are suitable for use in deployable space structure components. The fiber microbuckling of fiber-reinforced SMP composite (SMPC) is the primary deformation mechanism during the flexure deformation of SMPC, and it ensures that the SMPC can achieve high packaging strain and avoid fiber failure. During bending, the neutral SMPC with soft SMP matrix will move towards the outer stretching surface. For the analytical research, the strain energy containing four terms is derived. With minimum energy principle, the main parameters of deformations are obtained: the displacement of neutral plane, microbuckling wavelength and amplitude. Finally, The analytical prediction and experimental results (thickness of SMPC: 2 mm; curvature: 50 m^{-1}) correlated well. The following results are obtained: the ratio of neutral-plane displacement to the thickness is about 0.96, wavelength 2.80 mm, maximum amplitude 0.26 mm, and maximum recoverable strain: 9.6%. It implies that SMPC is a good candidate material for deployable structures.

7979-23, Poster Session

Design of a shape adaptive tail airfoil actuated by a shape memory alloy thin film

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Abstract

One of the factors that mainly affects the efficiency of the wing during a special flow regime is the shape of the cross section of its airfoil. Airfoils are usually designed for a specific flight condition. Therefore, traditional airfoils are not fully optimized in all flight conditions due to the fact that they are fixed in shape and must be used in several design points such as take-off, landing and cruise. It is very desirable to have an airfoil with that can change its shape based on the current flight regime. Such an airfoil will be optimal in any speed and regime of flow.

Shape memory alloy (SMA) undergo a phase transformation that can be activated with changes in the temperature. SMAs, due to this inherent transformation, are capable of recovering the deformations induced in their structure and restore their original configuration. SMAs are commercially available in the form of tubing, strip and wire all of which are suitable for using in adaptive airfoils. This study discusses the development of a method to control the shape of an airfoil using SMA actuators. In fact, the main objective of this study is to design an adaptive airfoil having the ability to achieve large deformations and retain its efficiency in response to variations in the flow conditions.

An SMA thin film was considered here as the actuator. To predict the thermomechanical behaviors of the SMA thin film, a 3-D incremental formulation of the SMA constitutive model was developed. The interactions between the airfoil structure and the SMA thin film actuator were investigated via the numerical model. Two separate films of SMA were bonded to the low and high surfaces of the airfoil which were activated by heating. As the film is heated, phase transformation is induced in the SMA and causes a bending deformation as a result of

the off-center placement of the SMA film. It was shown that controlling the shape of the deformed airfoil would enable the desired aerodynamic characteristics. Finally, the aerodynamic performance of the traditional airfoils with a plain flap was compared with the developed adaptive airfoil. Also, the response time and the electrical power required to activate the SMA film was calculated.

Keywords: Shape Memory Alloys, thermomechanical behavior, SMA thin film, Adaptive airfoils, Aerodynamic characteristics

7979-24, Poster Session

Sensor self-diagnostics for piezoelectric transducers operating in harsh temperature environments

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In many condition and health monitoring applications, it is necessary to be able to differentiate between response characteristics that result from structural and sensor specific damage types. An investigation is presented in this paper that considers the effectiveness of sensor self-diagnostic techniques for piezoelectric-based transducers that operate in harsh temperature environments. The motivation behind this work is to develop a method for interrogating sensor health when embedded within high-cost research systems. The theoretical basis for this approach is first presented, along with several analytical test cases in which temperature effects are examined within models of the piezoelectric transducer. Following this, a series of experiments are presented in which transducers with varying types and degrees of damage are subject to repeated temperature cycling from cryogenic to room temperature. The results of this study indicate that capacitive-based self-diagnostic techniques are capable of detecting both sensor delamination and cracking at room and liquid nitrogen temperatures.

7979-25, Poster Session

A study on real time monitoring system for railroad vehicle using energy harvesting

J. M. Kim, Korea Railroad Research Institute (Korea, Republic of); J. Lee, Sogang Univ. (Korea, Republic of)

Advanced high speed railway system requires absolute improvement of the reliability and safety of both the train and passengers and increase in cost for system maintenance has been emerged as another challenge. Thus it's necessary to develop the technologies that will satisfy the needs in two different aspects, dubbed as reliability & safety and maintenance cost. To that end, development of intelligent railway system including rolling stock is more than important. Intellectualization of railway system is based on development of constant real-time detection technology which requires structuring IT technology-integrated intelligent monitoring system.

Thus, this study was aimed at identifying the applicability of energy harvesting technologies which is regarded the new and renewable energy for monitoring the intelligent railway system and to that end, surrounding energy generated under the normal operation environment was monitored using high speed rail train in operation in an attempt to evaluate the applicability of energy harvesting monitoring technologies under the circumstance in which the thermal energy and vibration energy are generated.

Conference 7980: Nano-, Bio-, Info-Tech Sensors and Systems

Sunday-Tuesday 7-9 March 2010

Part of Proceedings of SPIE Vol. 7980 Nanosensors, Biosensors, and Info-Tech Sensors and Systems 2011

7980-01, Session 1

Nanotechnology research and development for military and industrial applications

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Researchers at the Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC) have initiated multidiscipline efforts to develop nano-based structures and components for insertion into advanced missile, aviation, and autonomous air and ground systems. The objective of the research is to exploit unique phenomena for the development of novel technology to enhance warfighter capabilities and produce precision weapons. The key technology areas that the authors are exploring include nano-based microsensors, nano-energetics, nano-batteries, nano-composites, and nano-plasmonics. By integrating nano-based devices, structures, and materials into weaponry, the Army can revolutionize existing (and future) missile systems by significantly reducing the size, weight and cost. The major research thrust areas include the development of chemical sensors to detect rocket motor off-gassing and toxic industrial chemicals; the development of highly sensitive/selective, self-powered miniaturized acoustic sensors for battlefield surveillance and reconnaissance; the development of a minimum signature solid propellant with increased ballistic and physical properties that meet insensitive munitions requirements; the development of nano-structured material for higher voltage thermal batteries and higher energy density storage; the development of advanced composite materials that provide high frequency damping for inertial measurement units' packaging; and the development of metallic nanostructures for ultraviolet surface enhanced Raman spectroscopy. The current status of the overall AMRDEC Nanotechnology research efforts is disclosed in this paper. Critical technical challenges, for the various technologies, are presented. The authors' approach for overcoming technical barriers and achieving required performance is also discussed. Finally, the roadmap for each technology, as well as the overall program, is presented.

7980-02, Session 2

Carbon nanotube heterojunctions: unusual deformations and mechanical vibration properties

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Carbon nanotube heterojunction are composed by two CNTs connected via an hybrid nanostructure. Although several types of heterojunctions have been evaluated and manufactured for nano-electronics applications, little is known about their overall mechanical and vibration properties. In a recent paper we have identified axial-bending coupling mechanisms in heterojunctions made of (5,5)-(10,10) nanotubes, with unusual Poisson's ratio and stiffness characteristics (F. Scarpa, J. W. Narojczyk, and K. W. Wojciechowski, Phys. Stat. Solidi B 2010, DOI 10.1002/pssb.201083984). In this work, we apply an atomistic continuum lattice model to predict the vibration properties of the heterojunctions using an approach that

some of the Authors have already applied to other nanostructures (F. Scarpa, L. Boldrin, H. X. Peng, C. Remillat, S. Adhikari, 2010. App. Phys. Lett. Accepted, F. Scarpa, M. Ruzzene, R. Chowdhury, S. Adhikari, SPIE Proceedings 2010). We show that the heterojunctions feature some strong modal density clustering and behave like waveguides to filter incoming travelling waves in selected bandwidths. The CNT heterojunctions could be used as potential elements for novel NEMS designs.

7980-03, Session 2

Collinear 2-dot QCA nano-electronic wire structure to improve QCA computing device reliability

L. R. Hook IV, S. C. Lee, The Univ. of Oklahoma (United States)

Demands to quickly and smartly process the vast amount of information gathered by current and future systems have initiated research into new computing paradigms which will be much more dense and powerful than even today's highest end computing devices. One of these paradigms, which is currently one of the most researched and developed nanoelectronic architectures, is based on Quantum-Dot Cellular Automata or QCA. QCA is a transistor-less computing paradigm which promises to extend the scaling of integrated circuitry past the physical boundaries of CMOS technologies. Many different physical implementations have been suggested and experimentally verified for QCA since its inception. Additionally, many computing architectures have been proposed extending the abilities of the QCA. However, the basic cell design, which consists of four logically active quantum-dots arranged in a rectangular pattern, has remained relatively unchanged during this progression. In QCA designs, the floor plan of the device layouts is dominated by communication paths, not logic operations. Additionally, the length of these communication paths largely relates to the expected correctness of the QCA devices because of thermal effects. For this reason, this paper proposes a new collinear two-dot QCA wire design which will provide a more reliable structure than the traditional four-dot designs, operating at the same temperature and device dimensions. Furthermore, because fewer QCAs are required per length of communication path, the new design may have the effect of easing fabrication requirements.

7980-04, Session 2

Synthesis of vertically aligned iron oxide nanotubes for engineering and biomedical applications

L. Chen, V. K. Varadan, Univ. of Arkansas (United States)

Due to their special structural, magnetic, electronic and optical properties, vertically aligned magnetic nanotubes have potential applications in data storage devices, sensors, nanoscale fluidics, chemical and biological separators, as well as catalysts. This paper reports our work on the synthesis of vertically aligned iron oxide nanotubes for the purposes of engineering and biomedical applications. The iron-oxide-nanotube template is synthesized by filtering iron nitrate ethanol solution through an anodic aluminum oxide (AAO) template, thermally decomposing the iron nitrate residing in the nanopores of the AAO template, followed by different heat treatments to achieve different types of iron oxides, such as hematite, magnetite and maghemite. Vertically aligned iron oxide nanotubes are obtained by depositing a supporting layer on one side of the iron-oxide-nanotube template and

then dissolving the AAO template. Different materials will be used for the supporting layer so that different electromagnetic and optical properties can be obtained. The structural properties of the vertically aligned iron oxide nanotubes will be analyzed by scanning electron microscopy (SEM) and transmission electron microscopy (TEM), and their crystalline properties will be characterized by X-ray diffraction (XRD). The magnetic properties of the aligned iron oxide nanotubes will be measured by a vibrating-sample magnetometer (VSM) at room temperature, and special attention will be paid on their magnetic anisotropy. The possible applications of vertically aligned magnetic nanotubes for engineering and biomedical purposes will be discussed, and some preliminary results will be reported.

7980-05, Session 3

Development of diagnosis and treatment technology for brain disease using quantum material and nano probe pin device

U. Lee, Gachon Univ. Gil Medical Ctr. (Korea, Republic of)

The present status of diagnosis and treatment of degenerative brain disease needs to be improved. For the improvement of neural probe devices, the development of Probe Pin Device (PPD) was initiated for detecting the brain chemicals, physiological information, wireless power system and simplification and minimization of deep brain stimulation (DBS) system, operation procedure, and device miniaturization using nanotechnology. The final targets of PPD project is that development of the wireless power feed system and PPD which can detect neurotransmitter, intracranial pressure and brain temperature for verification of safety and effectiveness of the wireless power feed system and PPD and Pre-clinical and clinical test of the wireless power feed system and PPD.

7980-06, Session 4

Synthesis and characterization of thiol-functionalized polymer as binder in conductive ink

J. Lee, V. K. Varadan, Univ. of Arkansas (United States)

The technology of electrical printing has received industrial and scientific attention due to wide variety of applications such as sensors, radio frequency identification cards (RFIDs), flexible display, and flexible solar cell. Especially a roll to roll gravure printing technique has been useful for mass production of electrical products. For the more high quality of conductive ink, the compatibility of organic binder and inorganic filler is very important. In this study, thiol-functionalized polymer was used as the binder. The thiol moieties in binder contribute to improving of binding force with filler. ¹H-NMR and FT-IR analysis have confirmed the functionality of the synthesized polymer. Also, the conductivity and viscosity of synthesized ink and compatibility of filler with binder were characterized in various conditions.

7980-07, Session 4

Optical properties of a novel nanostructured CdS/CdTe material

L. Cozzarini, Univ. degli Studi di Trieste (Italy); F. Antonioli, MaXun s.r.l. (Italy); V. Lughi, Univ. degli Studi di Trieste (Italy)

A novel nanostructured material consisting of cadmium telluride quantum dots embedded in a cadmium sulfide matrix has been synthesized by using low-cost, bench-top methods based on colloidal chemistry. Since the conduction bands in CdTe and in CdS are aligned, formation of an intermediate electronic band within the matrix's bandgap is expected, and is demonstrated by the fact that the material shows two

simultaneous photoluminescence peaks at about 1.4 eV (associated to the intermediate band) and 2.4 eV (associated to the matrix). By controlling the size and spacing of the embedded quantum dots, the emission corresponding to the intermediate band can be tuned between 1.3 and 1.6 eV. A number of interesting properties arise from this architecture, such as efficient photogeneration over a broad and tunable range of photon energies (possibly leading to novel, highly efficient photovoltaic devices), or tunable photon upconversion capabilities. The latter application will be discussed in more detail.

7980-08, Session 4

Magneto-resistance of flexible CNT-Fe composite thin films in a dynamic electric field

R. Isaac, D. Roy Mahapatra, Indian Institute of Science (India)

Room temperature magneto-resistance (MR) under AC electric field of a composite of carbon nanotubes (CNT) and Fe nanoparticles dispersed in a base polymer of epoxy resin and amorphous carbon is reported. The films made in varying weight concentrations (1% to 3% of CNT and 1% to 5% of Fe) reveal MR dependence over the entire frequency (0-1kHz) and amplitude range (0-3V). MR is found to increase with increase in either Fe or CNT concentration. The experiments reveal an enhanced MR as compared to the MR under a static electric field. On passing an alternating electric field through a CNT, the impedance increases due to the onset of the capacitive and inductive impedance, in addition to the already existing electrical resistance. The charge storage capacity of CNTs leads to the capacitive impedance. When electric field is applied parallel to the tube axis, electron flux along circumference is diverted into a helix current, similar to nanocoils. The Fe nanoparticles enhance the magnetic field concentration in the CNTs leading to an increased inductor like property of CNTs. The dynamics of the CNT-Fe system has been modeled using Maxwell's electromagnetic equations, with the Fe nanoparticles contributing to an additional current density in the form of spin polarized electrons. Hysteresis in MR is observed on sweeping the magnetic field. These highly tunable, flexible thin films can be used in room temperature magnetic field sensors and spintronic devices like magnetic random access memory (MRAM).

7980-09, Session 5

Biosensor made with organic-inorganic hybrid composite: cellulose-tin oxide

S. K. Mahadeva, J. Nayak, J. Kim, Inha Univ. (Korea, Republic of)

Cellulose is the most abundant polymer found in nature, inexhaustible, low cost, easy processing, renewable, biodegradable and biocompatible. SnO₂ is a known electrical conductor that is optically transparent in the visible spectrum with a wide band gap of 3.6 eV at room temperature. Thus, a hybrid nanocomposite of cellulose and SnO₂ can offer a unique property of cellulose combined with electrical properties of SnO₂. These unique properties of cellulose-SnO₂ hybrid nanocomposite can be capitalized to design flexible, biodegradable and low cost biosensors. Preparation and characterization of cellulose-SnO₂ hybrid nanocomposite and its application as a flexible urea biosensor was demonstrated in this paper.

It is observed sensitivity of cellulose-SnO₂ hybrid nanocomposite urea biosensor was increased linearly with deposition time. As deposition time increased, amount of tin oxide deposited over cellulose surface also increases, so as to increase the amount of enzyme immobilization and attachment of analyte, attributes to large current output and high sensitivity of sensor. Increasing enzyme activity is observed, with increasing urea concentration. Experimental results suggested that, the proposed biosensor under study is suitable for urea detection below 50 mM.

7980-12, Session 5

Graphene nano composite strain sensor

J. M. Kim, Pukyong National Univ. (Korea, Republic of)

To address the need for strain sensor made of new composite smart materials, this paper presents a graphene based nano composite strain sensor for structural health monitoring(SHM). Among several possible smart nanoscale materials, graphene has aroused the most interest in the research community because of its remarkable electrical, mechanical and other physical properties. In this study, development of the nano graphene composite strain is studied to realize the applications of graphene. For the application of sensor, a piezoresistive strain sensor for SHM applications was demonstrated. Static and dynamic responses were measure with the circuit consisting of voltage divider and signal processor. Experimentation showed that graphene composite strain sensor has lower sensitivity than carbon nanotube composite strain sensor, but its sensing responses are enough to be a promising sensor for SHM. Further study of the large strain sensing capability of the graphene composite sensor is aimed at increasing the band width of the dynamic response, minimization or correction of resistance drift, and determining the long term reliability of the sensor material. This will prepare the graphene based sensor for practical applications.

7980-13, Session 5

Printable low-cost sensor systems for healthcare smart textiles

P. Rai, P. S. Shyamkumar, S. Oh, H. Kwon, G. N. Mathur, V. K. Varadan, Univ. of Arkansas (United States)

Smart textiles-based wearable health monitoring systems (ST-HMS) have been presented as elegant solutions to the requirements of individuals across a wide range of ages. They can be used to monitor young or elderly recuperating /convalescent patients either in hospital or at home, or they can be used by young athletes to monitor important physiological parameters to better design their training or fitness program. Business and academic interests, all over the world, have fueled a great deal of work in the development of this technology since 1990. However, two important impediments to the development of ST-HMS are:-integration of flexible electrodes, flexible sensors, signal conditioning circuits and data logging or wireless transmission devices into a seamless garment and a means to mass manufacture the same, while keeping the costs low. Roll-to-roll printing and screen printing are two low cost methods for mass manufacture on flexible substrates and can be extended to textiles as well. These two methods are, currently, best suited for planar structures. The sensors, integrated with wireless telemetry, facilitate development of a ST-HMS that allows for unobtrusive health monitoring. In this paper, we present our results with planar screen printable sensors based on conductive inks which can be used to monitor EKG, EEG, abdominal respiration effort, blood pressure, pulse rate and body temperature. The sensor systems were calibrated, and tested for sensitivity, reliability and robustness to ensure reuse after washing cycles.

7980-55, Session 5

BioEncapsulation and biocatalysis with protein nanoCages

R. K. Watt, Brigham Young Univ. (United States)

Protein nanocages offer some unique properties that have great potential in bio engineering. The nanocages exist in defined sizes so provide repeatable units for templating. As a protein, the entire surface can be modified by molecular biology techniques, to locate desired amino acids at specific locations. In addition, the side chains of the protein can be modified by chemical modification reactions. The spherical nature of nanocages allows molecules to be sequestered inside the nanocage. Using the ferritin protein as a model nanocage, we present different

methods to sequester molecules inside the nanocage using a variety of techniques that are as simple as molecular diffusion of molecules through existing pores in the protein, to complex loading procedures involving redox reactions, co-deposition of molecules with metals, or pH disassembly and reassembly of ferritin. Finally, techniques to release the molecules entrapped in ferritin, catalytic reactions using molecules trapped in ferritin and methods to template ferritin to order the ferritin molecules will be presented.

7980-17, Session 7

Paper transistor made with regenerated cellulose and covalently bonded single-walled carbon nanotubes

S. Yun, H. Ko, Inha Univ. (Korea, Republic of); J. Kim, B. Lim, Chosun Univ. (Korea, Republic of); J. Kim, Inha Univ. (Korea, Republic of)

We report a flexible paper transistor made with regenerated cellulose and covalently bonded single-walled carbon nanotubes (RC-SWCNTs). Functionalized single-walled carbon nanotubes (SWCNTs) are reacted with N, N-Carbonyldiimidazoles to obtain SWCNTs-imidazolides. SWCNTs can be covalently bonded to cellulose by acylation of cellulose with SWCNTs-imidazolides. Using the product, RC-SWCNT paper is fabricated with mechanical stretching to align SWCNTs with cellulose. Finally, inter-digital (IDT) comb shaped source and drain electrode and bottom gate electrode are formed on the paper via lift-off process. We expect that alignment of SWCNTs obtained by mechanical stretching can contribute to establishing stable electron channel paths in dielectric cellulose layers and the alignment will be a key role in improving characteristics of RC-SWCNTs paper transistor. In present paper, the characteristics will be evaluated by measuring mobility, on-off ratio depending on alignment of SWCNTs in RC-SWCNTs paper.

7980-18, Session 7

2-2 mode piezocomposites made of PMN-PT single crystals for high-frequency medical ultrasonic transducers

H. Shin, Y. Roh, Kyungpook National Univ. (Korea, Republic of)

The 2-2 mode piezocomposite material in this study is made of the PMN-PT single crystal and urethane for application to medical ultrasonic transducers in the frequency as high as over 10 MHz. Since the structure of the piezocomposite is so minute at the high frequency, detailed design of a medical ultrasonic transducer with the full composite structure takes tremendous resources. Hence, we analyzed the resonant and anti-resonant behavior of 2-2 mode piezocomposite samples of various geometries to represent the piezocomposite as a single phase material having its elastic, piezoelectric and dielectric constants equivalent to those of the piezocomposite. These equivalent material constants were derived by means of the asymptotic averaging method. Based on the derivation, experimental prototypes of the 2-2 mode piezocomposite were manufactured and their properties were measured for comparison with simulation data. The comparison showed excellent agreement with each other, which verified the validity of the derived equivalent material constants as well as the derivation methodology. The methodology of deriving the equivalent properties of a 2-2 piezo-composite in this study will be useful for designing 2-2 piezocomposites and analyzing its performance for various transducers.

7980-19, Session 7

Investigation of dipole antenna based sensor for passive wireless structural health monitoring

S. Jang, D. Kim, J. Kim, Inha Univ. (Korea, Republic of)

In this paper, the feasibility of wireless sensor made with dipole antenna for strain and damage detection of structures is investigated. The resonance frequency of the dipole antenna is changed by the length of antenna. Mechanical strain of the structure or damage of the structure can change the length of antenna so as to shift the resonance frequency. Film type dipole antenna is fabricated using the conventional photolithography. Fabricated dipole antenna is attached on a cantilever beam. The return loss (S11) of the dipole antenna sensor is characterized using a network analyzer (NA). The strain sensitivity of the sensor is tested by correlation of return loss changing and bending strain of the cantilever beam. This wireless sensor based on dipole antenna can be used for wireless structural health monitoring system.

7980-20, Session 8

A new architecture for designing noise-tolerant digital circuits

J. M. Lakes, S. C. Lee, The Univ. of Oklahoma (United States)

Computational perfection in digital logic circuits is hard to achieve due to many random factors. Defects and faults arise from physical imperfections and noise susceptibility of analog circuit components used to create digital circuits resulting in computational errors. A probabilistic computational model is needed to measure and assess the affect of noise on computational accuracy in digital circuits. This paper shows how to compute the output probability of a digital circuit and addresses the reliability problem due to variable levels of environmental noise. The main purpose of this paper is to present a new architecture for designing noise-tolerant digital circuits. The approach we propose is a class of single-input, single-output circuits called Reliability Enhancement Wire (REW). REW is a concatenation of n simple logic circuits called Reliability Enhancement Cells (REC). Each REC can increase the reliability of a digital circuit to a predefined level. Reliability can approach any desirable level when a REW composed of a sufficient number of RECs is connected to the output of the logic circuit. Moreover, the proposed approach is a general method and is applicable to the design of any logic circuit with single or multiple outputs implemented with any logic technology.

A design example of a noise-tolerant 1-bit binary adder is given and is verified through software simulations and hardware tests. The software simulation will calculate reliability improvement using the probabilistic computational model and variable noise levels through Matlab software. The hardware test will be automated by using Labview to measure noise, detect hardware faults and verify reliability improvement of physical digital circuits.

7980-21, Session 8

Design of wireless electrocardiography measurement system with an algorithm to remove muscle noise

H. Kwon, S. Oh, P. S. Kumar, V. K. Varadan, Univ. of Arkansas (United States)

Electrocardiography(EKG) is an important diagnostic tool that can provide vital information about diseases that may not be detectable with other biological signals like, SpO₂(Oxygen Saturation), pulse rate, respiration, and blood pressure. For this reason, EKG measurement is mandatory for accurate diagnosis. Recent development in Information technology has

facilitated remote monitoring systems that can check patient's current status. Moreover, remote monitoring systems can obviate the need for patients to go to hospitals periodically. Such representative wireless communication system is Zigbee sensor network because Zigbee sensor network provide low power consumption and multi-device connection. When we measure EKG signal, another important factor that we should consider is about muscle noise mixed to EKG signal. The muscle noise can be mixed on EKG signal whenever measured person moves. Therefore, removing muscle noise on EKG signal is very important factor to acquire clean EKG signal. This paper describes the design method for EKG measurement system with Zigbee sensor network and proposes an algorithm to remove muscle noise from measured EKG signal. The algorithm will also remove motion artifacts which are a significant source of noise corrupting an EKG signal.

7980-22, Session 8

Probabilistic analysis and simulation of 2D 2-dot quantum-dot cellular automata logic circuits

S. C. Lee, L. R. Hook IV, The Univ. of Oklahoma (United States)

It is known that due to the many random factors, such as thermal fluctuations and wave interference, deterministic computation in NanoICs is difficult to achieve. Defects and faults arise from the instability and noise proneness of NanoICs, which lead to unreliable results. A probabilistic computational model is needed to reduce such errors and to achieve more reliable computation.

Recently, Hook and Lee proposed a new quantum-dot cellular automata (QCA) nanocircuit design method using 2-D 2-dot QCA cells. It is shown that this method, not only can implement any combinational and sequential circuit design, but also offers periodicity and symmetry characteristics that are widely found in naturally occurring materials (molecules, crystals, etc.) for fabrication.

The purpose of this paper is to stochastically analyze 2-D 2-dot QCA circuit behaviors in a noisy environment. In this analysis, circuit signals become random variables, circuit component functions are characterized by probabilistic circuit component models and for any given set of input signal probabilities, the probabilistic signal at any interior part and the outputs of the circuit can be calculated using the arithmetic expressions. Illustrative examples of this analysis method are presented and verified by simulation. In addition, techniques to reduce the random noise effects of 2D 2-dot QCA circuits operated in an inevitable noisy environment are also presented.

7980-23, Session 8

Remotely driven electro-active paper actuator by modulated microwaves

S. Y. Yang, S. K. Mahadeva, J. Kim, Inha Univ. (Korea, Republic of)

This paper reports a remotely-driven electro-active paper (EAPap) actuator by modulated microwaves. So far we have demonstrated a remotely driven EAPap actuator by means of rectenna and control circuit. The rectenna consists of dipole antenna and rectifying circuit, which converts microwave to dc power. Once microwaves are incident on the dipole rectenna, it converts microwaves into dc power and the control circuit feed the power to the EAPap actuator by alternating it so as to produce a bending vibration of the EAPap actuator. However, due to the power consumption of the control circuit, the remotely-driven actuator system requires more dc power to activate the control circuit.

Thus, we propose a remotely-driven EAPap actuator that does not require the control circuit. Instead of the control circuit, microwaves are modulated with the control signal, and by rectifying the modulated microwaves with the rectenna, the control signal can be regenerated for activating the EAPap actuator. This concept is important to improve the remotely-driven EAPap actuator without control circuit. Detailed modulated microwave, rectenna design, fabrication, characterization and the actuation of rectenna-EAPap by modulated microwave are explained.

7980-24, Session 9

Wireless power feeding to a mobile object with strongly coupled resonance

M. Koizumi, K. Komurasaki, Y. Mizuno, The Univ. of Tokyo (Japan); K. Kano, T. Shibata, DENSO Corp. (Japan)

Mid-range wireless power transmission technology is now in demand in the various fields. Since the year of 2007, the wireless power technology using a set of two resonating coils called "strongly coupled magnetic resonances" has been attracting attentions. A feature of this technology is high transmission efficiency in meter-order range. It makes possible to power feeding to various applications such as electric cars, micro-robots, battery-less sensors etc.

Power feeding using strongly coupled resonance from the transmitter resonator on the ground to an electric-powered toy helicopter in air was demonstrated. Impedance matching is very importance for effective power feeding to an object moving in 3-D space. The objective of this demonstration is to validate the theoretical relation between transmission distance and efficiency with impedance matching. Another objective is to develop an efficient, compact, and light-weight resonator as a receiver.

The relationship between the efficiency and altitude was shown for the case with impedance matching on the transmitter side. The result indicates that this one-side impedance matching is enough for the helicopter to lift up from the ground.

7980-25, Session 9

Wirelessly powered RFID with sensor array

V. K. Varadan, Univ. of Arkansas (United States); J. Kim, Inha Univ. (Korea, Republic of); J. Lee, Univ. of Arkansas (United States); S. H. Choi, NASA Langley Research Ctr. (United States)

Integration of flexible microelectronic devices on a small foot-print is very important for conformal suitability, application specific like RFID, and remote operations. However, these kinds of autonomous microelectronic devices have relied on the on-board batteries or direct wired power as a power source. Wireless power scheme for such devices offers a great flexibility in applications. Rectenna circuits that are tied up with sensor array/RFID are one of the options for autonomous operation under the wireless power on demand basis. The concept development of wirelessly powered RFID has been implemented for various application scenarios. The concept, potential applications, and low-cost/mass production capability of wirelessly powered RFID will be explored in the presentation.

7980-26, Session 9

Design and implementation of a bluetooth-based band-aid pulse rate sensor

P. S. Kumar, S. Oh, P. Rai, H. Kwon, N. Banerjee, V. K. Varadan, Univ. of Arkansas (United States)

Remote patient monitoring systems capable of collecting vital patient data such as blood pressure readings, Electrocardiograph (ECG) waveforms, and heart rate can obviate the need for repeated visits to the hospital. Moreover, such systems that continuously monitor the human physiology can provide valuable data to prognosticate the onset of critical health problems. The key to such remote health diagnostics is the design of minimally intrusive, low cost sensors that do not impede a patient's quotidian life but at the same time collect reliable noise free data. To this end, in this paper, we describe the design and implementation of a Bluetooth-based wireless sensor system with a disposable sensor element and a reusable wireless component that can be worn as a "band-aid". The sensor is a piezoelectric polymer film placed on the wrist in proximity to the radial artery. The band-aid sized sensor allows non-intrusive monitoring of the pulsatile flow of blood in the artery. The sensor, using the Bluetooth module, can communicate

with any Bluetooth enabled computer, mobile phone, or PDA. The data collected from the patient can be remotely viewed and analyzed by a physician.

7980-27, Session 9

Wireless remote monitoring system for sleep apnea

S. Oh, H. Kwon, V. K. Varadan, Univ. of Arkansas (United States)

Sleep plays the important role of rejuvenating the body, especially the central nervous system. However, more than thirty million people suffer from sleep disorders and sleep deprivation. That can cause serious health consequences by increasing the risk of hypertension, diabetes, heart attack and so on. Apart from the physical health risk, sleep disorders can lead to social problems when sleep disorders are not diagnosed and treated. Currently, sleep disorders are diagnosed through sleep study in a sleep laboratory overnight. This involves large expenses in addition to the inconvenience of overnight hospitalization and disruption of daily life activities. Although some systems provide home based diagnosis, most of systems record the sleep data in a memory card, the patient has to face the inconvenience of sending the memory card to a doctor for diagnosis. To solve the problem, we propose a wireless sensor system which enables remote monitoring while the patient is at home. The system has 5 channels to measure ECG, Nasal flow, body position, abdominal/chest efforts, and oxygen saturation. A wireless transmitter unit transmits signals with Zigbee, and a receiver unit which has two RF modules, Zigbee and Wi-Fi, receives signals from the transmitter unit and retransmits signals to the remote monitoring system with Zigbee and Wi-Fi, respectively. By using both Zigbee and Wi-Fi, the wireless sensor system can achieve a low power consumption and wide range coverage. The system's features are presented, as well as continuous monitoring results of vital signals

7980-28, Session 9

Closed loop cyber system for monitoring sleep apnea

H. Kwon, S. Oh, P. S. Kumar, V. K. Varadan, Univ. of Arkansas (United States)

Sleep apnea is a condition where patients suffer from anomalies in body function while asleep. The aftermaths of sleep disorder could be benign (e.g., sleep walking and disturbed dreaming) or harmful (e.g., respiratory disorder--potentially leading to death). Constant monitoring of patients while asleep is the only practical solution to provide remedial action when an individual suffers from sleep apnea. Such a setup requires patients to be admitted to a sleep center which can perturb his ordinary sleep routine. To avoid this inconvenience we propose a wireless remote monitoring solution that will allow the patient to sleep at home rather than a sleep lab. In this system, sensors for respiration are placed on a patient's key body points and the sensor transfers data to a monitoring station with Zigbee wireless communication technology. Zigbee technology provides the advantages of low power consumption and multi-device connectivity. The sensor that is attached to body to detect patient's status communicates with a human-carryable wireless device with Zigbee wireless system. The wireless device transfer acquired data from sensor to host computer that will be at a remote location, such as doctor's room, through TCP/IP communication skill. The host computer detects sleep apnea abnormalities using an algorithm that checks the patient's status automatically. The system can notify a caregiver in case of benign symptoms and can notify emergency alarm when he suffers from respiratory ailment.

7980-29, Session 9

Smart e-bra with nanosensors and smart electronics display and cell phone communications for heart rate monitoring

V. K. Varadan, P. S. Kumar, S. Oh, H. Kwon, P. Rai, G. N. Mathur, N. Banerjee, Univ. of Arkansas (United States)

No abstract available

7980-10, Poster Session

The fabrication of glucose sensor by nanoporous silicon film and its switching characteristics on visible color light response

J. Lin, M. Hsu, St. John's Univ. (Taiwan); H. Hou, Tamkang Univ. (Taiwan); J. Wu, Chinese Culture Univ. (Taiwan)

A new glucose sensor made by nanoporous-silicon (NPS) thin films which emit distinct visible color lights for identification under glucose treatment is proposed in the paper. Based on the high surface to volume ratio (SVR) property of NPS films, the Si-based glucose sensor has a high sensitivity and stability. In addition, the visible light response on the film surface switches obviously between distinct colors with/without glucose treatment. It has a potential application on small-size, low-cost, portable and electric-free sensor systems. In the study, the nanoporous silicon films are examined by scanning-electron-microscope (SEM), atomic-force-microscope (AFM), and photoluminescence (PL) and so on.

The fabrication of NPS films are started with etching procedure by using an adjusting electrolyte of HF : C₂H₅OH = 1 : 4 on 100-oriented p-type prime Si wafer. In the procedure, a fixed current-control mode (anodization current = 80 mA, area = 1.21π cm², etching time = 10 min) is utilized. After the anodization on the Si wafers, the NPS structures are formed, which consists of many nano-pores and nano-pillars. Hence, an island profile with high SVR can be obtained on the contact surface that provides a high sensitivity. In the experiments, the film depth of NPS is about 3.3 μm. The peak of PL-intensity curve is 610 nm under normal air condition. However, after the glucose immersion treatment on the NPS samples, an obvious blue-shift behavior of PL-feature (from 610 to 560 nm) is observed at room temperature. The color switching can be read by a naked-eye easily.

7980-47, Poster Session

Wireless brain machine interface systems: today and tomorrow

V. K. Varadan, Univ. of Arkansas (United States)

Advances in neurobiology, nanowire based sensors, and wireless communication tools help develop brain-machine interfaces for the treatment of diseases and disability including epilepsy. Both invasive and non-invasive nanosensors are being used in monitoring and control of various diseases. Neural-implants such as deep brain stimulation and Vagus nerve stimulation are increasingly becoming routine for patients with Parkinson's disease and clinical depression respectively. The non-invasive sensors include EEG, EOG and EMG. The technological advances have allowed the development of prototype systems that read and interpret electrical information flow in the brain to predict upper extremity movement. Since wide progresses have made in these areas, there is a great promise of long-term benefits in human implantable devices and Neural Electronics Interfaces (NEI) drawing the expertise in areas of materials, microelectromechanical systems (MEMS), wireless networking, neurosciences and neurosurgery in general and motor and sensory control in particular. Selected movies will be shown in the talk

7980-48, Poster Session

Low-cost methylene chloride assisted bonding of PMMA microfluidic chips

D. D. Hilbich, A. Khosla, Simon Fraser Univ. (Canada)

Over a last decade μ-TAS/LOC's devices have attracted many researchers world wide. Among many materials which have been employed to fabricate such devices, most common materials are glass, polydimethylsiloxane (PDMS), SU-8, Cyclic Olefin Copolymer (COC) and poly(methyl methacrylate) (PMMA). Fabrication involves using expensive techniques and equipment such as photolithography, x-ray lithography, injection molding and hot embossing. PMMA has a great potential to be used for μ-TAS devices because of its low cost, biocompatibility, chemical inertness and optical properties.

The micro-channels were engraved in 5-mm thick PMMA sheet using the Universal Laser System's VersaLASER® laser ablation system. The same system was used to dice PMMA sheet and drill inlet and outlet ports. One of the key steps involved in fabrication is covering the channels with a cover plate. Various techniques have been reported in order to achieve layer to layer bonding of PMMA to PMMA such as thermal, pressure, surface modification and solvent assisted bonding. However, mixed results have been achieved for bonding PMMA to PMMA.

In this paper we present low cost rapid prototyping of (PMMA) μ-TAS devices and Methylene Chloride assisted bonding. This bonding technique developed at Micro-instrumentation Laboratory, Simon Fraser University is a single step process, does not involve pressure or heat treatment and has a yield of 100%. The bond formed between PMMA-PMMA is permanent and no leakage is observed.

7980-49, Poster Session

Effect of corona discharge surface treatments and soft bake on adhesion of SU-8 on a glass substrate for MEMS and microfluidic systems

P. F. J. Hsiao, A. Khosla, Simon Fraser Univ. (Canada)

SU-8 is an insulating near-UV negative-tone photoresist used as a structural material in both MEMS and microfluidic communities. Adhesion of SU-8 on glass is poor and often leads to delamination. Adhesion properties of SU-8 applied directly on glass substrates have not been investigated in depth as compared to silicon substrates. In this paper, we present the effect of corona discharged surface treatment and baking temperatures aimed to improve adhesion and minimize the edge bead on glass substrates.

The substrate pretreatment and baking stages are the two main factors that determine the adhesion between the SU-8 layers and glass slides. The substrate pretreatment begins with ultrasonic bathing the glass slide in Decon 90 solution followed by rinsing with water, Acetone, IPA, and Di water subsequently. The substrate is blown dry using a Nitrogen gun and then a dehydration bake is carried out at the temperature of 125 °C for 20 minutes. Lastly, corona discharge is applied on the glass substrate to complete the pretreatment. Upon pretreatment, SU-8 2100 is spun coated on the substrate at desired rotational speeds according to target thicknesses. This is followed by a two-step soft bake to evaporate the solvent in the SU-8. Once soft baking is performed, the test structures are patterned with a photomask under the exposure unit at near UV wavelengths of 350-400nm. Full crosslinking of SU-8 is achieved by a post-exposure bake starting at the temperature of 55°C to 95°C and finally cooled down to room temperature. The structured layer is developed in MicroChem's SU-8 developer for the completion of the master. The parameters and procedures involved in the corona surface treatment and the baking steps are discussed throughout this article.

7980-50, Poster Session

Graphene-based nano composite smart material

J. Cha, Pukyong National Univ. (Korea, Republic of)

To address the need for new composite smart materials, this paper presents graphene based nano composite processing and its characteristics to develop a smart material having piezoresistivity for sensing. Among several possible smart nanoscale materials, graphene has aroused the most interest in the research community because of its remarkable electrical, mechanical and other physical properties. While graphene has been reported impressive material properties in nanoscale, the properties of the bulk composite materials are not enough to be studied an engineering material in macro scale. Therefore fabrication of a nano hybrid material and its material characterization to develop a novel smart material for sensors is studied to realize the applications of graphene. In this study, 1, 3 and 5 wt% graphene/epoxy composites were fabricated and their resistivity was measured. The electrical conductivity was obtained from 3 wt%. The resistance change of 3 wt% composite was measured with respect to the change of strain and the gauge factor of the composite was derived and compared with other carbon nanotube composites as well. The corresponding gauge factor of the graphene composite is 0.35 which is much smaller than CNT composites. The largest contribution of piezoresistivity of the composite may come from slippage of overlaying or bundled graphene in the matrix, from a macroscopic point of view. Nano interfaces of graphene in a matrix polymer also contribute to the strain response compared to other micro size nano filler.

7980-51, Poster Session

Poly(methyl methacrylate) (PMMA) as a structural mold material for soft lithography

A. Khosla, Simon Fraser Univ. (Canada)

Various stand alone MEMS and microfluidic devices have been fabricated by micromolding poly(dimethylsiloxane) (PDMS) against SU-8 photopolymer masters (called as soft lithography) including in order micromixers, microchannels, valves, pumps, and interconnect structures for a wide variety of applications for lab-on-a-chip (LOC) analysis. However, SU-8 is vulnerable to organic solvents such as heptane, toluene. These organic solvents, are used while fabricating PDMS nanocomposite polymers. Any trace of organic solvent left in the polymer nanocomposite tends to swell the mold material such as SU-8. Hence, investigation on choice of substrates for master molds is critical. Different substrates such as PMMA, polycarbonate, polystyrene were tried. It was observed in our experiments that PMMA was the best structural mold material for micromolding PDMS nanocomposite polymer because of its chemical inertness. PMMA can be easily etched using a CO₂ laser in any desired shape. We also present the etch rate properties of PMMA substrate, which is dependent on the following three factors: 1. Type of PMMA; 2. Intensity of CO₂ Laser 3. Speed of the Laser. These three parameters will be presented in this paper.

7980-52, Poster Session

Thermal effect on the IV characteristics of TiO₂ and GaN sol-gel driven Schottky diode

Y. Chen, M. Maniruzaman, J. Kim, Inha Univ. (Korea, Republic of)

Thermal annealing GaN through NH₃ has been shown to have a great influence on improving the electrical mobility of GaN, which will directly affect the current-voltage behavior of GaN thin film Schottky diode. In this paper, Ga(NO₃)₃ has been dispersed in ethanol, Acetic acid was added and stirred for 24 h. Resulting solution was spin-coated onto a Si substrate, and annealed in tube furnace with constant flow of NH₃ gas at high temperature. Final films were investigated with X-ray diffractograms and atomic force microscopy. To characterize Schottky characteristics of GaN films, Al electrode was deposited on top of the GaN layer, and current-voltage characteristics were investigated.

TiO₂ is another most important wide-bandgap semiconductor due to its physical and chemical stability, and so on. TiO₂ sol-gel was fabricated by disperse Titanium isopropoxide in ethanol, HCl was added as a catalyst. Finally, the solution was kept stirring for 24 h. After spin coated on Si wafer, TiO₂ films were annealed in tube furnace. Since TiO₂ crystalline phases include anatase, rutile and brookite phases, annealing treatment of TiO₂ thin film would give different semiconducting behavior due to the transformation of different crystalline phase of TiO₂ during the annealing process. Phase transformation was observed by X-ray diffractograms and Atomic force microscopy. Current-voltage characteristics were measured by semiconductor parameter analyzer.

7980-53, Poster Session

Study of a novel micro-fluidic-chip measurement system for red blood cell deformability

Y. Liao, Chongqing Univ. (China); C. Liu, Chongqing Institute of Technology (China); S. Zhai, Univ. of Nevada, Las Vegas (United States); H. Luo, X. Zheng, Chongqing Univ. (China)

A novel micro-fluidic-chip system, which is characterized by a chip with the double faced microstructure and the dual-channel microscopic image processing function, was developed for the on-chip measurement of red blood cell deformability. The development process involved the fabrication of the double faced chip, the introduction of a microstructure for the image processing based microchannel flow velocity measurement and the dual-channel microscopic image processing. The preliminary experiments were carried out to verify the feasibility of such a systematic design scheme. The results indicate that the proposed one-time molding method of double faced PDMS chips would provide a good means to improve the layout of micro-fluidic-chip system and integration of functional modules. Moreover, by the use of the dual-channel microscopic image based measurement method, microchannel flow velocity and red blood cell movement can be measured on chip at the same time. This would greatly simplify the peripheral configuration of the whole system. Therefore, the work presented in this paper is of significance in the development of new technology of micro-fluidic chips and new on-chip analysis approaches for blood cells.

7980-30, Session 10

X-ray diffraction wafer mapping method for SiGe twin defects control

Y. Park, H. Kim, G. C. King, NASA Langley Research Ctr. (United States); K. Lee, Turner-Fairbank Highway Research Ctr. (United States); S. H. Choi, NASA Langley Research Ctr. (United States)

Group IV semiconductors, Silicon, Germanium, and Carbons are today's most important semiconductors that form a cubic diamond structure. Recently developed rhombohedral super-hetero epitaxy technology enabled the single-crystalline growth of cubic diamond semiconductors on the basal plane of selected trigonal crystals for the first time. This kind of hetero-crystal-structure epitaxy was thought to be impossible or very difficult before. We found that this difficulty came of the lack of a proper characterization tool and present the newly invented X-ray diffraction characterization methods to control twin crystal defect in this new rhombohedral-trigonal epitaxy scheme. This patented X-ray diffraction methods not only measure the total density of the twin defect crystals but also map the distribution of the defects on the wafer with a high sensitivity and high spatial resolution.

7980-31, Session 10

Micropatternable nanocomposite polymers for MEMS: process technology and applications

A. Khosla, Simon Fraser Univ. (Canada)

Although micromachining and MEMS originated within the Silicon and IC community, more recently as new and wide applications of MEMS have been forthcoming, new materials and fabrication technologies have been developed, examples include polymer microfabrication such as soft lithography/micromolding and micro-injection molding. MEMS, with microfluidics, can enable precise control of fluids on very small scales e.g. drug delivery systems. In order to realize such systems all of the required components needed must be miniaturized and interconnected into a complete functional system. These systems may include contain multiple components for sample/drug storage, chemical reaction chambers, fluid control, analyte separation and detection, and data acquisition, to accomplish complex tasks such as the detection of disease markers or environmental toxins in small (e.g., nanoliter) samples of fluid and monitoring.

While many materials have been employed to flexible MEMS and microfluidic devices such as stated above, polydimethylsiloxane (PDMS), a silicone based elastomer, has been widely used because of its biocompatibility, low cost, low toxicity, high oxidative and thermal stability, optical transparent, low permeability to water, low electrical conductivity, and ease of micropatterning. Various stand alone MEMS and microfluidic devices have been fabricated by micromolding PDMS against SU-8 photopolymer masters (called as soft lithography) including in order micromixers, microchannels, valves, pumps, and interconnect structures for a wide variety of applications for lab-on-a-chip (LOC) analysis.

However, most of these devices based on PDMS are passive and if active devices are made, then they are bonded to substrates like glass which has active components like electrodes, heaters etc patterned on it. This is because it is proven fact that it is difficult to integrate, embed or pattern conducting lines, magnetic materials on PDMS because of the weak adhesion between PDMS and metals. The integration of functional material (electrically conductive and magnetic) structures in bulk PDMS is extremely important for signal routing, interfacing to signal processing electronics, to power active devices and actuation purposes. In the case of metal/metal-alloys patterning, microcracks appear on the surface of the patterned conductive lines on being flexed, bent, or twisted, leading to electrical disconnection. Hence, there is a need to develop PDMS-based active materials of similar flexibility to the undoped and insulating PDMS that can also be easily micromolded using similar soft lithography techniques, to provide robust system electrical routing. In

addition, for MEMS and microfluidic systems, the ability to manipulate fluid on chip (fluid control) via on-chip microvalves and pumps is usually required, with magnetically actuated valves and pumps a good choice due to the high energy density of magnetic actuation schemes. While PDMS is inherently electrically insulating and non magnetic, these properties can be modified by the introduction of conducting and/or magnetic.

nanoparticles in the polymer matrix. Such active polymers are of great interest to the microelectronic, MEMS, microfluidic and lab-on-a-chip (LOC) communities for packaging, microsensor, and microactuator applications, leading to development of fully integrated flexible systems. Thus, there is a need to develop both conductive and magnetic PDMS-based micropatternable nanocomposite polymers.

In order to solve the problem of combining electronic and magnetic functionality with passive PDMS devices, we have developed nanoparticle doped multifunctional polymers which either are electrically conducting, magnetic in nature and or both. The idea to develop silicone based elastomers which are electrically conducting; magnetic and electrically conducting + magnetic is not new; however, micropatternability and stability of these elastomers always remained a big challenge which will be addressed in this talk. Different nanocomposite polymer fabrication processes, nano-particles employed for specific applications and low cost large scale micro-patterning processes will be presented and discussed in detail.

7980-32, Session 11

Use of the electro-mechanical impedance method for the assessment of dental implant stability

G. Boemio, P. Rizzo, Univ. of Pittsburgh (United States); L. De Nardo, Politecnico di Milano (Italy)

The robustness and reliability of the Electro-Mechanical Impedance (EMI) method to assess dental prostheses stability is presented. The study aim at addressing an increasing need in the biomedical area where robust, reliable, and non-invasive methods to assess the bone-interface of dental and orthopedic implants are increasingly demanded for clinical diagnosis and direct prognosis.

In this study two different dental screws were entrenched in polyurethane foams and immersed in a solution of nitric acid to allow material degradation, inversely simulating a bone-healing process. This process was monitored by bonding a Piezoceramic Transducer (PZT) to the implant and measuring the admittance of the PZT over time. To simulate healing, a second set of experiments was conducted. It consisted of placing four dental screws inside a joint compound specimen and observing the setting of the fresh compound allocated in the alveolus containing each implant.

In all cases it was found that the PZT's conductance and the statistical features associated with the analysis of the admittance signatures were sensitive to the degradation or the setting process.

7980-33, Session 11

System-in-package LTCC platform for 3D RF to millimeter wave modules

T. Vaha-Heikkila, VTT Technical Research Ctr. of Finland (Finland); M. Lahti, VTT Elektronikka (Finland)

This presentation shows recent trends and results in 3D millimeter wave Low Temperature Co-Fired Ceramics (LTCC) modules with hermetic sealing capability. The system-in-package LTCC platform is a true three dimensional module technology. LTCC is a lightweight multi-layer technology having typically 6-20 ceramic layers and metallizations between. The metallization levels i.e different metal layers can be patterned and connected together with metal vias. Passive devices can also be fabricated on LTCC while active devices and other chips

are connected with flip-chip, wire bonding or soldering. In addition to passives directly fabricated to LTCC, several different technologies/ chips can be hybrid integrated to the same module.

LTCC platform is also well suited for the realization of antenna arrays for microwave and millimeter wave applications. Potential applications are ranging from short range communications to space and radars. VTT has designed, fabricated and characterized microwave and millimeter wave packages for Radio Frequency (RF) Micro Electro Mechanical Systems (MEMS) as well as active devices. Wideband performance has been achieved for LTCC package transitions with measured loss less than 1.0 dB up to 90 GHz. Also, several types of system-in-package modules have been realized containing hybrid integrated CMOS and GaAs MMICs and antenna arrays.

7980-35, Session 11

Preparation and characterization of fluorinated cellulose material

J. Amalraj, J. Kang, J. Kim, Inha Univ. (Korea, Republic of)

The surface and in-depth chemical modification of cellulose is getting importance because of its potential application in reinforcing elements in composite materials, inducing highly hydrophobic and lipophobic properties through the grafting of fluoro components, and other applications in paint and pharmaceutical products. In this work, we will discuss about the homogeneous fluorination of cellulose and cellulose acetate material. Heterogeneous modification of cellulose can be limited to the OH groups at or near the surface of the fibers, whereas in the homogeneous fluorination fluorination will be the throughout the material. Cellulose and cellulose acetate will be fluorinated with long chain aliphatic fluorinated compound and the products will be characterized by spectral, thermal, optical and mechanical methods.

7980-36, Session 11

Roll-to-roll manufacturing and nanoimprint technology for flexible electronics and smart sensor systems in engineering and medicine

V. K. Varadan, Univ. of Arkansas (United States); J. Kim, Inha Univ. (Korea, Republic of); S. H. Choi, NASA Langley Research Ctr. (United States)

For more than a decade, organic thin film transistors (OTFT) based on conjugated oligomers, polymers, and other molecules have found use in a number of low-cost, large-area electronic applications including flat panel displays, smart cards, radio frequency identification cards (RFIDs), sensors and electronic paper. Nanoimprint technology enables continuous printing of nanostructures on OTFT with drastically increase throughput, and thereby pushes the nanometer-scale lithography for many nanosensor and system devices in engineering and medicine. This talk will present the recently designed and developed Roll-to-Roll manufacturing unit at the NSF Center for Wireless Nanosensors and Systems of the University of Arkansas and many applications which may be derived from collaboration with Inha University and NASA Langley Research Center

7980-37, Session 12

Logical and thermodynamic analysis of 2-dot quantum-dot cellular automata super cell

L. R. Hook IV, S. C. Lee, The Univ. of Oklahoma (United States)

To keep up with the requirements of increasingly innovative applications, computing devices have gotten progressively faster and more complex, made possible largely through CMOS device scaling. However, continuing CMOS device scaling beyond the current technology is becoming increasingly difficult and expensive. For this reason, designers are turning to other methods, such as parallel, reconfigurable, and highly specialized designs, to continue the growth of computing capacity. Concurrently, researchers are exploring new nano-electronic computing architectures which may be scaled down to at or near the molecular level to replace the CMOS paradigm. One very promising approach is Quantum-dot Cellular Automata (QCA). The QCA paradigm allows for extremely low power, THz clock speeds, and size scaling to the molecular level. However, with the significant investment and distribution of CMOS computing devices, any completely new architecture should offer not only continued scaling, but also fundamental improvement in the way computing is achieved to justify the massive investment required to change technologies. One promising QCA alternative architecture, which provides this, is based on the recently presented "Super-Cell" QCA (SCQCA). The SCQCA provides a construct upon which a highly parallel, fault tolerant, reconfigurable, and reversible architecture can be developed. In order to continue development of the SCQCA, it is important to understand certain properties associated with its operation by performing analysis of its logical and thermodynamic properties. This paper will provide this analysis along with future directions for a SCQCA based nano-electronics architecture.

7980-38, Session 12

Electrical and noise characteristics of graphene devices: prospects of electronic and sensor applications

A. A. Balandin, Univ. of California, Riverside (United States)

Extraordinary properties of graphene, such as its extremely high electron mobility, make this material promising for applications in electronics and sensors. We have recently discovered that graphene has superior thermal conductivity [1], which improves its prospects for practical applications. Most of the proposed applications require low levels of the electronic 1/f noise, which dominates the noise spectrum at low frequencies. The up-conversion of noise, unavoidable in electronic systems, results in serious limitations. Thus, it is important to investigate the noise level in graphene devices and identify its sources. In this talk, I will overview the results of our experimental study of graphene devices [2]. A special attention will be given to the noise sources in these devices and effects of aging on their characteristics. The exposure of graphene devices to ambient for over a month resulted in substantially increased noise, which was attributed to the decreasing mobility of graphene and increasing contact resistance. The obtained results can be used for graphene device optimization for electronic and sensor applications.

The work at UCR was supported by the DARPA - SRC Focus Center Research Program (FCRP) through its Center on Functional Engineered Nano Architectonics (FENA) and Interconnect Focus Center (IFC).

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7980-39, Session 12

Electrochemical investigation of nano-electrodes for biomedical sensing applications in the brain

C. S. Smith, C. M. Bowie, C. E. Keyes, K. D. Song, Norfolk State Univ. (United States); V. K. Varadan, Univ. of Arkansas (United States); W. Kim, Eastern Virginia Medical School (United States); H. Yoon, Norfolk State Univ. (United States)

Using neural probing devices implanted in the brain, neural activity from neural cells can be recorded in-vivo for long term periods over months. This research is to develop and investigate a neural sensing device using nanotechnology which can enhance the quality and longevity of sensing. In this research, several neural electrode array designs were employed with nanostructure, which distinguishes them from 2-dimensional planar electrode configuration. According to electrochemical analysis, higher neural sensing efficiency of nano-electrodes has been observed. The investigated results of the 3-dimensional nanoelectrode efficacy by electrochemical analysis are also introduced in this presentation, depending on materials and structures of electrodes. This presentation will also discuss the thermodynamic and kinetic interaction between nanoelectrodes and sensing species within 3-D nanoscale geometry.

7980-40, Session 12

Near field effects of millimeter-wave power transmission for medical applications

K. D. Song, Norfolk State Univ. (United States); H. Yoon, Univ. of Arkansas (United States); S. H. Choi, NASA Langley Research Ctr. (United States)

Our research goal is to replace implanted battery power supply with a wireless power coupling system using millimeter-wave rectenna. In order to prove the design concept and investigate wireless power coupling efficiency under the system design, near-field wireless power transmission was studied in terms of wave frequency, power transmission rate, coupling coefficient, and skin depth.

7980-41, Session 12

Nanotechnology based soldier portable power systems and management

V. K. Varadan, Univ. of Arkansas (United States)

No abstract available

7980-43, Session 13

Prediction of micromotion-induced strain in the brain cell around an implanted smart electrode

K. Lee, Old Dominion Univ. (United States); M. A. Polanco, NASA Langley Research Ctr. (United States); H. Yoon, Norfolk State Univ. (United States)

The brain cells located adjacent to an implanted electrode is susceptible to secondary mechanical damage in addition to the insertion damage as brains undergo micromotion due to pulsation and breathing. This secondary damage can significantly reduce the sensitivity of the implanted device. The soft tissues must face and interact with probe materials that are approximately 10 million times stiffer than them. Designing a neuron probe that will remain effective for years to come

may require new approaches. One may use multiple layers of coating materials with varying stiffness levels 1) to enhance the attachment of the immediate needle-tissue interface and 2) to gradually introduce the stiffness mismatch between the probe and the cells. However, this would require a sufficiently large needle that can compensate for the original extreme mismatch. Alternatively, one may design a smart electrode 1) that allows the probe to conform, to some degree, to the motion of the brain tissues and 2) that maintains the electrical resistivity during deformation.

In this study, we will examine the effect of introducing the smart electrode on the secondary damage via assessing the interaction between a needle probe and brain tissue. Micromotion between the probe and the brain was first assessed by performing static finite element analyses. The probe was modeled using silicon properties ($E=165$ GPa, $\nu=0.22$) within a linear elastic material formulation in LS-DYNA. The brain was also modeled using a linear elastic formulation in LS-DYNA with a Young's modulus of 15 kPa and a Poisson's ratio of 0.499. Using quarter-symmetry conditions, a 4 μ N load was applied longitudinally onto the probe. Variables such as von mises strain, maximum, and relative displacement were examined. Once these variables have been quantified within reason, dynamic interaction between the probe and brain tissue will be examined. In addition, a constitutive model for the smart electrode will be developed considering the nano-architecture of the smart electrode materials.

7980-44, Session 13

Metallic nanoparticles-decorated bismuth telluride/silver telluride as nano-bridges for thermoelectric application

H. Kim, S. H. Choi, G. C. King, Y. Park, NASA Langley Research Ctr. (United States); K. Lee, Turner-Fairbank Highway Research Ctr. (United States)

The enhancement of thermoelectric (TE) figure of merit (FoM) is essential for practical energy conversion. The FoM for thermoelectricity is described by the equation $S^2\sigma/\kappa$, where S is Seebeck coefficient, σ is electrical conductivity, and κ is thermal conductivity. Therefore, high S and/or σ , and low κ are desirable for high FoM.

A new and innovative design of TE materials has been introduced at NASA Langley to achieve a FoM beyond the current state of the art. The design of TE material is based on the morphological arrangement of grains surrounded with metallic nanoparticles [1]. Under the aspect of TE material design, Bi₂Te₃/Ag₂Te grains surrounded with metallic nanoparticles was developed. These metallic nanoparticles surrounding a grain act as bridges between Bi₂Te₃/Ag₂Te grains providing electrical conductivity of bulk TE material. This type of morphological arrangement shows significant performance improvement by reducing the thermal conductivity across grain boundaries, that are formed by a separation gap between grains that is greater than the phonon mean-free path.

NASA Langley Research Center successfully fabricated Ag₂Te grains whose surfaces are decorated with bismuth (Bi) nanoparticles. The Seebeck coefficient of Ag₂Te grains covered with Bi metallic nanoparticles show a slight increase versus that of Bi₂Te₃. A pellet of Ag₂Te grains covered with Bi-rich metallic nanoparticles has less than half of the thermal diffusivity of Bi₂Te₃. Furthermore, the electrical conductivity doubled near room temperature. Thus, the nanoparticle/matrix interface on grain geometry serves to reduce thermal energy, caused by obstructing phonon transmission, while allowing electrons to move across the nanoparticle interfaces effectively.

7980-45, Session 13

Nanostructured chalcopyrite $\text{CuIn}_{1-x}\text{Ga}_x\text{Se}_2$ thin films for high-performance solar cells

A. K. Pradhan, Norfolk State Univ. (United States)

An enormous amount of effort has been invested to fabricate and develop low-cost, high efficiency solar cells with chalcopyrite CIGS ($\text{Cu}_{1-x}\text{Ga}_x\text{Se}_2$) thin films as a major constituent layer. CIGS thin films are deemed desirable materials primarily due to their high absorption coefficient ($>10^5 \text{ cm}^{-1}$), direct band gap and stability against photo-degradation. Efficiencies of this absorber layer in solar cells have been reported at a high of 19.5%. However, the attainment of such laboratory efficiencies has been obtained via sophisticated and expensive vacuum technology. We report here the synthesis of CIGS films by one-step electro-deposition technique from a salt bath coupled with complex electrolytes. Various annealing schedules were performed. The influence of deposition reduction potentials as well as the salt concentrations on the structure, morphology, composition and the optical properties were performed. A reproducible Cu-In-Ga-Se precursor layer deposition with consistent composition control was demonstrated. The as-deposited films demonstrate remarkable hierarchical nanostructures that contain nano-sheets all over; however the films displayed good crystallization after annealing. The films show very uniform and dense nano grain/sheet formation. The band gaps were evaluated from the optical measurements. The electrical conductivity measurements demonstrate that the transport mechanism is influenced by three different temperature regions: the ionization, extrinsic and intrinsic regions, respectively, as found in other semiconductors. However, the annealed films display downturn in conductivity at low temperature indicating that there may be trapping at localized sites or scattering of the free carriers, which may be attributed to the over growth and defect sites. The electro-deposition technique demonstrates promise of growing high-quality CIGS thin films and may be considered for future potential technology.

7980-46, Session 13

Temperature dependant electrical behavior of cellulose based transistor

J. Kim, B. Lim, Chosun Univ. (Korea, Republic of); S. Yun, J. Kim, Inha Univ. (Korea, Republic of)

By covalently bonding carbon nanotube with cellulose, we can make the aligned electronic paths in insulating cellulose. Upto now there is no report about temperature dependant electrical behavior of cellulose, it is important to investigate the detail electrical characterization of functionalized cellulose. Temperature dependant electrical characteristic of leakage current was studied. Due to the covalently bonded carbon nanotubes with cellulose, the leakage current may be strongly related to the measurement temperature. By increasing the measurement temperature, the electronic hopping behavior among the covalently bonded carbon nanotubes in cellulose will be discussed. Therefore we will suggest the main leakage current mechanism and reveal the detailed electrical behavior of cellulose based transistor.

Conference 7981: Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems

Monday-Thursday 7-10 March 2011

Part of Proceedings of SPIE Vol. 7981 Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2011

7981-03, Session 2a

An implementation of a data-transmission pipelining algorithm on imote2 platforms

X. Li, S. Dorvash, Lehigh Univ. (United States)

Over the past several years, wireless network systems and sensing technologies have been developed significantly. This has resulted in the broad application of wireless sensor networks (WSNs) in many engineering fields and in particular structural health monitoring (SHM). The movement of traditional SHM toward the new generation of SHM, which utilizes WSN, relies on the advantages of this new approach such as relatively low costs, ease of implementation and the capability of onboard data processing and management. However, the application of WSN in SHM still needs validation through experimental and large scale deployments.

In the particular case of long span bridge monitoring, a WSN should be capable of transmitting commands and measurement data over long network geometry in a reliable manner. While using single-hop data transmission in such geometry requires a long radio range and consequently a high level of power supply, multi-hop communication may offer an effective and reliable way for data transmissions across the network. Using a multi-hop communication protocol, the network relays data from a remote node to the base station via intermediary nodes. We have proposed a data-transmission pipelining algorithm to enable an effective use of the available bandwidth and minimize the energy consumption and the delay performance by the multi-hop communication protocol. This paper focuses on the implementation aspect of the pipelining algorithm on Imote2 platforms for SHM applications, describes its interaction with underlying routing protocols, and presents the solutions to various implementation issues of the proposed pipelining algorithm. Finally, the performance of the algorithm is evaluated based on the results of an experimental implementation.

7981-04, Session 2a

* Hybrid smart sensor network for full-scale structural health monitoring of a cable-stayed bridge

H. Jo, S. Sim, K. A. Mechitov, R. Kim, B. F. Spencer, Jr., Univ. of Illinois at Urbana-Champaign (United States); J. Park, S. Cho, H. Jung, C. Yun, KAIST (Korea, Republic of); J. A. Rice, Texas Tech Univ. (United States); T. Nagayama, The Univ. of Tokyo (Japan)

Rapid advancement of sensor technology has been changing the paradigm of Structural Health Monitoring (SHM) toward a wireless smart sensor network (WSSN). The WSSNs have been using with many SHM applications, but there are only few cases of full-scale SHM. For a long-term operation of the full-scale SHM using WSSN, many challenges such as power, memory, stable communication, and MEMS sensor's low resolution issues etc. still need to be overcome. In this study, the full-scale SHM of a cable-stayed bridge using WSSN is explored. As the 2nd year deployment, more number of sensor nodes, total 113 nodes and 669 channels, are deployed. All the nodes are self-powered using solar panel or wind turbine and the charging status is monitored in this deployment. RemoteFlashSensing is used as basic sensing tool; which saves data to the non-volatile flash memory for secure data saving and efficient power management. Decentralized Data Aggregation (DDA) is considered to reduce radio communication, and high-sensitivity sensorboards (SHM-H board) are used as the cluster heads to better utilize the DDA. CableTensionEstimation algorithm for efficient monitoring

of the tension force of the stay cables is implemented in the WSSN, and multi-hop communication is also used with RemoteFlashSensing and CableTensionEstimation. In addition, temperature and wind effects are monitored. All these applications are implemented together with autonomous SHM software and experimentally verified through a long-term operation of the full-scale SHM of a cable-stayed bridge in Korea.

7981-05, Session 2a

Comparison study of feature extraction methods in structural damage pattern recognition

W. Liu, B. Chen, R. A. Swartz, Michigan Technological Univ. (United States)

Extraction of damage-sensitive features from sensor measurements plays an important role in structural damage pattern recognition, and consists of two equally important parts: feature selection and feature generation. In feature selection, data attributes with high discrimination capability are identified that can lead to large between-class distance and small within-class variance within the feature vector space. In feature generation, the goal is to discover compact and informative representations, based on the feature selection findings, for a given set of sensor measurements.

This paper compares the performance of a structural damage pattern recognition algorithm for a variety of feature extraction methods applied to structural sensor measurements acquired in-situ, from an operational bridge. Various feature extraction methods are applied to sensor data to generate feature vectors for normal and damaged structure data patterns. The investigated feature extraction methods include linear/nonlinear time domain methods as well as frequency domain methods. The evaluation of feature extraction methods is performed by examining distance values among different patterns, distance values among feature vectors in the same pattern, and pattern recognition success rate. To facilitate dynamic update of pattern representations, the effect of environmental factors (e.g., temperature and humidity) on the location of pattern representative feature vectors in the feature vector space is also investigated. The test data used in the comparison study are from the System Identification to Monitor Civil Engineering Structures (SIMCES) Z24 Bridge damage detection tests, a rigorous instrumentation campaign that recorded the dynamic performance of a concrete box-girder bridge under progressively increasing damage scenarios. A number of progressive damage test case data sets, including undamaged cases, pier settlement cases (different depths), a foundation tilt case, and restored pier conditions, are used to test the separation of feature vectors among different patterns and the pattern recognition success rate for different feature extraction methods is reported.

7981-06, Session 2a

Embedding empirical mode decomposition within an FPGA-based design: challenges and progress

J. D. Jones, J. Pei, The Univ. of Oklahoma (United States); J. P. Wright, Weidlinger Associates, Inc. (United States)

This paper presents further advancements made in an ongoing project following a series of presentations made at SPIE in the past. Compared with traditional microprocessor-based systems, rapidly advancing field-programmable gate array (FPGA) technology offers a more powerful, efficient and flexible hardware platform. An FPGA-based design is

developed to classify three types of nonlinearities (including linear, hardening and softening) of a single-degree-of-freedom (SDOF) system subjected to free vibration. This significantly advances the team's previous work on using FPGAs for wireless structural health monitoring. The classification is achieved by embedding two important algorithms - empirical mode decomposition (EMD) and backbone curve analysis. A series of systematic efforts is made to embed EMD, which involves cubic spline fitting, in an FPGA-based hardware design. Throughout the process, we take advantage of concurrent operation and strive for a trade-off between computational efficiency and resource utilization. We have started to pursue our work in the context of FPGA-based computation. In particular, handling fixed-point precision is framed under data-path optimization. Our approach for data-path optimization is necessarily manual and thus may not guarantee an optimal design. Nonetheless, our study could provide a baseline case for future work using analytical data-path optimization for this and numerous other powerful algorithms for wireless structural health monitoring.

7981-07, Session 2a

Investigating the electromechanical performance of carbon nanotube strain sensors embedded in GFRP composites

B. R. Loyola, K. J. Loh, V. La Saponara, Univ. of California, Davis (United States)

The recent trend towards incorporation of fiber-reinforced polymers (FRPs) in aerospace and civil structures has led to the investigation methodology for embedding sensing and structural monitoring mechanisms within the structure itself. One such methodology involves the use of carbon nanotube-based nanocomposites to impart strain and damage sensing properties throughout FRP structures. This self-sensing capability stems from electromechanical coupling between the carbon nanotubes, the nanocomposite, and the FRP structure, and several sensing methods have been validated using electrical resistance and impedance methods. However, models connecting the sensor response to the nanocomposite and FRP response under loading are not as prevalent. This study presents an electromechanical model for a multi-walled carbon nanotube (MWNT) thin film deposited directly onto the glass fiber reinforcement of the FRP using a layer by layer deposition method. Using electrical measurements in the time- and frequency-domains, a model linking the change in electrical properties to nanotube reorientation, nanotube separation, and nanocomposite damage during static and dynamic tensile loading will be validated. Scanning electron microscopy will also be utilized for evaluating how the nanocomposite/FRP physical morphology responds to applied static and dynamic strains.

7981-08, Session 2b

Ultra-low power wireless sensing for long-term structural health monitoring

A. Bilbao, D. Hoover, J. A. Rice, Texas Tech Univ. (United States); J. Chapman, Vestas Technology R&D (United States)

Researchers have made significant progress in recent years towards realizing long-term structural health monitoring (SHM) utilizing wireless smart sensor networks. These efforts have focused on improving the performance and robustness of such networks to achieve high quality data acquisition and in-network processing. One of the primary challenges still facing the use of smart sensors for long-term monitoring deployments is their limited power resources. Periodically accessing the sensor nodes to change batteries is not feasible or economical in many deployment cases. While energy harvesting techniques show promise for prolonging unattended network life, low-power design and operation are still critically important. This research presents a new, fully integrated ultra-low power wireless smart sensor node and a flexible base station, both designed for long-term SHM applications. The power consumption

of the sensor nodes and base station has been minimized through careful hardware selection and the implementation of power-aware network software, without sacrificing flexibility and functionality. The in-network data processing and overall network performance are validated on a historic truss bridge.

7981-09, Session 2b

Leveraging real-time hydrologic data for the control of large-scale water distribution systems in the Sierra Nevada

B. Kerkez, S. D. Glaser, Univ. of California, Berkeley (United States); C. U. Grosse, Technische Univ. München (Germany)

Recent water shortages, particularly evident in the state of California, are calling for better predictive capabilities, and improved management techniques for already existing water distribution infrastructure. One particular example involves large-scale water distribution systems (on the scale of reservoirs and dams) in the Sierra Nevada, where the majority of water is obtained from melting snow. Current control strategies at this scale rely on sparse data sets, and are often based on annual perditions of snowmelt. Sudden, or unexpected, snowmelt can thus often lead to dam overtopping, or downstream flooding.

This paper assesses the feasibility of utilizing real-time hydrologic data, acquired by large-scale wireless sensor networks (WSNs), to control reservoir releases. A sixty node WSN, spanning a square kilometer, was deployed in the Kings River Experimental Watershed, a research site in the Southern Sierra Nevada Mountains, at an elevation of 1,600-2,000 m. The network provides real time information on a number of hydrologic variables, with a particular emphasis on those pertaining to snowmelt processes. We investigate how data obtained by this network can be used to improve predictions of water quantities at a nearby reservoir. Furthermore, we show how these improved predictions can be used to control reservoir releases to ensure that safety demands are met, while minimizing water waste.

7981-10, Session 2b

Data transmission performance modeling for rotating wireless sensors using automatic repeat request

F. Yang, L. Tang, K. Wang, Y. Huang, Clemson Univ. (United States)

Wireless sensors are gaining popularity in different industrial monitoring applications for their small-size, low energy-consumption, and ease in implementation. Especially, wireless sensors are favored in monitoring rotating structures such as the rotating spindle of machine tools by wirelessly transmitting torque, vibration, and temperature information from these structures. Commonly adopted IEEE 802.15.4 wireless sensor radios trade off robustness for low cost, resulting in a higher probability of transmission errors in harsh factory floor environments, for example, on fast rotating structures in manufacturing facilities. To achieve reliable data transmission of wireless sensors, one feasible approach is to use automatic repeat request (ARQ), in which case non-acknowledged packets are retransmitted immediately after timeout.

The objective of this paper is to model the ARQ throughput performance of IEEE 802.15.4 wireless sensor radios on rotating mechanical structures. A fixed packet interval-based throughput model is proposed and further validated for wireless sensors mounted on a rotating apparatus and a machine tool spindle, respectively, where ARQ is implemented. Results show that the throughput predictions match well with the experimental measurements. Moreover, an analytical saturated throughput model is proposed to compare the transmission performance under two different scenarios: without and with ARQ implemented. Both models enable predictive analysis of the sensor data throughput under different rotation speeds and channel error patterns.

7981-11, Session 2b

An equivalent circuit model of supercapacitors for applications in wireless sensor networks

H. Yang, Y. Zhang, Georgia Institute of Technology (United States)

Energy harvesting technologies have been extensively researched to develop long-lived wireless sensor networks. To better utilize the harvested energy, various energy storage systems are proposed. As one of the most used energy storage devices, rechargeable batteries have limited cycle life which actually determines the lifetime of wireless sensor networks. On the other hand, supercapacitors have extremely long cycle life. However, the energy leakage rate is much higher for supercapacitors. Accurate supercapacitors models are needed to analyze and design storage systems with high energy efficiency. Currently adopted supercapacitor models are usually based on the supercapacitor energy leakage profile. Models developed in this way are characterized by an energy recursive formula. No electric circuit elements such as capacitors and resistors are involved. Even though the characterization process is straightforward, such models are difficult to be integrated into the storage systems. To address this issue, an equivalent circuit model of supercapacitors is proposed. This model characterizes supercapacitors with three resistor-capacitor branches with different time constants. It also considers short term and long term energy leakage characteristics. The proposed model is integrated into a hybrid energy storage system containing both supercapacitors and rechargeable batteries. Under various energy harvesting and consuming profiles, the storage system is evaluated in terms of energy efficiency as well as lifetime. Results show that performance of the storage system is strongly dependent on its configurations which provide guidelines for designing efficient storage systems.

7981-12, Session 2b

Multi-scale hybrid sensor nodes for acceleration-impedance-temperature monitoring in truss structures

D. Ho, J. Park, J. Kim, Pukyong National Univ. (Korea, Republic of)

Structural health monitoring (SHM) systems are widely adopted to monitor the structural response, to detect damage, and to assess the effect of damage on the structural integrity. Many researchers have developed novel sensing technologies and damage monitoring techniques for the practical SHM applications. The SHM system mainly includes a number of sensors, a huge amount of signal transmitting wires, data acquisition instruments, and one or more centralized data storage servers. The costs associated with installation and maintenance of SHM systems, however, can be very high. The high costs associated with wired SHM systems can be greatly reduced through the adoption of multi-scale wireless sensor technologies.

In this study, a multi-scale smart sensor node is developed for hybrid health monitoring in truss structures. In order to achieve the objective, the following approaches are implemented. Firstly, the multi-scale sensor node which is able to measure acceleration, impedance and temperature signals is described on the design. Acceleration and impedance signals are used for global and local damage monitoring. Also, temperature signals are used for examining the effect of temperature on structural damage. Secondly, a hybrid health monitoring algorithm using multi-scale smart sensor is proposed for SHM of truss structures. Finally, the performance of the developed multi-scale sensor node is evaluated using a lab-scaled truss structure for which dynamic tests are carried out on a series of damage cases.

7981-13, Session 3a

A structural health monitoring system with ultrasonic MEMS transducers

R. O. Guldiken, O. Onen, Univ. of South Florida (United States);
M. Gul, F. N. Catbas, Univ. of Central Florida (United States)

According to the most recent American Society of Civil Engineers (ASCE) report card, over 150,000 of our nation's bridges (25.6%) are either structurally deficient or functionally obsolete. Structural health monitoring using various sensing and analysis methods offers promise for global and local assessment. In this paper, we present the design and fabrication of low cost, low power, non-destructive ultrasonic MEMS structural monitoring system (SHM) to identify structural damage at the local level. This is essential for predicting the structure's remaining life. State-of-the-art SHM systems employ bulk piezoelectric transducers. However, they are not environmentally benign (contain lead), not cost feasible for monitoring every bridge in the U.S., require significant power for operation, lack integration capability for wireless interrogation, need precise matching layers, and have only 25-50 percent fractional bandwidth, limiting the detection resolution. To alleviate most of these shortcomings, a low impedance MEMS transducer, called a capacitive micromachined ultrasonic transducer (CMUT), is explored. The main advantages of this MEMS transducer alternative are very low power consumption, full-integration capability with wireless circuit, eliminating the need for a matching layer, environmentally benign, low-cost (~\$1 when mass produced), and feasible field deployment of several arrays. In this study, an inter-digital excitation scheme is employed to selectively excite Lamb waves to inspect thin plates and shell structures, and Rayleigh waves to inspect surface defects. We will also discuss our novel coupled finite element modeling to capture the response from our device. Finally, experimental verification and field implementation studies will be reviewed.

7981-14, Session 3a

* Photocurrent generation and characterization of a photoelectric nanocomposite sensor

D. Ryu, K. J. Loh, Univ. of California, Davis (United States)

There is a dire need to develop novel robust and reliable sensing technologies for identifying the onset of structural damage and for preventing sudden catastrophic structure failures. While numerous sensors (e.g., fiber optics, wireless sensors, piezoelectrics, and remote sensing) have been proposed for structural health monitoring, the current generation of sensing systems suffer from some fundamental limitations, namely: (1) discrete sensing, (2) energy demand, and (3) electrical input stimuli. This study draws its inspiration from nature's creations and biological assemblies for developing a novel sensor platform that does not require electrical energy or stimuli to operate. Specifically, this research is inspired by the photosynthesis electron-transfer reactions in plants and algae for converting photonic to electronic energy. First, regioregular poly(3-hexylthiophene) (P3HT) conductive polymers are synthesized in the laboratory and characterized via electron microscopy, UV-Vis, and NMR. Second, P3HT-carbon nanotube (CNT)-based thin films are fabricated via spin-coating, and the nanocomposite's photocurrent generation capabilities are investigated and evaluated. However, instead of using P3HT-CNT nanocomposites as an energy harvesting or photovoltaic device, the thin films are utilized as strain sensors. Finally, thin film specimens are loaded in an electromechanical load frame, and the preliminary results show that the magnitude of generated photocurrent varies in tandem with applied tensile and compressive strains.

7981-15, Session 3a

Field investigation of a vibration monitoring wireless sensor network on a huge cantilever structure

H. Zhou, The Hong Kong Polytechnic Univ. (Hong Kong, China); J. Liu, The Hong Kong Polytechnic Univ. Shenzhen Research Institute (China); Y. Ni, The Hong Kong Polytechnic Univ. (Hong Kong, China); D. Zhu, Georgia Institute of Technology (United States)

Over the past decade, a number of wireless sensor network prototypes have been developed for applications to structural health monitoring. With intent to validate the wireless sensor network, varieties of tests have also been conducted in laboratory settings. Different from laboratory tests, field tests are usually subject to more uncertainties due to noises, interferences, weak responses, obstructions, etc. To advance the wireless structural monitoring system mature into a reliable substitute to wired structural monitoring system, more efforts should be paid to investigate their in-field performance on real civil structures, especially complex mega structures. This study carries out an investigation into a vibration monitoring wireless sensor network for the system identification of a huge cantilever structure.

The testbed under study is the New Headquarters of Shenzhen Stock Exchange (NHSE), which is a supertall building with a total height of 228 m. One outstanding feature of NHSE is its huge floating platform, which is a steel truss structure with an overall plan dimension of 98×162 m and a total height of 24 m. It overhangs from the main tower 36 m along the long axis and 22 m along the short axis at a height of 36 m above the ground, making it the largest cantilever structure in the world. Recognizing the uniqueness of this floating platform, the performance of a wireless sensor network for the ambient vibration monitoring is examined on this structure. With intent to identify not only modal frequencies but also mode shapes, multi-point synchronous acceleration measurements are conducted. Practical issues in the use of wireless sensor network for ambient vibration test are also studied, such as signal conditioning, wireless transmission distance, influences of obstructions, etc. This study demonstrates that the wireless sensor network is capable of monitoring the ambient vibration and identifying the modal properties of a huge cantilever structure.

7981-16, Session 3a

A wireless sensor node for high-frequency active-sensing SHM of wind turbine blades

S. Taylor, E. Raby, K. Farinholt, G. Park, C. R. Farrar, Los Alamos National Lab. (United States); M. D. Todd, Univ. of California, San Diego (United States)

Active sensing provides a powerful tool with which to interrogate a structure. However, active sensing systems typically require a chassis or rack-mounted system with bulky power amplifiers and a PC. Notable exceptions include the SHiMmer (UCSD) and the Intelli-Connector SHM Node (metis design). Furthermore, many structures of interest, such as wind turbine blades or aircraft wings, have severe weight limitations restricting the type of system that can be installed. Such systems are also often inaccessible during normal operation, and inspection methods must rely heavily on off-line, scheduled nondestructive evaluation (NDE). This paper presents a new active sensing node based on smartphone technology and compact power amplification that can provide structural excitation and synchronous measurements for high-frequency responses in SHM, as well as on-board sensor diagnostics. The wireless active sensing node is designed for integration within a utility-scale wind turbine blade. With a powerful ARM processor, the WAD is fully integrated with SHMTools and mFUSE, an open-source function sequencer and SHM platform for Matlab. This paper presents the features of the WAD and presents experimental results highlighting its capabilities as a stand-alone active sensing platform.

7981-17, Session 3a

Toward triboluminescent sensor realization for SHM

T. J. Dickens, The Florida State Univ. (United States); O. O. Okoli, High Performance Materials Institute (United States)

Damage associated with composite systems can lead to catastrophic and expensive failures. Extensive research efforts have been expended to develop a single inspection technique used on its own to provide reliable real-time and cost effective results. The answer may lie with the development of SHM systems that utilize triboluminescent (TL) materials, in conjunction with a transport mechanism that may be incorporated throughout the entire composite structure.

In recent work, Triboluminescent materials (ZnS:Mn phosphors) have shown to be compatible in composite matrices to utilize their inherent luminescent properties for potential structural health monitoring capabilities. Incorporation of Triboluminescent materials into composites raised many important problems involving extraction of TL emissions and sensory capabilities. This work examines the use of TL crystals embedded in the composite matrices to act as indicators of localized damage. These crystals react to straining or fracturing by emitting light of varied luminous intensity, giving an indication of crack initiation well ahead of catastrophic failure(s). Initial testing has shown that light can propagate through doped resins alone, as well as doped fiber reinforced plastics (FRP) laminates with material transparency being a major hindrance. Because of the opaqueness of most composite systems, a novel extraction method is being assessed for ballistic transport capabilities.

Titanium dioxide has come under extreme scrutiny for its stable composition and photocatalytic abilities and might prove useful as an in situ sensor realization for light extraction. This research discusses a visible route to developing visibly (400 - 700 nm) active titania nanoparticles templated on CNT substrates. Because of the exceptional electrical properties of CNTs, a network of semiconducting CNTs known as "buckypaper" has been evaluated for its ballistic transmission capabilities. Dye sensitized solar cells were fabricated with thus stated visible receptors (N-doped titanium dioxide) and buckypaper electrodes. The cells were used as light harvesting devices for subsequent emission by triboluminescence. Tribo-emissions captured by thus stated device revealed composites doped with a highly TL material can be detected with an optoelectronic cell. The collection efficiencies for the constructed light sensors are less than 10%, with quantum efficiency for 585 nm TL wavelength of nearly 50%. UV/vis analysis has revealed a blue shift in N-doped titania nanoparticles toward the visible region. The inclusion of N is verified through FTIR and EDS analysis.

7981-18, Session 3a

A wireless multifunctional radar-based displacement sensor for structural health monitoring

J. A. Rice, C. Li, Texas Tech Univ. (United States)

Wireless smart sensor technology offers many opportunities to advance infrastructure monitoring and maintenance by providing pertinent information regarding the condition of a structure at a lower cost and higher density than traditional monitoring approaches. Many civil structures, especially long-span bridges, have low fundamental response frequencies that are challenging to accurately measure with sensors that are suitable for integration with low-cost, low-profile, and power-constrained wireless sensor networks. Existing displacement sensing technology is either not practical for wireless sensor implementations, does not provide the necessary accuracy, or is simply too cost-prohibitive for dense sensor deployments. This paper presents the development and integration of an accurate, low-cost wireless radar-based sensor for the enhancement of low-frequency vibration-based bridge monitoring and the measurement of static bridge deflections. The sensors utilize both a nonlinear vibrometer mode and an

arctangent-demodulated interferometry mode to achieve sub-millimeter measurement accuracy for both periodic and non-periodic displacement. Experimental validation results are presented and discussed.

7981-19, Session 3b

Nonlinear ultrasonic guided waves for prestress level monitoring in prestressing strands for post-tensioned concrete structures

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Monitoring load levels in multi-wire steel strands is crucial to ensuring the proper structural performance of post-tensioned concrete structures, suspension bridges and cable-stayed bridges. The post-tensioned box-girder structural scheme is widely used in several bridges, including 90% of the California inventory. In this structural typology, prestressing tendons are the main load-carrying components. Therefore loss of prestress as well as the presence of structural defects (e.g. corrosion and broken wires) affecting these elements are critical for the performance of the entire structure and may conduct to catastrophic failures. Unfortunately, at present there is no well-established methodology for the monitoring of prestressing (PS) tendons able to provide simultaneous and continuous information about the presence of defects as well as prestress levels.

In this paper the authors develop a methodology to assess the level of load applied to the strands through the use of ultrasonic nonlinearity. Since an axial load on a multi-wire strand generates proportional contact stresses between adjacent wires, ultrasonic nonlinearity from the inter-wire contact must be related to the level of axial load. The work presented shows that the higher-harmonic generation of ultrasonic guided waves propagating in individual wires of the strand varies monotonically with the applied load, with smaller higher-harmonic amplitudes with increasing load levels. This trend is consistent with previous studies on higher-harmonic generation from ultrasonic plane waves incident on a contact interface under a changing contact pressure. The paper presents the results of experimental researches on free strands and embedded strands, and numerical studies (nonlinear Finite Element Analysis) on free strands.

7981-20, Session 3b

Enabling dissimilar fibre embedding and explicit fibre layout in ultrasonic consolidation

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Ultrasonic Consolidation (UC) is a manufacturing technique based on the ultrasonic joining of a sequence of metal foils which are bonded to one another. Due to moderate pressures and low temperatures, UC operates as a solid-state process. This research investigates the use of UC to fabricate smart material structures by integration of sensors, actuators and reinforcement by means of different types of fibres such as Smart Memory Alloys, Optical Fibres and Silicon Carbide.

Previous problems with the optimal placement of fibres directly between foils have been identified. Also, different types of fibres require different process conditions and thus present complications to integrate them in combination.

Research on new capabilities to consolidate fibres securely and more accurately during UC will be presented. Channels created by laser processing prior to UC within metal matrix composites are investigated as a method to aid the embedding of high volume fractions of different fibres in unison without damage. Laser processing is conducted with a Fiber laser which has been identified as a promising method to create narrow channels with regard to beam profile, spot size and focussing capability.

Microstructural studies such as cross-sectioning perpendicular to the fibre axial direction have been carried out to observe secure integration such as the amount of plastic flow around fibres and potential voids. Mechanical testing is used to evaluate the bonding quality of the samples. The post-UC functionality of fibres will be determined by testing their active and passive characteristics such as signal or light transmission or thermomechanical response.

7981-21, Session 3b

Effect of decay on ultrasonic velocity and attenuation measurements in wood

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Ultrasonic velocity and attenuation measurements were carried out using seventy wooden block cube specimens prepared following the ASTM Standard Test Method (ASTM D 1413-99). Ten blocks were kept for control and the remaining sixty blocks were exposed to *Gloeophyllum trabeum* fungus from periods of 1 week to 12 weeks under controlled temperature (27 °C) and humidity conditions (70%). At the end of each week for the next twelve weeks, five specimens were removed for testing. X-ray computed tomography (CT) was used to evaluate mass loss during the decay process. Ultrasonic longitudinal and shear velocity and attenuation measurements in the frequency range of 20 to 100 kHz were carried out. It was observed that velocity and attenuation are dependent upon frequency, amount of decay, and orientation. For example, for the control blocks with no decay, the energy velocities of the fastest mode through the longitudinal direction were approximately 4500 and 6000 m/s at 20 kHz and 100 kHz, respectively; for blocks with 12 weeks of decay, the velocities were 3300 m/s and 3750 m/s at 20 kHz and 100 kHz, respectively. With no decay the attenuation coefficients in the longitudinal direction for the frequency range of 20 to 100 kHz were found to be in the range of 0.1 to 0.2 Np/cm, respectively; for blocks with 12 weeks of decay, they were found to be in the range of 0.8 to 1.1 Np/cm. Similar variations in velocity and attenuation measurements were observed in the radial and tangential directions.

7981-22, Session 3b

Planar rotary motor using ultrasonic horns

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One of the first piezoelectric motor designs with significant rotational speeds was outlined by Barth (Barth 1973). This device used extensional piezoelectric elements to produce a time varying force at a distance r from the center of a centrally supported disk. These extensional actuators produced micro-steps at a high frequency with the end result being macroscopic rotation of the disk and high torque. The rotation direction is controlled by the choice of the actuators and the direction of the extension about the rotor center. A recent advancement in producing pre-stressed power ultrasonic horns using flexures allows for the development of high torque ultrasonic motors based on the Barth's idea that can be fabricated in a 2D plate or in more complicated 3D structures. In addition to the pre-stress flexures the design also allows for the use of flexures to produce the rotor/horn normal force. The torque can be controlled by the number of actuators in the plane and the amplitude of the normal force. We will present analytical and experimental results obtained from testing prototype planar motors.

Barth H.V. (1973): Ultrasonic Driven Motor, IBM Technical Disclosure Bulletin, 16, pp. 2263

7981-23, Session 3b

Structural health monitoring using flexible ultrasonic transducer arrays on an aircraft component

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Damage detection capability of the flexible ultrasonic transducer (FUT) array bonded onto a planar and a curved surface is presented. The piezoelectric PZT composite film FUT arrays are fabricated on the 75 μm titanium membrane substrate using a sol-gel spray technique. The test article was a complex aluminum component that is representative of aircraft structural complexity. Room temperature curable adhesive is used as the bonding material and ultrasonic couplant between the FUT and the test article. The glue has been successfully tested in the temperature range of $-80\text{ }^{\circ}\text{C}$ to $100\text{ }^{\circ}\text{C}$, which covers the sensor operating temperatures commonly required for aircraft structures. For a planar surface the selected FUT arrays were able to detect the fasteners and the 2.54 mm long EDM notch up to the distance of 176 mm with sufficient SNR. The pulse-echo measurements obtained by the FUT array were compared with the ones using a commercial 10 MHz ultrasonic transducer (UT). The results showed that the performance of the FUT array was as good as the commercial UT. Another FUT array was bonded onto a curved surface of the test article using the same adhesive. No measurement using commercial UTs was taken on the curved surface because restricted access around this area did not allow such measurement. The pulse-echo measurements confirmed the detection of EDM notches of 2.54 mm long and 1.27 mm long. The experimental results demonstrated the potential of FUT arrays for aircraft structural health monitoring.

7981-24, Session 4a

New materials for isolators in civil infrastructures: stainless steel-metallic pseudo rubber and SMA-metallic pseudo rubber

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Base isolation has been widely investigated and used in civil infrastructures all over the world. However, it still has some problems need to be solved. For example, extra buffers are needed for some types of isolators to prevent them from generating too large deformation. These buffers increase the cost of isolators and make them more complicated. In addition, some isolators may have residual deformation and need to be repaired or replaced after large earthquake. This also induces large cost. In order to develop novel isolators with self buffer and with residual deformation self-recovery ability, two types of materials, stainless steel metallic pseudo-rubber (SS-MPR) and shape memory alloy metallic pseudo-rubber (SMA-MPR), were fabricated and investigated in this study. Mechanical behaviors of these two materials were investigated, together with deformation self-recovery ability of SMA-MPR material. Meanwhile, three types of SMA-MPR specimens with various processing procedures were fabricated. Mechanical behavior of the SS-MPR and SMA-MPR specimens under cyclic sinusoidal compression loadings with various loading frequencies were test. After that, the three types of SMA-MPR specimens with residual deformation were put into a temperature controlled stove and their deformation recovery ability were tested. In order to address if these SMA-MPR specimens still have stable mechanical properties after deformation recovery, they were installed in the test machine and their stress-strain behavior under cyclic sinusoidal loads were tested again. Experimental results indicated that both SS-MPR and SMA-MPR are good potential material to develop novel seismic isolators for civil infrastructures.

7981-25, Session 4a

Design of the thermal insulating test system for doors and windows of buildings

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Thermal insulating properties of doors and widows are important to measure the quality of windows and doors. This paper develops the thermal insulating test system of doors and windows for the sake of the large temperature difference in the winter in northern China according to national standards. This system consists of temperature measurement subsystem, temperature control subsystem, the heating power measurement subsystem, heat transfer coefficient calculated subsystem. The temperature measurement subsystem includes temperature sensor which is implemented by sixty-four thermocouple sensors to measure the key positions of cold room and hot room, and the temperature acquisition unit which adopts Agilent 34901A data acquisition card to achieve self-compensation and accurate temperature capture. The temperature control subsystem including temperature controller and compressor system used to control the temperature between 0 degree to 20 degree for hot room and -20 degree to 0 degree for cold room. The hot room controller uses fuzzy control algorithm to achieve accurate control of temperature and the cold room controller firstly uses compressor to achieve coarse control and then uses more accurate temperature controller unit to obtain constant temperature(-20 degree).The heating power measurement is mainly to get the heat power of hot room heating devices. After above constant temperature environment is constructed, the software of the test system is developed. Using the software, temperature data and heat power data can be accurately got and then we could use the standard formula to calculate heat transfer coefficient which represents the thermal insulating properties of doors and widows. Experimental results show that the test system is simple, reliable and precise. It meets the testing requirements of national standard and has a good application prospect

7981-26, Session 4a

Experiments on the focusing and use of acoustic energy to enhance the rate of polymer healing

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Self-healing materials should be considered for use in lightweight space structures and other applications where repairing damage sustained with manual methods is difficult, and/or economically challenging. Our study hopes to accelerate, using applied acoustic pressure, the curing of a two-part epoxy sample, which can be considered analogous to the self-healing process of the same material. A time reversal algorithm is also in development and will be used to locate defects and to then focus energy at the damaged location in an attempt to accelerate the natural healing tendencies of fractured polymers. Epoxy curing studies monitor the process by tracing vibrational responses as well as internal temperatures during the cure. In this period of study variables that were leading to inconsistent or even inconclusive test results have been realized and reduced. A fluctuating ambient air temperature surrounding the tests being conducted was discovered to have a significant effect on the curing rate: this variability has been greatly reduced by controlling the environment's temperature with a thermostat and heater. Air inclusion in epoxy samples was another cause of variability but has been reduced by the implementation of improved degassing techniques. Consistent test results are beginning to emerge, and it is from this place that acoustic energy will be added and monitored as a variable.

7981-27, Session 4b

Impact damage detection in composites using an active nonlinear acousto-ultrasonic piezoceramic sensor

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The development of effective SHM methods for composite structures receives high attention, as the volume of composite materials used in primary aerospace, transport and energy structures is rapidly increasing. Among the various types of damage which may coexist in a composite structure, early detection and monitoring of foreign body impact damage is desirable, as the latter may easily occur, remain hidden and propagate catastrophically. Non-linear ultrasonic NDE techniques, are newly developed methodologies for which are reported to provide high sensitivity in the detection of small crack damage. However, little work has been reported on the application of non linear ultrasonics for damage detection in composite structures; moreover, the reported techniques are suitable for non destructive inspection, and not for permanent structural health monitoring.

The authors have introduced the concept of the active nonlinear acoustoultrasonic piezoelectric sensor (ANAUPS), using permanently attached piezoelectric wafers as actuators and sensors, which has demonstrated capability to detect delamination and matrix cracks in composites [1,2], through in-situ generation and nonlinear modulation of an acoustoultrasonic carrier wave. Previous experimental measurements using nonlinear ultrasonics methodology based on the usage of the Acoustic Nonlinear Piezoelectric Sensor described above, presented high sensitivity to reveal the delamination debondings and matrix cracks in composite beams even for significantly small damage sizes.

The objective of this paper is to experimentally and analytically investigate the potential of non-linear acousto-ultrasonic modulation method to detect impact damage in composite structures, and to develop and evaluate a novel SHM methodology based on the usage of solely in-situ piezoelectric devices (ANAUPS). Glass/epoxy composite plates and strips are fabricated with [90/0]2S and [90/0/45/-45]S laminate configurations. These specimens are subjected to impact loading, for various low energy levels, to create impact damage in the composite laminate. These specimens are tested using at minimum 3 surface bonded piezoceramic wafers: two piezoceramic actuators exciting the low-frequency nonlinear vibration and the high-frequency carrier wave, respectively, and a piezoceramic sensor picking up the modulated wave signal. Apparent objective of the present work is to investigate the feasibility to detect impact damage developed in composite structures caused for various energy levels, and to quantify the effect of impact energy/damage size and the carrier wave excitation frequency level on the resultant carrier modulation. Comparison with previously obtained frequency spectra of the modulated signal for a single delamination crack, or matrix cracking in the composite will be presented, to demonstrate changes in the sensor signal pattern for each type of damage.

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7981-28, Session 4b

Detecting the point of impact on a cylindrical surface by the acoustic emission technique

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The conventional triangulation technique is not reliable for locating the impact point in an isotropic pipe because the guided waves generated in the pipe wall by the impact phenomenon propagate in different directions with different wave speeds. The conventional triangulation technique that assumes constant wave speed in all directions although can locate the acoustic source in isotropic plates it does not work for a cylindrical geometry even if it is made of an isotropic material. An alternative method of detecting the impact point on isotropic and anisotropic plates developed by Kundu and his associates [1, 2] is extended here to the cylindrical geometry. An objective function is defined that uses the cylindrical coordinates of four sensors attached to the cylinder and four arrival times to locate the point of impact by minimizing the least squares error.

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7981-29, Session 4b

Automated detection and quantification of impact damages in composite structures using pulsed thermography

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An automated method to detect and quantify the extent of impact damage in composite structures is proposed using pulsed thermography set up. The method involves a two step approach. In the first step, the data is preprocessed. The pros and cons of the existing methods is compared and studied. The wavelet based filtering method is chosen. In the second step, a novel method based on the one dimensional heat conduction model to detect and quantify damages is proposed. The results will be presented on a carbon fiber reinforced plastic (CFRP) plate with simulated delaminations. The results obtained show the validity of the model based on the simple one dimension heat conduction equation. The proposed two step approach has numerous advantages like data compression, denoising of the raw data, automated defect detection and quantification.

7981-30, Session 5a

Analysis of a micro piezoelectric unimorph power generator operating at d₃₃ mode

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Recent advancement of MEMS and nano-electronic devices triggered great needs for ultra-low power sources. MEMS power generators are among current interests of energy harvesting community as they are compact, low-cost, lightweight, and very easy to be integrated to systems. The structure of the MEMS power generator is generally a PZT (Lead zirconate titanate) thin film cantilever operating at the d₃₁ or d₃₃ mode. For the d₃₁ type piezoelectric energy harvester, the vibration energy is converted to the electrical energy through a

piezoelectric bimorph which has a top and bottom electrode. The d₃₃ type piezoelectric energy harvesters have advantages over d₃₁ type as they eliminate the need for a bottom electrode and can generate a higher output voltage. Although the fabrication process of these PZT thin film energy harvesters are technically mature, theoretical analyses in this field are still few and scattering, especially for the d₃₃ type piezoelectric energy harvesters. In this article, a theoretical analysis for the performance of a PZT thin film micro cantilever operating at d₃₃ mode is performed based on the 3-D theory of piezoelectricity. A 3-D finite element model for the micro piezoelectric cantilever beam with an interdigitated electrode pattern is built using COMSOL software and analyzed. The finite element result is shown to be consistent with the theoretical result. A comparison for the micro piezoelectric generator operating at the d₃₃ mode and d₃₁ mode is made and discussed.

7981-31, Session 5a

Evaluation of a micro-turbulence sensor fabricated by lithography

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This paper describes the fabrication of a micro-turbulence sensor. The sensor features a hairy structure inspired by aquatics. The design and optimization of sensor geometry was conducted to achieve the highest sensitivity. A few advanced fabrication technologies were employed for sensor fabrication. These include the use of advanced lithographic technology for sensor electrode deposition. The sensor was polarized under high voltage gradient and was subsequently evaluated under controlled laboratory conditions in a micro wind tunnel. The results of sensor performance are discussed in this paper.

7981-32, Session 5a

Laboratory validation of MEMS-based sensors for post-earthquake damage assessment

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The evaluation of seismic damage is today almost exclusively based on visual inspection, as building owners are generally reluctant to install permanent sensing systems, due to their high installation, management and maintenance costs. To overcome this limitation, the EU-funded MEMSCON project aims to produce small size sensing nodes for measurement of strain and acceleration, integrating Micro-Electro-Mechanical Systems (MEMS) based sensors and Radio Frequency Identification (RFID) tags in a single package that will be attached to reinforced concrete buildings. To reduce the impact of installation and management, data will be transmitted to a remote base station using a wireless interface. During the project, sensor prototypes were produced by assembling pre-existing components and by developing ex-novo miniature devices with ultra-low power consumption and sensing performance beyond that offered by sensors available on the market. The paper outlines the device operating principles, production scheme and working at both unit and network levels. It also reports on validation campaigns conducted in the laboratory to assess system performance. Accelerometer sensors were tested on a reduced scale metal frame

mounted on a shaking table, back to back with reference devices, while strain sensors were embedded in both reduced and full-scale reinforced concrete specimens undergoing increasing deformation cycles up to extensive damage and collapse. The paper assesses the economical sustainability and performance of the sensors developed for the project and discusses their applicability to long-term seismic monitoring.

7981-33, Session 5a

On electrostatically actuated NEMS/MEMS circular plates

D. Caruntu, The Univ. of Texas-Pan American (United States)

This paper deals with electrostatically actuated micro and nano-electromechanical clamped circular plates. The model includes Casimir and van der Waals forces. These two forces are each dominant at different length scale. The method used to investigate the clamped circular plate system is the method of multiple scales (MMS), a perturbation method. MMS is used for weakly nonlinear systems. A small parameter ϵ is used as a bookkeeping device. Two time scales, fast and slow, are considered in this work. The amplitude-frequency relationship of the system is obtained.

7981-34, Session 5b

Detection of cracks on a plate by piezoelectric interdigital transducers

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Much work has been reported on the use of piezoceramic patch sensors in structural health monitoring due to their simple structure and moderate performance. However, the patch uses the inherent electromechanical properties of a piezoceramic element itself. Once the piezoceramic element is given, not much controllability is available on its operation frequency, directionality, and sensitivity. This paper proposes and verifies the feasibility of a new ultrasonic sensor to estimate the quantitative configuration of cracks on a plate: an inter-digital transducer (IDT) type Lamb wave sensor. This IDT type sensor is more readily controllable than conventional patch sensors in terms of its operation frequency and directionality by altering the IDT pattern on a given piezoceramic element. In this work, two different types of IDT sensors are designed and fabricated: annular IDT and rectangular IDT sensors. The IDT sensors are implemented in the experiments to investigate the length, the number and the orientation angle of the cracks artificially imposed on an aluminum plate. The variation of amplitude and time-of-flight (TOF) of Lamb waves are measured and analyzed to estimate the crack configurations. The results show that the annular IDT sensor is similar to the conventional patch sensors in terms of its omni-directional beam pattern. The rectangular IDT sensor is highly directional, thus the sensor has superior sensitivity to a particular direction, which means more robust to environmental noise coming from arbitrary directions. The measured configuration shows excellent correlation with real configuration of the cracks, which confirms the efficacy of the IDT sensors.

7981-35, Session 5b

Measurement of fatigue damage progression in aluminum alloy lug joints using laser ultrasonic methods

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During metal alloy fatigue processes, distributed microcracking can evolve and influence the effective elastic moduli of the material. With increased microcrack density (crack number density and/or crack area), moduli decrease in ways related to the distribution and orientation

of the microcrack population. In this work, elastic wavespeeds have been measured in aluminum alloy lug joints using a femtosecond laser to generate ultrasound and a Michelson-type interferometer to receive ultrasound in a through-thickness transmission geometry. These measurements allow us to determine the longitudinal and shear stiffnesses in a well-defined direction relative to sample loading. To assess related fatigue-damage-induced modulus variations, lug joint samples were oriented with the rolling direction parallel to the loading direction to establish well-defined directions for initial material anisotropy and interrupted fatigue tests were performed with ultrasonic data being taken every 20 kcycles up to the point of visible macrocrack formation. Preliminary results show a 2-3% decrease in stiffness for both longitudinal and shear waves in the aluminum alloy 2024-T351 undergoing fatigue. For the loading used in this study, fatigue levels below 80 kcycles primarily show monotonic reductions in stiffness related to increases in microcrack density while at higher levels wavespeed variations were irregular. Since the measured effective elastic moduli can be interpreted using microcrack density as well as crack distribution in the sample, it appears that such irregular variations might correspond to stages in which macrocracking produces complicated redistribution of stresses affecting the role of microcracks on effective modulus.

7981-36, Session 5b

UCSD/FRA non-contact ultrasonic guided-wave system for rail inspection: an update

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The University of California at San Diego (UCSD), under a Federal Railroad Administration (FRA) Office of Research and Development (R&D) grant, is developing a system for high-speed and non-contact rail defect detection. A prototype has been designed and field tested with the support of Volpe National Transportation Systems Center and ENSCO, Inc. The goal of this project is to develop a rail defect detection system that provides (a) better defect detection reliability (including internal transverse head defects under shelling and vertical split head defects), and (b) higher inspection speed than achievable by current rail inspection systems. This effort is also in direct response to Safety Recommendations issued by the National Transportation Safety Board (NTSB) following the disastrous train derailments at Superior, WI in 1992 and Oneida, NY in 2007 among others.

The UCSD prototype uses non-contact ultrasonic probing of the rail head, ultrasonic guided waves, and a real-time statistical analysis algorithm that maximizes the sensitivity to defects while minimizing false positives. The current design allows potential inspection speeds up to 40 mph, although all field tests have been conducted up to 15 mph so far.

This paper summarizes (a) the latest technology development test conducted at the rail defect farm of Herzog, Inc. in St Joseph, MO in June 2010, and (b) the completion of the new Rail Defect Farm facility at the UCSD Camp Elliott Field Station with partial in-kind donations from the Burlington Northern Santa Fe (BNSF) Railway.

7981-37, Session 5b

Structural condition assessment based on factor analysis and sequential probability ratio test

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A method of structural condition analysis based on factor analysis and sequential probability ratio test was proposed. The structural condition features, which were extracted from the monitoring data, was not only affected by structural condition, but also influenced by environmental

factors, measurement noise and analysis errors. When the environmental factors, which affect the structural condition features, was unknown or cannot be completely measured, the common factors of structural condition features field, which was calculated by the factor analysis, can be used to express the influences of the environmental factors. The change of the structural condition can be identified based on the sequential probability ratio test. In this paper, the factor analysis theory was introduced at first and the matrix excluding method of the factor analysis was derived. And then the structural condition can be identified correctly by the sequential probability ratio test based on the Mann-Whitney rank sum test. Finally, a numerical example of a cable-stayed bridge was used to validate the method, and the result shown that the method can correctly identify the change of structural condition, especially the small damage.

7981-38, Session 6a

Ultrasensitive low-power multifunctional spintronic nanowire sensors for magnetic field, pressure, and strain sensing

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We discuss the design, modeling and fabrication of a state-of-the-art ultrasensitive, tunable, nanowire sensor with potential room temperature sensitivity to strain of $10^{-16}/\text{Hz}^{1/2}$ as well as sensitivity to magnetic field of 30 femto-Tesla/ $\text{Hz}^{1/2}$. This sensitivity is obtained with a sensing area of 1 cm^2 and power dissipation of 2 mW. The sensor is scalable to an area of $100 \mu\text{m} \times 100 \mu\text{m}$, resulting in a reduced strain sensitivity of $10^{-14}/\text{Hz}^{1/2}$ and magnetic field sensitivity of 30 pico-Tesla/ $\text{Hz}^{1/2}$. The power dissipated in operating such a miniaturized sensor is estimated at only 200 nW.

The uniqueness of the approach is the use of a tri-layered nanowire spin-valve that would enable ultrasensitive strain and magnetic field detection. The spin-valve consists of two ferromagnetic layers separated by a semiconductor spacer layer. Applying stress/strain or magnetic field changes the magnetization in the ferromagnetic layers and reduces their spin-filtering efficiency. This alters the spin polarized current flowing in the nanowire leading to ultrasensitive pressure and strain sensing.

The sensitivity, low power requirements and tunability of this device make it well suited to applications in a miniaturized array for in-situ structural health monitoring, pressure, flow, acoustic and seismic sensing.

7981-39, Session 6a

On carbon nanotube resonators

D. Caruntu, The Univ. of Texas-Pan American (United States)

This paper deals with nonlinear behavior of electrostatically actuated Carbon Nanotubes (CNT) for sensor applications. The van der Waals force is included in the model. The electrostatic force is due to AC voltage. This is a strongly nonlinear system. Both the Method of Multiple Scales and direct integration will be used to find the nonlinear dynamics of the CNT. Nonlinear resonances of the system have the potential of enhancing resonator's sensitivity.

7981-40, Session 6a

Graphene-based ultrasensitive nanostructures enabled by morphologic instability

T. Li, Z. Zhang, Univ. of Maryland, College Park (United States)

Graphene, a monolayer graphite, is the thinnest material ever made and the strongest ever measured. It has the highest intrinsic electron

mobility ever demonstrated. Graphene's two dimensional structure exposes its entire volume to its surrounding with well amenable surface chemistry, making it highly efficient for sensing. While preliminary explorations of graphene-based sensing are promising, significant gaps remain to realize high performance sensing, largely due to the small amplitude of indicators of change. Recent discovery of graphene's morphologic instability reveals fertile opportunities to achieve high performance sensing. Morphologic instability leads to a sharp change in graphene properties of large amplitude, thus substantially enhancing the sensing fidelity. In this paper, we report two types of morphologic instability of graphene: snap-through instability and formation of carbon nanoscrolls (CNSs). Particular efforts are focused on deciphering the underlying mechanisms of these two types of morphologic instabilities, and quantitatively determining the relation between such instabilities and critical conditions of governing parameters, through a multiscale modeling framework. We demonstrate the snap-through instability of graphene on a wide range of nanoscale engineering surfaces, such as surface grooves, herringbone and check board wrinkling patterns and patterned nanowires. We also demonstrate an all-dry physical approach to achieve reversible formation of CNSs from graphene.

7981-41, Session 6a

Fiber optics photoacoustic generation using gold nanoparticles as target

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Ultrasound transducers have been used in various applications such as nondestructive testing, acoustic response analysis of vascular tissues, and medical imaging. Most recent applications lead to a demand of more advanced ultrasound generators featuring higher central frequency, wider bandwidth and miniature size. In this paper, a novel ultrasound generator on an optical fiber tip is designed, fabricated and characterized. The ultrasound generator was fabricated by coating several layers of gold nanoparticles (Au NPs) on the end face of a piece of commercially available optical fiber via a layer-by-layer (L-b-L) technique. The Au NPs were synthesized by a traditional sodium citrate reduction method and the diameter of Au NPs was controlled at 20nm. The ultrasound is generated through photoacoustic procedure. By introducing excitation laser pulses on the Au NPs layer, the energy of laser is converted into the heat through photothermal mechanism. Then, the heat transforms into kinetic energy through thermalelastic mechanism. Thus, ultrasound can be generated. The experiment results showed that this kind of ultrasound generator shows wide bandwidth, high frequency and miniature size. By comparing to the conventional energy absorption material such as graphite, the Au NPs show high energy absorption efficiency and high thermal expansion rate. Therefore, the generator exhibits great potentials in intravascular imaging due to its miniature size.

7981-42, Session 6a

Magnetic nanoparticle (MNP)-based sensing for environmental applications

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The use of magnetic nanoparticles in microfluidic systems is emerging and is receiving growing attention due to the synergistic advantages of microfluidics and magnetic nanoparticles. Biomagnetic separation techniques based on magnetic nanoparticles are becoming increasingly important with a wide range of possible applications. However, the separation products are difficult to be detected by general method due to the small size of MNPs. Here, we demonstrate magnetic nanoparticles can greatly enhance the signal of surface plasmon resonance spectroscopy (SPR). Features of MNPs-aptamer conjugates as a powerful amplification reagent for ultrasensitive detection are explored. Our results confirm that MNPs is an excellent amplification reagent for SPR based sensing for small toxic molecules in the environment and SPR has a great potential for the detection of magnetic nanoparticles-based

separation products. Finite-element simulation technique is further used to demonstrate the magnetic enhancement and moreover investigate wide range of design parameters involved in the development of novel and efficient magnetically actuated mixing, separation and detection processes on chip. The simulation and experimentation results obtained in this work provided an excellent estimate of the potential to use magnetic nanoparticles for integrated lab-on-a-chip devices.

7981-43, Session 6b

Development of a non-contact PZT excitation and sensing technology via laser

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In recent years, guided wave based structural health monitoring (SHM) techniques have attracted much attention, because they are not only sensitive to small defects but also capable to cover a wide range in plate and pipe like structures. The guided waves in a structure can be generated and sensed by a variety of techniques. This study proposes a new wireless scheme for PZT excitation and sensing where power as well as data can be transmitted via laser. A generated waveform by modulation of a laser is wirelessly transmitted to a photodiode connected to a PZT on the structures. Then, the photodiode converts the light into an electrical signal and excite the PZT and the structure. Then, the reflected response signal received at the same PZT is re-converted into a laser, which is wirelessly transmitted back to another photodiode located in the data acquisition unit for damage diagnosis. The feasibility of the proposed power and data transmission scheme has been experimentally investigated in a laboratory setup. Using the proposed technology, a PZT transducer can be attached to a structure without complex electronic components and a power supply.

7981-44, Session 6b

Impedance-based non-destructive evaluation of the FRP adhesive joints in corrosive environment with re-usable technique

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In this study, a Non-Destructive Evaluation (NDE) method is introduced for evaluating the effects of FRP adhesive joint bond strength subjected to various environmental conditions using Electromechanical impedance (EMI) method. The applicability of Fibre Reinforced Plastics (FRP) as a construction material is being globally recognized for their high stiffness and strength to weight ratio and this method proposes a possibility of detecting any strength loss to the adhesive bond without damaging the structure, such as FRP joint itself. PZT (Lead-Zirconate-Titanate) patches were utilized to detect any changes to the bond strength of the FRP adhesive joint exposed to different kinds of environmental conditions by measuring the electrical admittance of the PZT sensors. In addition, a re-usable technique has been introduced with a utilization of magnet to allow multiple sensing of specimens with a single sensor. The results show a possibility of detecting decrease in the bond strength of FRP adhesive using the EMI method.

7981-45, Session 6b

Impedance-based damage assessment using piezoelectric sensors

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Conventional method to assess the health of structures has to be performed when the operation of structures is stopped, and it needs experts. Therefore there are much time loss and human strength. Moreover it's difficult to prepare the suddenly occurred damage or

impact. To solve these problems, recently structural health monitoring (SHM) systems are being focused because they make real-time assessment possible. SHM systems can be applied in many application fields such as aircraft, aerospace, civil structures and so on.

Piezoelectric materials generate voltage when pressure is applied to them, and their impedance is changed when the impedance of attached structures is changed. Because of these characteristics, piezoelectric materials are widely used for sensors of SHM systems. There are three typical methods to monitor damage, vibration-based, Lamb wave-based and impedance-based method. Impedance-based method is commonly used to monitor damage of critical parts such as bolted joints. Bolted joints could be loosened by vibration, thermal cycling, shock, corrosion, and they cause serious mechanical failures.

In this paper, impedance-based method using piezoelectric sensors was applied for real-time SHM system. Some kinds of specimens were designed as two parts are connected by bolts and piezoelectric sensors are attached close to them. Polymer type piezoelectric materials, PVDFs were used for sensors to monitor the condition of bolted joint connections. The impedances of piezoelectric sensors were measured in several damage cases. Damage cases were assumed as some bolts were loosened. The impedances of damaged structures were compared with healthy structure whose all bolts were fastened.

7981-46, Session 6b

Transient response of smart piezoelectric composite plate using NURBS-based isogeometric analysis

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This research studies the transient response of smart piezoelectric composite plate using NURBS based Isogeometric analysis. First order shear-deformation theory is used for field definition and equations of motion are derived using variation formulation in virtual work sense. Perfect bonding between the layers is assumed. NURBS basis are used to present both the geometry and displacement field variables i.e. Isogeometric analysis. NURBS lower and higher order elements are constructed using internal refinement processes like h , p and k -refinement processes. k -refinement has no analogous in regular finite element. Transient response of smart plate is analyzed under distributed and concentrated loading and for different length to thickness ratios, ply-angles, and boundary conditions. Also, the response is analyzed for various lower and higher order elements, especially, with k -refinement.

7981-47, Session 6b

Active carbon filter health condition detection with piezoelectric wafer active sensors

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The impregnated active carbon used in air purification systems degrades over time due to exposure to contaminations and mechanical effects (packing, settling, flow channeling, etc.). A novel approach is proposed to detect the health condition of impregnated active carbon filters by combining the electromechanical impedance spectroscopy (EMIS) and electrochemical impedance spectroscopy (ECIS). ECIS is currently being used to evaluate active carbon filtration material; however, it cannot differentiate the impedance changes due to chemical contamination from those due to mechanical changes. The electromechanical impedance has been used to measure the coupled high-frequency sensor-structure dynamics in structural health monitoring and biomechanical research. Mechanical properties of the filter (e.g. density, stiffness, apparent viscosity, etc.) will change when contaminated with chemical agents or water, which in turn will change the mechanical impedance. This mechanical impedance change will be detected by the EMIS method and

used to monitor the filter condition and better interpret the ECIS results. Piezoelectric active wafer sensor (PWAS) is used in the EMIS method. Preliminary experimental study has shown that the electromechanical impedance of PWAS embedded in the active carbon filter material will demonstrate peak amplitude and frequency changes when the filter is subject to different level of packing and water absorption. Damage index was also used to provide quantitative measure of these changes.

7981-48, Session 7a

Temperature and stiffness correction of saw devices for wireless strain sensing

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Strain monitoring is a nondestructive inspection method that can reveal anomalous structural behavior. Surface acoustic wave (SAW) devices are small, robust, inexpensive solid-state components in which a wave propagates along the surface of a piezoelectric material. Changes in strain or temperature alter the acoustic wave speed and/or the propagation distance, shifting the pulse arrival time. The IDT (interdigitated transducer, formed by a pattern of electrodes) on a SAW device can be terminated as an antenna and interrogated with a wireless RF probe to act as a passively-powered device with reasonable stand-off distances. We present analytical and experimental studies of SAW devices fabricated on lithium niobate wafers, operated as passively-powered (wireless) strain sensors. We show excellent sensitivity, reproducibility, and linearity when measuring strain at constant temperature, and we develop and test the correction when the elastic stiffness of the SAW device package is not negligible compared to that of the structural specimen. However, changes in ambient outdoor temperature will also produce significant shifts in the pulse arrival time, and therefore temperature compensation is needed if the SAW devices are to have practical application as structural strain sensors. A simple solution would be to incorporate a second SAW device, free to expand or contract with temperature. We present experimental studies of temperature sensitivity and we show new device configurations to implement temperature compensation. We conclude with laboratory tests of strain sensing incorporating temperature compensation.

7981-49, Session 7a

Multidirectional circular microstrip patch antenna strain sensor

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In this paper, a new design for microstrip patch antenna strain sensors is proposed. The new antenna sensor works based on the meandered microstrip patch antennas. It is 3 times more sensitive and 5 times smaller than previously proposed circular microstrip patch antenna strain sensors. The current sensor is able to detect strain in any direction and therefore could be used for wireless applications where a multidirectional scanner must be used, such as wireless structural health monitoring.

In order to reduce the cost and time of the experimental tests to investigate different configurations of the antenna and strain, Finite Element Analysis of the antenna sensor is performed. ANSYS software was chosen for structural Analysis whereas HFSS software was used to derive antennas resonant frequency. However, to combine these two different analyses ANSYS Finite Element Modeller is used to transfer the deformed shape of the antenna from ANSYS to HFSS. As a result, coupled field analysis of the antenna strain sensor made possible. FEA results show good agreement with experimental tests.

To confirm FEA results, a meandered circular microstrip patch antenna was designed and fabricated. A 3-point bend test used to bend the plate while strain and resonant frequency of the antenna was measured at different stages. The results show that this antenna strain sensor is three times more sensitive than previously proposed circular patch antennas. To further investigate the sensitivity of the antenna sensor in different directions, the plate was tested in 0, 45, and 90 degrees bend.

7981-50, Session 7a

RFID-based passive wireless strain sensor

X. Yi, T. Wu, Y. Wang, R. T. Leon, M. M. Tentzeris, Georgia Institute of Technology (United States)

This paper presents a microstrip patch antenna designed for passive and wireless strain sensing. The electromagnetic resonance frequency of the patch antenna is determined by the antenna length, which changes in accordance with the strain experienced by the antenna. A folded design pattern is adopted to form a quarter-wavelength microstrip patch, which helps to reduce the antenna size. Integrated with an off-the-shelf commercial radiofrequency-identification (RFID) chip, the patch antenna can be interrogated by a portable RFID reader. Since the RFID chip is activated by the interrogation signal from the reader, the patch antenna serves as a passive (batteryless) and wireless strain sensor. Design and experimental characterization of the prototype wireless strain sensor are presented.

7981-51, Session 7a

Carbon nanotube sensors integrated inside microfluidic channels for water quality monitoring

Y. Liu, X. Li, M. R. Dokmeci, M. L. Wang, Northeastern Univ. (United States)

Single-walled carbon nanotubes (SWNTs) with their unique electrical properties and large surface area are promising materials for the detection of low concentrations of toxic and hazardous chemicals (both from the gaseous and liquid phases). In addition, several SWNT based pH and chemical sensors have been demonstrated. However, most of these nanosensors require bulky external components to test the response of SWNTs to ions in liquid. Here, we report a water quality monitoring sensor composed of SWNTs integrated inside microfluidic channels with on-chip testing components and a wireless transmission board. To detect multiple analytes in water requires the functionalization of SWNTs with different chemistries. In addition, microfluidic channels are needed to isolate the sensors from each other and to guide liquids into the nanotube sensors in an efficient manner. Furthermore, the microfluidic system enables sample mixing, separating multiple components and guiding the liquid flow over SWNTs sensor. To realize the nanosensors, first, microelectrodes were fabricated on an oxidized silicon substrate. Next, PDMS micro channels were fabricated and bonded on to the substrate. These microchannels can be incorporated into a larger micro fluidic system which can be designed to manipulate different analytes for detecting specific molecules. Low temperature, solution based Dielectrophoretic (DEP) assembly was next conducted inside the microfluidic channels and successfully bridged the SWNTs between the microelectrodes. The SWNT pH sensors were next characterized with different pH buffer solutions. The resistance of SWNTs displayed a linear increase when the pH values were varied from 5 to 8. The SWNT nanosensors integrated with a microfluidic system is a versatile platform and can be utilized to detect numerous water pollutants, including toxic organics (TNT, DMMP) and microorganisms (E. coli) down to low concentrations. On-chip processing and wireless transmission enables the realization of a full autonomous system for real time monitoring of water quality.

7981-52, Session 7a

Unified experimental observation of dynamic vehicle-bridge interactions by wireless telemetry

J. Kim, J. P. Lynch, Univ. of Michigan (United States); J. Lee, Sejong Univ. (Korea, Republic of); C. Lee, Korea Expressway Corp. (Korea, Republic of)

Bridges constantly undergo complex dynamic behavior due to the interaction between vehicles and the underlying bridge. Traditionally, finite element method (FEM) models for bridges and vehicles have been intensively studied to analytically explore vehicle-bridge interaction. Reliance on FEM models is largely due to the numerous challenges inherent to observation in the field. Foremost among the challenges is that unified measurement of two different systems, i.e., mobile vehicles and bridges, is challenging due to limitations of existing cable-based sensor technologies. Thus, most experimental studies have been limited to monitoring the bridge and not the vehicle. However, the recent emergence of wireless sensors in the field of structural health monitoring has created opportunities for directly monitoring vehicle-bridge interaction within a single, unified wireless monitoring system. In this study, mobile wireless sensors with long-range radio communication capabilities are leveraged to monitor the dynamics of a test vehicle as it crosses a bridge. The integration of mobile vehicle-based wireless sensor nodes with a static wireless monitoring system provide time-synchronized input-output bridge response data which will serve as the basis of the observation of complex vehicle-bridge interactions. Experimental testing of the wireless sensor network on the GeumDang Bridge (Icheon, Korea) is presented in this paper.

7981-53, Session 7b

Assessing corrosion rate in prestressed concrete with acoustic emission

J. D. Mangual, M. K. ElBatanouny, P. H. Ziehl, F. Matta, Univ. of South Carolina (United States); M. A. Gonzalez, MISTRAS Group, Inc. (United States)

In the present research, Acoustic Emission (AE) sensing is employed to assess the presence and rate of steel corrosion evolving inside reinforced concrete samples. Test setup consists of grade 4,000 psi concrete blocks with dimensions 4.5 x 4.5 x 20 inch (114 x 114 x 508 mm); a 30 inch (760 mm) long - 1/2 inch (13 mm) diameter strand was embedded in the concrete to serve as anode of the rapid corrosion cell. Samples were either notched or unnotched and 0.016 inch (0.4 mm) cracks were extended through the centerline of the samples via three-point bending to analyze the effect of crack presence in byproduct development. The corrosion process is accelerated in a laboratory environment employing a potentiostat to supply a constant potential difference, 3% NaCl solution as electrolyte, and a copper plate beneath the concrete samples served as a cathode. In addition, a series of T-beams measuring 16 ft-4 in (2,350 mm) will be corroded at different levels, then tested under four-point bending to determine the effect of corrosion on the members load bearing capacity. Galvanic current, half-cell potential readings and AE activity are recorded continuously during the duration of each test and are compared to determine the most efficient non-destructive method towards accurately detecting the presence of corrosion in steel reinforced elements. At the end of each test, the blocks are taken apart and the steel strands are cleaned and re-weighted to determine the mass loss and use it as base of comparison with the AE data gathered. The initiation and propagation stages of corrosion are correlated with the percentage mass loss of steel and the energy acquired from the AE signal; this relation will be effective towards determining the residual service life of concrete structures in the field. Finally, locations of possible corroded areas are determined using the source triangulation option provided by AE technique. This work is performed under the support of

the U.S. Department of Commerce, National Institute of Standards and Technology, Technology Innovation Program, Cooperative Agreement Number 70NANB9H9007.

7981-54, Session 7b

Steel reinforcement corrosion detection with coaxial cable sensors

I. Muchaidze, Missouri Univ. of Science and Technology (United States)

Corrosion processes in the steel reinforced structures may result in structural deficiency and with time create a threat to human lives. Millions of dollars are lost each year because of corrosion. According to Highway Research Program (SHRP) in the United States the average annual cost of corrosion is about \$\$(8.3 billion). Timely remediation/ retrofit and effective maintenance can extend the structure's live span for much less expense. Thus the considerable effort should be done to deploy corrosion monitoring techniques to have realistic information on the location and the severity of damage. Nowadays commercially available techniques for corrosion monitoring require costly equipment and certain interpretational skills. In addition, none of them is designed for the real time quality assessment. In this study the crack sensor developed at Missouri University of Science and Technology is proposed as a distributed sensor for real time corrosion monitoring. Implementation of this technology may ease the pressure on the bridge owners restrained with the federal budget by allowing the timely remediation with the minimal financial as well as labor expense. The sensor is instrumented in such a way that the location of any discontinuity developed along its length can be easily detected. When the sensor is placed in immediate vicinity to the steel reinforcement it is subjected to the same chemical processes as the steel reinforcement. And corrosion pitting is expected to develop on the sensor exactly at the same location as in the rebar. Thus it is expected to be an effective tool for active corrosion zones detection within RC members.

A series of laboratory tests were conducted to validate the effectiveness of the proposed methodology. Nine sensors were manufactured and placed in the artificially created corrosive environment and observed over the time. To induce accelerated corrosion 3% and 5% NaCl solutions were used. Based on the test results, the proposed/corrosion distributed sensor is capable of delivering fairly accurate information on the location of a discontinuity along the sensor caused by corrosion pitting. Forensic study was also conducted to validate the concept.

In order to test the sensors in real live condition, 27 sensors were prepared to be placed into reinforced concrete beams. The beams will be subjected to corrosive environment. After that the sensors will be monitored over the time for signs of corrosion.

7981-55, Session 7b

Structural monitoring of a historic bell tower with synchronized wireless sensor networks

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Structural monitoring is in an increasingly important part of the maintenance of many historic structures. With the implementation of wireless sensors, this monitoring can be accomplished with minimal disruption to the aesthetics and functionally of these culturally important buildings. In this study, Altgeld Hall Bell Tower, a historic masonry structure built in 1897 on the campus of the University of Illinois, is monitored with wireless smart sensors fitted with accelerometers. Monitoring of structures with wireless sensor networks has inherent challenges including communication, synchronization, and low vibration levels. Because of poor communication between the wireless sensors at different levels of the bell tower, two independent networks of wireless sensors were necessary to monitor this structure. Data from these networks were combined together in post processing to produce a highly

synchronized data set for the whole structure, which was then used for modal analysis. The low vibration level of the tower under wind loading prevented ambient vibration data from producing high quality modal analysis results. Consequently, two input sources, ringing of the tower's bells and hammer strikes, were used to excite the structure. Results from these two input sources are compared and the quality of the modal analysis using synchronized wireless sensor networks in this historic structure is discussed.

7981-56, Session 7b

Development of fast wireless detection system for fixed offshore platform

Y. Yu, J. Wang, Z. Li, J. Ou, Dalian Univ. of Technology (China)

This project presents a new kind of fast wireless detection and damage diagnosis system for fixed offshore platform using wireless sensor networks, that is, wireless sensor nodes can be put quickly on the offshore platform, detect offshore platform structure global status by wireless communication, and then make diagnosis. This system is operated simply, suitable for offshore platform integrity states rapid assessment.

The designed system consists in intelligence acquisition equipment and 8 wireless collection nodes, the whole system has 64 collection channels, namely every wireless collection node has eight 16-bit accuracy of A/D channels. Wireless collection node, integrated with vibration sensing unit, embedded low-power micro-processing unit, wireless transceiver unit, large-capacity power unit, and GPS time synchronization unit, can finish the functions such as vibration data collection, initial analysis, data storage, data wireless transmission. Intelligence acquisition equipment, integrated with high-performance computation unit, wireless transceiver unit, mobile power unit and embedded data analysis software, can totally control multi-wireless collection nodes, receive and analyze data, parameter identification. Data is transmitted at the 2.4GHz wireless communication channel, every sensing data channel in charge of data transmission is in a stable frequency band, control channel responsible for the control of power parameters is in a public frequency band. The test is initially conducted for the designed system, experimental results show that the system has good application prospects and practical value with fast arrangement, high sampling rate, high resolution, capacity of low frequency detection.

7981-57, Session 7b

Wireless monitoring of the longitudinal displacement of a suspension bridge deck under changing environmental conditions

N. de Battista, R. Westgate, K. Y. Koo, J. M. Brownjohn, The Univ. of Sheffield (United Kingdom)

In order to be able to monitor the health of a civil structure it is essential to understand how it behaves under different environmental conditions. It is a well documented fact that the dynamic properties of bridges and other structures are altered considerably when they are subjected to changes in environmental conditions. This paper describes a study investigating the longitudinal movements of the road deck on Tamar Bridge in Plymouth, U.K. over a number of months. The expansion joint of the bridge deck was instrumented with two pull-wire type extensometers. The data was transmitted wirelessly using commercial wireless sensor nodes and collected at a data acquisition PC that was available online for remote monitoring. In addition, displacement data of various locations on the bridge deck were collected using a Robotic Total Station (RTS). Environmental data, such as the temperature and wind speed, and the number of vehicles crossing the bridge was acquired from other monitoring systems. A comparison of the bridge deck's longitudinal displacement with respect to different environmental conditions is demonstrated in this paper, showing a clear correlation between the two sets of data.

7981-58, Session 7b

Imote2-based multi-channel wireless impedance sensor nodes for local SHM of structural connections

K. D. Nguyen, J. Park, J. Kim, Pukyong National Univ. (Korea, Republic of)

This paper presents a technique for local structural health monitoring (SHM) of structural connections by using multi-channel wireless impedance sensor nodes based on Imote2 platform. To achieve the objective, following approaches are implemented. Firstly, an Imote2-based multi-channel wireless impedance sensor node is designed for cost-efficient SHM of structural connections. Secondly, an interface washer associate with impedance measurements is designed to monitor the bearing stress which is considered as main effect on structural connections. Thirdly, a damage monitoring method for structures with multiple connections is proposed and embedded in the wireless impedance sensor node to examine the strength of each individual connection. Finally, the performance of multi-channel wireless impedance sensor node is experimentally validated for a girder connection model.

7981-178, Poster Session

Smart and comprehensive structural health monitoring solution

P. Kung, QPS Photonics Inc. (Canada)

A novel sensor, called VibroFiber™ sensor, recently is developed by QPS Photonics, which actually is an FBG-based twin grating interferometer sensor. In comparison with FBG sensors, this novel sensor can output analog signals; it has improved accuracy and sensitivity as well as high-speed response for measurements of vibrations and dynamic strains. Now VibroFiber™ sensors mainly are used in the field of high power turbine generators for condition monitoring of Stator End windings in generators like hydro, Gas and coal fired generator. Another version of the technology has been adapted to become a comprehensive solution for the wind turbines, very similar in structure to what will be discussed in this paper: its backbone is based on the novel architecture of multi-process interrogation system, VibroFiber™ sensors also can be developed to form a sensor network capable of simultaneously measuring vibration, temperature and dynamic strain, chloride sensors, corrosion sensing, crack sensing via acoustic emission which provides the good foundation for an all-aspect border security monitoring, for Civil or aerospace applications. This is because VibroFiber™ sensors can be expanded into a serially connected chain of multi-function sensor each chain can support up to 30 sensors or more. In fact the VibroFiber™ sensor technology has many attractive performances and potentials employed in other fields, such as border security and wind energy generation system. Besides being long life, consuming no power, built into the technology is a self calibrating function: sensors do not need to be removed for calibration for the next 25 years.

7981-179, Poster Session

Traffic monitoring and weight measurement using fiber optic microbend sensor

N. Naorin, North South Univ. (Bangladesh)

In this work we are proposing a method for monitoring vehicle traffic and vehicle weight measurement in highway. Our proposed method includes calibration of a fiber optic microbend pressure sensor that is placed on any specific lane of highways. If a fiber is subjected to small deformation, light passing through the fiber is forced to move out the core, into the fiber cladding causing light intensity loss. When the fiber is subjected to periodically positioned deformed, loss caused by the deformed is drastically increased. By monitoring the intensity loss caused by the

deformed various types of microbend sensors can be designed. The light transmission loss of the fiber due to different weight specimens is measured in laboratory and graphically plotted. A software program has been written for this project where this microbend pressure sensor can be used for real time vehicle weight measurement in highways. In the simulation part randomly generated vehicles cross a specific fiber optic microbend sensor. Individual vehicle weight, crossing time, time spent on the sensor for each crossing vehicle can be monitored. The program simulates for a specific time and after that it concludes the nature of the traffic pattern. The simulation shows graphical representation of individual vehicle information that has been previously monitored along with the result of the traffic pattern such as heavy congestion, light congestion, congestion free road. The objective of this research is to distinguish congestion-free road from the opposite.

7981-180, Poster Session

Relative-story displacement sensor for measuring five-degree-of-freedom movement of building layers

I. Matsuya, Waseda Univ. (Japan); R. Katamura, Kajima Corp. (Japan); M. Sato, M. Iba, H. Kondo, K. Kanekawa, Waseda Univ. (Japan); M. Takahashi, T. Hatada, Kajima Corp. (Japan); Y. Nitta, Ashikaga Institute of Technology (Japan); T. Tanii, S. Shoji, A. Nishitani, I. Ohdomari, Waseda Univ. (Japan)

Recently, relative-story displacement measurement attracts much attention because of its capability of directly monitoring damages of a building structure. It is, however, difficult to measure precise relative-story displacement because the detector is inclined due to the floor bending during earthquake. In order to resolve this issue, we have developed a relative-story displacement sensor which is capable of 5-degree-of-freedom (DOF) measurement for structural health monitoring. Three pairs of position sensitive detector (PSD) units were used for measuring the relative-story displacement, the inclination angle of the floor, and the torsion angle of the ceiling simultaneously. For verification, laboratory tests were carried out using an Xθ-stage and a shaking table. In the static experiment, it is verified that the inclination angle of the detector can be measured as well as the displacement by this measurement. The resolution of the sensor system in the displacement measurement was evaluated to be 0.0958 mm, and that in the inclination angle measurement was evaluated to be 25.5 μrad. In the dynamic experiment, the accuracy of the sensor system was experimentally evaluated to be approximately 0.15 mm in the relative displacement measurement and 0.1 mrad in the inclination angle measurement. These results indicate that the developed sensor achieves sufficient accuracy for the measurement of relative-story displacement and inclination angle.

7981-181, Poster Session

Comparison of embedded, surface bonded, and reusable piezoelectric transducers for monitoring of concrete structures

B. Sabet Divsholi, Y. Yang, Nanyang Technological Univ. (Singapore)

Piezoelectric lead zirconate titanate (PZT) transducers have been used for health monitoring of various structures over the last two decades. There are three methods to connect PZT transducers to structures, namely, surface bonded, reusable setup and embedded PZTs. Embedded PZTs and reusable PZT setups can be used for structures under construction. On the other hand, surface bonded PZTs can be installed on existing structures. In this study, the applicability and limitations of each method is experimentally studied. A real size concrete structure is cast, where surface bonded, reusable setup and embedded PZTs are installed. Monitoring of concrete hydration and structural damage is conducted by the electromechanical impedance (EMI) method and the

pitch catch method. It is observed that embedded PZTs are suitable for monitoring the hydration of concrete through both the EMI method and the pitch catch method. For damage detection in concrete structures, the embedded PZTs can be used with the pitch catch method, but they are not suitable for the EMI technique. It is also found that the surface bonded PZTs are sensitive for damage detection through both the EMI and pitch catch method. The reusable PZT setups are able to monitor the hydration of concrete. However they are less sensitive in damage detection in comparison to the surface bonded PZTs.

7981-182, Poster Session

Development of micro-pump for bio-MEMS by using new bio-compatible piezoelectric material MgSiO₃

N. Okamoto, H. Hwang, Y. Morita, E. Nakamachi, Doshisha Univ. (Japan)

Recently, the micro fluid system has been widely studied to use for Bio-MEMS, which includes Drag Delivery System (DDS) and Health Monitoring System (HMS). The micro-pump is important element to transport a very few amount fluid for DDS and HMS. The piezoelectric thin film pump is applied to the micro-pump due to high reactivity and strong driving force. Now, PbTiO₃ and Pb(Zr,Ti)O₃ have been applied to thin film pump as the driving source due to their very high piezoelectricity. However, they have toxic substance for the human body and the environment because of lead. We try to generate the micro-pump for Bio-MEMS by using a new bio-compatible piezoelectric thin film.

At first, we generate MgSiO₃ thin film on Ti and Cu buffer layer and Si(100) substrate by using RF-magnetron sputtering method. We measured crystallography orientation by using X-ray diffractometer and piezoelectric property by the ferroelectric measurement system. We confirmed that MgSiO₃(101) crystal has been generated on Cu/Ti/Si(110) substrate. Its displacement-voltage curve indicated the typical butterfly type hysteresis loop, which means MgSiO₃(101) thin film had piezoelectricity. The piezoelectric strain constant d₃₃ was calculated by using the displacement-voltage curve, such as 179.4pm/V. Then, we carried out the performance assessment of our piezoelectric thin film pump of a newly designed micro-fluid system by using finite element method, which can consider the interaction between the piezoelectric solid and the fluid. The result of numerical analysis shows a enough transportation ability of our micro-pump, such as a flow rate of 3.1nl/s. Further, we fabricate the MSO piezoelectric monomorph-actuator type pump by using the micro-fabrication technology. The deflection under the voltage loading was calculated as 730.4 pm/V. We conclude that a new bio-compatible MSO thin film pump has a enough ability of fluid transportation in Bio-MEMS.

7981-183, Poster Session

Prediction of pavement friction with high definition CCD laser and genetic programming

S. Chen, J. Lin, C. Hung, J. Zheng, W. Chao, Feng Chia Univ. (Taiwan)

Pavement texture is the most important factor to affect its friction. Although Sand Patch approach is popularly used, its accuracy is doubted. Based on above, the study tried to measure surface texture with new technology and develops a friction prediction model with various methods. Firstly, mixture were prepared in laboratory and compacted by pavement roller. All the specimens were 50cm×50cm×5cm and about 30 kg. Compaction control processes adopt the electronic field pavement instrument to make sure its density. Before test, every specimen should be curing one day. High Definition Circular Texture Meter (HDCTM) was adopted to measure Dense Grade Asphalt Concrete (DGAC) and Stone Mastic Asphalt (SMA). HDCTM is not only confirmed with ASTM E2157, but also its resolution is ten times of conventional CTM. British pendulum Tester was relatively used to evaluate surface

friction. The correlation coefficient between mean texture depth of Sand patch and mean pavement depth of HDCTM is 0.87. HDCTM should be an option to replace Sand Patch. According to Results, the texture parameters have high positive relative with British Pendulum Number (BPN). But linear regression approach is not enough to explain the relationship with BPN and texture. The relationship is supposed not be a linear mode. Genetic programming is used to discover their nonlinear correlation. Sum of positive deep texture depth and sum of positive shallow texture depth have great prediction ability to dry and wet friction of DGAC and SMA with GP. All R-Square are above 0.7 and Mean Absolute Percent Error were also less than 4%. Compared with linear regression, GP should be better method on this topic. The results demonstrate the combination HDCTM and GP to develop a friction forecast model is remarkable. It is worth further studying.

7981-184, Poster Session

Vibration-based structural health monitoring of harbor caisson structure

S. Y. Lee, S. Lee, J. Kim, Pukyong National Univ. (Korea, Republic of)

In this study, the vibration-based damage detection methods in foundation-structure interface of harbor caisson structure are analyzed. In order to achieve the objective, the following approaches are implemented. Firstly, vibration-based damage detection method is considered to choose the method which is more efficient to detect damages on caisson structures. Secondly, finite element analysis on a lab-scaled harbor caisson is performed. Free-vibration analysis and forced-vibration analysis are implemented to determine target frequency range for experimental test and to examine performance of selected vibration analysis methods numerically, respectively. Thirdly, dynamic test on a lab-scaled harbor caisson structure which is on foundation mound are performed to examine performance of selected vibration analysis methods experimentally. Finally, performance of vibration analysis methods is examined based on the numerical and experimental results.

7981-185, Poster Session

Mechanical monolithic tiltmeter for low frequency measurements

F. Acernese, Univ. degli Studi di Salerno (Italy); R. De Rosa, Univ. degli Studi di Napoli Federico II (Italy); G. Giordano, R. Romano, S. Vilasi, F. Barone, Univ. degli Studi di Salerno (Italy)

The paper describes the application of a monolithic folded pendulum (FP) as a tiltmeter for geophysical applications, developed at the University of Salerno. Both the theoretical model and the experimental results of a tunable mechanical monolithic FP tiltmeter prototype are presented and discussed. Some of the most important characteristics, like the possibility of tuning its resonance frequency to values as low as 70 mHz and its measured resolution better than 0.1 nrad at 100 mHz, are detailed. Among the scientific results, earth tilt tides have been already observed with a monolithic FP tiltmeter prototype

7981-186, Poster Session

Mechanical monolithic sensors for mechanical damping of a suspended mass

F. Acernese, Univ. degli Studi di Salerno (Italy); R. De Rosa, Univ. degli Studi di Napoli Federico II (Italy); G. Giordano, R. Romano, S. Vilasi, F. Barone, Univ. degli Studi di Salerno (Italy)

In this paper we present the control system we implemented for test the control of a suspended mass using monolithic tunable folded pendulum sensors in the band 0.01 - 100 Hz. The main goal of this experiment is to

test the performances of monolithic sensors as main acceleration sensors for application in inertial damping control systems. The main advantages of these sensors with respect to the others are the sensitivity (better than $10^{-11} \text{m/s}^2/\sqrt{\text{Hz}}$ in the band 0.1 - 10 Hz), the large band (0.01 - 100 Hz), the tunability of the resonance frequency (necessary to match the sensors to the suspension mechanics) and the high sensitive integrated laser optical readout, consisting of an optical lever and an interferometer, and a very good immunity to environmental noises. Preliminary results are presented and discussed in this paper together with the planned further developments and improvements of monolithic sensors.

7981-187, Poster Session

Development of a tilt meter based on a hetero-core fiber optic sensor

Y. Honda, Soka Univ. (Japan)

In recent years, a sediment disaster has occurred a serious damage all over the world. Especially, landslides due to earthquake and heavy rain could induce the fatal damage for human daily activities.

It is necessary to observe a ground condition on a slope by means of installing a sensor, which can detect the danger to prevent these damages from disasters.

On the other hand, an optical fiber sensor has several advantages such as resistance to corrosion and immunity of electromagnetic interference. Additionally, a hetero-core fiber optic sensor that we have proposed can detect the moderate bending action of the sensor portion with high sensitivity and independency on temperature fluctuation, and the transmission line is unaffected to external disturbance because of its single-mode stable propagation scheme. Therefore, the hetero-core fiber sensor could be suited for the landslides detection in the fields such as mountains.

In this paper, we propose a tilt meter based on a hetero-core optical fiber sensor. In order to convert the tilt action to the bending action of hetero-core portion, the hetero-core portion is located between two clampers in the developed tilt meter. The distance between two clampers is changed with the tilt angle by means of the structure of the pendulum with a weight and a bearing. The inclination characteristic of hetero-core fiber tilt meter indicated a monotonic optical loss change of approximately 4.0 dB with the tilt angle ranging of 0 - 30 degrees.

7981-188, Poster Session

Development of an optical fiber sensor to monitoring the formation of cracks in concrete structures

K. Rodriguez Carmona, A. Márquez Lucero, Ctr. de Investigación en Materiales Avanzados, S.C. (Mexico)

The Interest in the supervision of structures in civil engineering has been growing constantly in order to improve the durability and safety of those structures. Because of this, development of fiber optic sensors has been researched for a number of engineering applications. One of these applications is the continuous supervision of crack formation into concrete structures. Indeed, Many times when a fissure in a concrete structure is discovered it is too late because the fissure has already propagated. Because of this, a fiber optic sensor for detecting fissures at their origin has been developed in this work. This type of continuous supervision has many advantages when compared to visual inspection. This is because visual inspections sometimes cannot detect fissures inside a structure unless these fissures propagate to the surface, which many times cause irreparable damage. The continuous supervision of optical sensors allows the permanent monitoring of the condition of a structure. These sensors are recommended for structures that have variable loads such as bridges and dams. The ability of permanently monitor a structure has been recognized as an important development in the supervision of civil infrastructure. The goal of developing this type

of sensor is to monitor the formation of fissures in their initial stages before they propagate and, in this way, avoid the failure of a structure. The sensor is of a multimode fiber mark Thorlabs, this sensor has a form geometric sinusoidally with small curve radii. The behavior of the optical signal of the sensor is monitored with the OTDR equipment.

7981-189, Poster Session

Damage detection in prestressed pile to bent cap connections

A. K. Larosche, Univ. of South Carolina (United States)

South Carolina is one of the most seismically active states in the eastern U.S. Due to this high level of seismic activity, structural health monitoring is important for ensuring a high level of confidence in the South Carolina Highway infrastructure. The University of South Carolina is currently studying the behavior of prestressed pile to bent-cap connections that are typical of construction used in the state. Typically bent caps are constructed with multiple piles. In these tests single pile specimens were created for both Interior and Exterior piles. Interior piles were subject to a constant compressive load while Exterior specimens experienced both compressive and tensile loads. Acoustic Emission (AE) sensing has been utilized on full-scale test specimens to investigate the feasibility of detecting and characterizing damage in these connections during a seismic event. Seven full-scale prestressed concrete piles have been embedded into cast-in-place (CIP) reinforced concrete bent caps and tested under reverse cyclic loading. AE data has been gathered with eight strategically placed AE sensors. The AE data received is promising with respect to the detection of damage prior to detection by visual observation. AE activity is used to detect both the onset and location of cracking and to characterize the extent of damage at later stages of degradation. One focus of the work is to minimize the amount of AE data recorded for the development of wireless systems with low power consumption.

7981-191, Poster Session

Structural damage identification using adaptive immune clonal selection algorithm and acceleration data

R. Li, A. Mita, Keio Univ. (Japan)

In order to identify the damage of civil engineering structures precisely and efficiently, a new approach for damage identification by employing Adaptive Immune Clonal Selection Algorithm (AICSA) is proposed. By utilizing secondary response, adaptive mutation regulation and vaccination operator, AICSA achieves the dynamic control of evolution process, which realizes global optimal computing combined with the local searching. It is a non-destructive testing technique inspired by natural immune system which can be used to develop a new, efficient and simple damage identification method for civil engineering structures. The fundamental idea of the adaptive immune clonal selection algorithm is to use acceleration response before damage as training data to determine the detectors to evaluate the test data. For the measured structural vibration responses data always contain noise. The output inevitably has some errors when the data with noise is inputted into the identification system. The proposed approach was enhanced to have stability against such noise by considering variations in signals. The results of numerical simulations show that our proposed approach can indeed identify the structural damage for shear frame structures using only acceleration before and after damage. Finally, a series of vibration experiments for the 8-storey shear frame structure were performed to verify the performance of our proposed approach. Compared with basic clonal selection algorithm, AICSA improves convergence rate and global optimum searching ability. The experimental results show that AICSA can efficiently and precisely identify single and multiple damages of civil engineering structures respect to different damage location, extent and measurement noise.

7981-192, Poster Session

Hybrid structural health monitoring method for girder connections using wireless acceleration and impedance sensor nodes

D. Hong, P. Lee, J. Kim, Pukyong National Univ. (Korea, Republic of)

The wireless sensor nodes are designed for global acceleration-based monitoring and local impedance-based monitoring of girder connections. Thus, the performance of the wireless sensor nodes is examined in the manner of hybrid structural health monitoring (SHM) at the same moment of structural operation. To achieve the objective, the following approaches are implemented. First, the methodology of the hybrid SHM is described in parallel with global acceleration-based monitoring and local impedance-based monitoring. Second, the wireless sensor nodes that enable acceleration and impedance measurements is described on the design of hardware components and embedded software to operate. Third, the performance of the wireless sensor node for hybrid SHM in girder connections is analyzed experimentally.

7981-194, Poster Session

Recognition of flow in everyday life using sensor agent robot with laser range finder

M. Goshima, A. Mita, Keio Univ. (Japan)

We would like to establish a life environment system that is adaptive to each life style. "Biofied living space" is a more advanced space than the intelligent space, and is the key to realize such a system.

Flow in everyday life is essential information to design a living space. However, most designers rely on their experience and literatures. They don't use quantitative data on flow, taken from real life.

Recently, flow in everyday life is recognized by experiment. The tester, who carries with him a RFID reader, lives in an experimental living space embedded with many RFID tags under the floor. However, it is a burden for the tester.

We focus on establishment of recognition of flow in everyday life using sensor agent robot. Rather than using information by many sensors embedded in the rooms, using the robot has many merits. It can get flow by tracking human and reflect the results on the floor map. It is noted that information about tracking and mapping is synchronized. This robot has following functions, mapping, localization of the robot, human tracking and visualization of robot's movement.

In this paper, we propose floor mapping algorithm for recognition of life flow using laser range finder installed on the robot. Extensive experiments are conducted to test its feasibility.

7981-195, Poster Session

Recognition of human emotion using sensor agent robot for interactive and adaptive living spaces

S. Murata, A. Mita, Keio Univ. (Japan)

Recently, safer, more comfortable and energy-efficient living spaces are needed. However, most buildings are designed based on prescribed scenarios so that they do not act on abrupt changes of environments. We propose "Biofication of Living Spaces" that has functions of learning occupants' lifestyles and taking actions based on collected information. By doing so, we can incorporate the high adaptability to the building.

Our goal is to make living spaces more "comfortable". However, human beings have emotion that implies the meaning of "comfortable" depends on each individual. Therefore our study focuses on recognition of human emotion. We suggest using robots as sensor agents. By using robots

equipped with various sensors, they can interact with occupants and environment. We developed a sensor agent robot called "e-Bio". The e-Bio has proximity sensors, microphones, acceleration sensors and a camera.

As the first step of our study, robots should track occupants to get data when occupants move. To do that, we use laser range finder (LRF). LRF is to know the angle and range of objects from that. Second step is data analysis to recognize occupants' emotion. We decide to use sound data such as voice and footsteps. We filter out the background noise and extract their feature. Next, we divide emotion into some levels and recognize occupant's feelings in each situation using stored learning data. Finally, we get threshold value depending on situations, different people and sexuality. As a result, our research goal is to realize a space that reacts on occupant's emotion.

7981-196, Poster Session

Real-time soil deformation monitoring through laser-based deflection measurements

R. Bearce, Colorado School of Mines (United States); C. Rudkin, U.S. Bureau of Reclamation (United States); S. Kimmel, M. Mooney, Colorado School of Mines (United States)

Soil compaction monitoring is a critical technology in almost all earthworks projects, including roadways, earth dams, and levees. Current methods for soil compaction monitoring require testing with a device disconnected from the compaction machine that halts production and provides sparse coverage, e.g., 0.1% of the soil is tested. Real-time measurement of soil properties during compaction offers several advantages in the construction industry. A real-time roller compactor-integrated measurement system not only provides more comprehensive soil stiffness measurement than standard spot testing, but also provides a feedback control for the operator (i.e. operator can in real-time identify softer/stiffer zones). This system potentially saves time and machine wear, and eliminates the need for post-compaction spot testing. In large scale static soil compaction, pad foot rollers are used to "knead" soils over several passes, creating indentations in the soil surface. The depth of these indentations is directly correlated to the soil stiffness. In uncompacted soil, roller induced deflections can be as large as 14 cm. As compaction occurs, the roller induced deflections become progressively smaller until the soil is compacted (i.e. deflections around 1-2 cm). A laser-based measurement system has been developed to characterize the deflections caused by a pad foot roller in order to estimate soil compaction and soil stiffness during compaction. The laser sensors were selected to be rugged enough for field operation and capable of measuring a variable soil surface while traveling at the speed of the roller. The location of the laser sensors was selected to measure specific deflections, and custom hardware was fabricated to attach the lasers to the roller. In addition, the laser measured deflections were synchronized with GPS-measured position to provide a spatial reference. The system was implemented on a commercially-available padfoot roller compactor and evaluated in a series of field tests. To validate the system, small scale field tests were conducted where individual laser-measured deflections were compared to hand measured deflections. It was shown that the system was capable of measuring pad indentations to within + 2.5 mm of the hand measured values. Large scale field testing was performed on four test beds of granular soil with varying moisture content. Laser data was recorded while the roller made several passes over each test bed. Data for each pass was compared to spot tests measuring density, moisture content, and light weight deflectometer (LWD) modulus. The results of these tests showed that the laser measured deflection generally agreed with soil density tests, which are a good measure of soil compaction.

7981-197, Poster Session

Real-time soil compaction monitoring through integrated machine strain measurements: modelling to inform strain gage placement on machine

S. Kimmel, M. Mooney, Colorado School of Mines (United States)

Soil compaction monitoring is a critical technology in almost all earthworks projects, including roadways, earth dams, and levees. Current methods for soil compaction monitoring require testing with a device independent to the compaction machine that halts production and provides sparse coverage, i.e., less than 0.1% of soil is tested. A system has been developed for static padfoot rollers that will monitor compaction using the compaction machine, providing feedback in real-time and vastly increasing coverage. The proposed system works by measuring strains generated within the pads of static padfoot soil compactors during operation. As the pads compact the soil, they are themselves loaded, and deform as a result. Strain measurements can potentially be used to monitor the level of compaction, as well as extract mechanical soil properties such as stiffness and modulus. The crux of this research lies in how to position the strain sensors in the pad and how to interpret the measurements at those locations in order to extract desired soil properties. Modelling can be used as a tool to investigate the nature of machine-soil interaction. Here, a Finite Element Model (FEM) was developed and used as an analysis tool to determine desirable locations for strain gages on a soil compactor pad. The goal of this analysis was to identify strain sensor locations that assisted in the extraction of total normal force and contact stress distribution, both of which are necessary for determining desired soil properties. The strain fields in the pad were investigated with the model by applying various contact pressure distributions and load magnitudes to the pad that would be representative of possible soil conditions. Soil behavior theory predicts different contact stress distributions for different soils, i.e. granular soils exhibit parabolic distributions while cohesive soils exhibit inverse parabolic distribution. Additionally, contact stress distribution for a given soil changes with load, i.e. the gradient becomes steeper. Strain gage placements of interest were identified by (a) sufficient magnitude of strain exists for measurement, (b) strain sensitivity to force, and (c) strain sensitivity to contact pressure distribution. From the model analysis, twelve locations were chosen to be instrumented. All locations exhibited sufficient strain magnitude to be measured, five exhibited sensitivity to force without heavy influence of contact pressure distribution, and seven exhibited high sensitivity to contact pressure distribution and force. The pad was instrumented with strain gages at the chosen locations and tested experimentally in the lab. The lab results supported the modeling analysis, in that the chosen gage locations were sensitive to force and contact stress distribution in a manner consistent with that shown in the model. These results show great promise for using a pad as a soil compaction monitoring tool.

7981-198, Poster Session

Effects of rolling-induced anisotropy and precipitate chemistry on fatigue crack initiation and short crack propagation in Al 2024-T351 under uniaxial state of stress

A. Makas, P. Peralta, Arizona State Univ. (United States)

The influence of rolling-induced anisotropy on fatigue properties is important for the prediction of useful life of aerospace structures via computational modeling. In this work, fatigue behavior is studied using notched uniaxial samples with load axes along either the longitudinal or transverse direction, where local composition and crystallography are quantified using Energy Dispersive Spectroscopy and Electron Backscattering Diffraction. Subsequently, interrupted fatigue testing at stresses close to yielding is performed on the samples to nucleate and propagate short fatigue cracks and nucleation sites are located and

characterized using standard optical and Scanning Electron Microscopy. Experimental results shall be used to calculate statistics on fatigue performance in both orientations. Early results indicate transverse direction has higher fatigue strength, conversely, the longitudinal samples experience multisite cracking which leads to crack coalescence at higher cycle counts possibly leading to lower fatigue strength in these samples. Transverse samples also experience a larger variance in cycles till crack in the matrix and cycles till crack reaches 1 millimeter. Moreover, chemical composition of critical precipitates shall be quantified to observe effects precipitate chemistry has on fatigue behavior. Early results indicate that iron rich precipitates break first and propagate cracks into the matrix. The chemistry profiles obtained from in-situ precipitates shall be used to construct test samples for mechanical testing to obtain material performance parameters for the precipitates. Work funded by Department of Defense, AFOSR Grant FA95550-06-1-0309, David Stargel program manager.

7981-199, Poster Session

Application of a decentralized damage detection method to large scale shake table tests

Z. Xing, A. Mita, Keio Univ. (Japan)

A damage detection method that allows for the decentralized damage detection for shear building structure was applied in large scale shake table tests. This method requires only three sensors to identify the localized damage in any story of a building structure. A substructure method was used in this method to divide a complete structure into several substructures. Thus each substructure has a considerably smaller number of degrees of freedom (DOFs) when compared with the entire structure, which also means that the number of unknown parameters for each substructure is very small. The smaller number of the unknown parameters makes fewer requirements on the computing power of the data processing system and the computation time needed will be reduced significantly. Moreover the damage detection process can be independently conducted on each substructure since every substructure is independent. For each substructure, we use an autoregressive-moving average with exogenous inputs (ARMAX) model to extract the modal information. The extent of damage is measured by using the squared original frequency and the squared damaged frequency. In this method, every substructure can be analyzed simultaneously and independently. Application of this damage detection method was carried out by large scale shake table tests. The experimental results showed that this method worked very well.

7981-200, Poster Session

Asset health monitors-development, sustainment, advancement

F. Mauss, Pacific Northwest National Lab. (United States)

PNNL has developed the Hellfire II Missile Health Monitor Unit (HMU) and the Patriot Missile HMU. Each of these devices provides end users information that can be used to ensure the proper maintenance and performance of the missile. These two efforts have led to the ongoing development and evolution of the next generation Hellfire HMU and the next generation Patriot HMU. These next generation efforts are in turn, leading to the future of HMUs. This evolutionary development process inherently allows for direct and indirect impact toward new HMU functionality, operability and performance characteristics by influencing their requirements, testing, communications, data archival, and user interaction.

Current designs allow systems to operate in environments outside the limits of typical consumer electronics for up to or exceeding 10 years. These designs are battery powered, and typically provided in custom mechanical packages that employ sensors for temperature, shock/vibration, and humidity measurements. The data taken from these sensors is then analyzed onboard using unique algorithms. The algorithms are developed from test data and fielded prototypes.

On-board data analysis provides field users with a simple indication of missile exposure. The HMU provides information to the user in order for them to make a decision on whether or not to use a missile.

To continually advance current designs PNNL evaluates the potential for enhancing sensor capabilities either by performance or power saving features, increasing algorithm and processing abilities, and by adding new features. Future work at PNNL includes the utilization of power harvesting, using a defined wireless protocol, and defining a data/information structure all of which will lead to improved performance allowing the HMUs to benefit users with direct access to HMUs in the field as well as benefiting those with the ability to make strategic and high-level supply and inventory decisions in real-time.

7981-201, Poster Session

The eigenvalue problem associated with the nonlinear buckling of a shear bending column

I. Nishimura, Tokyo City Univ. (Japan)

This paper describes the post buckling behavior of the shear bending columns under a large deformation. The author discovered the fact that there is a special condition that makes the post buckling behavior stable after considering the geometrical nonlinearity.

Even if the geometrical nonlinearity is considered, the buckling load of this problem is kept constant. In other words, the eigenvalue of this nonlinear problem looks like a linear problem. The author attempts to explain the hidden linear formation that makes the buckling load, or equivalently the eigenvalue, stable even under a large deformation.

This rigorous solution of the given problem is obtained and expressed in a time-independent Schrodinger Equation, whose potential function is given by the Elliptic function. The quite similar relation does exist in the formation of nonlinear wave propagation known as soliton. The soliton wave has a variety of constant physical quantities regardless of the nonlinearity inherent with itself.

As a result of this study, the eigenvalue problem associated with the nonlinear buckling problem is expressed in a mathematical function and the stable post buckling behavior of the nonlinear buckling is physically explained.

7981-202, Poster Session

Seismic performance of RC shear wall structure with novel shape memory alloy dampers in coupling beams

C. Mao, China Earthquake Administration (China); J. Dong, Northeast Forestry Univ. (China); H. Li, Harbin Institute of Technology (China); J. Ou, Dalian Univ. of Technology (China)

Shear wall system is widely adopted in high rise buildings because of its high lateral stiffness in resisting earthquakes. According to the concept of ductility seismic design, coupling beams in shear wall structure are required to yield prior to the damage of wall limb. However, damage in coupling beams results in repair cost post earthquake and even in some cases it is difficult to repair the coupling beams if the damage is severe. In order to solve this problem, a novel passive damper was proposed in this study. The coupling beams connecting wall limbs are cut off in the middle and the dampers are installed between the ends of the two half coupling beams. Then the relative flexural deformation of the wall limbs is transferred to the ends of coupling beams and then to the SMA dampers. After earthquakes the deformation of the dampers can recover automatically because of the pseudoelasticity of austenite SMA material. In order to verify the validity of the proposed dampers, seismic responses of a 12-story coupled shear wall with such passive SMA dampers in coupling beams was investigated. The additional stiffness and yielding deformation of the dampers and their ratios to the lateral stiffness and yielding displacements of the wall limbs are key design parameters and were addressed. Analytical results indicate that the displacement

responses of the shear wall structure with such dampers are reduced remarkably. The deformation of the structure is concentrated in the dampers and the damage of coupling beams is avoided.

7981-203, Poster Session

Piezoelectric composite morphing control surfaces for unmanned aerial vehicles

O. J. Ohanian III, AVID LLC (United States)

The authors have explored the use of morphing control surfaces to replace traditional servo-actuated control surfaces. The morphing actuation is accomplished using Macro Fiber Composite (MFC) piezoelectric actuators in a bimorph configuration to deflect the aft section of a control surface cross section. The resulting camber change produces forces and moments for vehicle control. The flexible piezoelectric actuators are damage tolerant and provide excellent bandwidth. The large amplitude morphing deflections attained in bench-top experiments demonstrate the potential for excellent control authority. Aerodynamic performance calculations using experimentally measured morphed geometries indicate changes in sectional lift coefficients of as much as 2.25 are possible. This morphing flight control actuation technology could eliminate the need for servos and mechanical linkages in small UAVs and will thereby increase reliability and reduce drag.

7981-204, Poster Session

A basic approach for wing leading deicing by smart structures

S. Struggl, J. Korak, H. Witschnig, PROFACTOR GmbH (Austria)

An investigation regarding de-icing of wing leading edges through the use of smart structures with low energy consumption is performed. Piezoelectric actuators are used to excite the structures at their natural frequencies. This vibration excites shear stresses at the surface, which lead to the shedding off of ice. For optimal excitation of the structure, the frequency and the placement of piezo elements are determined, in order to maximize the shear stress in relation to the applied energy. First, experimental investigations on a clamped aluminum plate are carried out. With these findings, the transition to an aluminum sample of a wing leading edge is performed. Different piezo placements have been tested on the sample wing. Depending on the arrangement more or less energy can be put into the structure. Practical experiments have been carried out on aluminium wing leading edges of different size. First, the structural behavior is determined by a modal analysis so that the natural frequencies and the eigenmodes can be calculated. By FE simulation all parameter combinations can be calculated, so the practical tests can be adapted accordingly. Practical experiments have been carried out under realistic conditions in terms of ice formation in a wind tunnel and in a climate chamber. Different types of ice have been considered, which require a different level of shear stresses for the de-icing. Further investigations show the influence of the shape of the structure. The studies point to a further possibility of energy efficient de-icing. In addition, the influence of structural form could be used in the construction process to influence the design of smart de-icing structures.

7981-205, Poster Session

Enhancement of PV system output power using a computer based automatic sun tracker

A. Abou-Elnour, Ajman Univ. of Science & Technology (United Arab Emirates)

To get the maximum output power from PV system, the PV panel must remain in the front of the sun during the whole day. Conventional

PV sun tracking systems usually compare the input signals from a set of sensor circuits, at least four for two-axial tracking, and then generate the output control signals to the tracking motors. For these systems, additional computer software program is usually needed for data recording and monitoring. The different natures of the previously mentioned components of the conventional PV tracking system are the main difficulties which have to be carefully considered when the system is designed, implemented, or upgraded.

The aim of the present work is to design and implement a two axial Computer Based Automatic Sun Tracker which will provide the best alignment of the PV solar panel with the sun to get the maximum output. The unique feature of our tracking system is that the controlling, recording, and monitoring processes are all done using a single programming environment. No additional sensor circuits and no additional microcontroller circuits are required in our system.

The only inputs needed by the programming environment are the latitude and longitude positions of the place in which the PV system is constructed. The current time (hour, day and month) when calculations are performed is automatically read from the computer system clock. From the sun equations, the computer programming environment will automatically generate the controlling signals to the motors to set the PV panel in the required position.

7981-206, Poster Session

Structural health monitoring (SHM) needs S³ (sensor-structure-system) logic for efficient product development

C. Peters, Faserinstitut Bremen e.V. (Germany); P. Zahlen, C. Bockenheimer, Airbus Deutschland GmbH (Germany); A. S. Herrmann, Faserinstitut Bremen e.V. (Germany)

Intelligent light weight constructions with carbon composite materials for future aircraft and automotive industry play an important role to contribute significantly to the reduction of production cost and structural weight and hence energy and CO₂ savings. One goal for the application of SHM-systems is to increase the weight reduction potential for a given structure without reducing the component reliability in service.

At present time a variety of SHM technologies for monolithic and sandwich structures exist. In general all these SHM technologies have in common that NDT sensing systems - comprising sensor, cabling and connector - are being combined to structural elements. These combinations of systems with structures lead to multi-variables optimisation problems and resulting conflicts. A wide range of criteria requirements needs to be fulfilled: on one hand the sensing system has its specific requirements and criteria (e.g. allowable temperature range, robustness, contacting etc.) and on the other hand the structure has additional requirements (e.g. material, geometry, strain levels, etc.). Moreover, the manufacturing process and in-service aspects deliver further requirements (e.g. manufacturing parameters, handling, positioning, inspection, repair, etc.). In order to develop a globally optimized solution for the integration of a sensing system in a structure for a given SHM use case, this paper proposes the S³ (sensor-structure-system) development logic. In the S³ logic the aspects of the sensor-system, the structure and the manufacturing process are being considered at the same time during the development. Therefore the S³ logic enables a multi-disciplinary system development in a pragmatic way.

7981-207, Poster Session

NSF Project presentation

S. Liu, National Science Foundation (United States)

No abstract available

7981-208, Poster Session

Design, flexibility, and stress analysis of nano-skin

Y. Lin, Northeastern Univ. (United States)

Monitoring human state is a very useful to improve the performance of human-machine systems. Generally, human physiological cues are more suitable for monitoring human state in human-machine systems than machine dynamic cues. The physiological cues can be measured from human-machine contact surfaces. Nano-Skin is designed to be placed on human-machine contact surfaces for physiological measurement. It should work under complicated stresses. This study was focused on analyze the mechanics of Nano-Skin in applications and then instruct the design of Nano-Skin. When human-machine contact surfaces are curved, a Nano-Skin should be flexible enough to match the surfaces well. A question is how to evaluate and increase the flexibility of Nano-Skin.

In addition, a Nano-Skin may be bent to match curved surfaces. Due to these curved surfaces, pressure applied by the human is able to be resolved into two component forces, a radial force and a tangential force. The radial force compresses the Nano-Skin in the radial direction of the curved surface. Its effect to Nano-Skin is ignorable because the thickness of Nano-Skin is small. However, the tangential force leads to stretch the Nano-Skin. It is essential to investigate the response of Nano-Skin to bending and stretching.

The result of this study is highly useful to select the materials of Nano-Skin and design the components of Nano-Skin.

7981-209, Poster Session

* Continuous piezoelectric health monitoring systems based on ultrasonic guided waves

S. Li, C. J. Lissenden, J. L. Rose, The Pennsylvania State Univ. (United States)

The research presented by this poster is supported by the NSF Sensors and Sensing Systems program. The objective of the project is to develop strip-like transducers to generate ultrasonic guided waves for structural health monitoring of fatigue cracks and corrosion in plate and shell structures. The comb transducers propagate Lamb waves transverse to the long dimension and are comprised of piezoelectric fiber elements. The many design variables include: number and size of elements, fiber orientation and volume fraction, poling direction, and electric field direction. Candidate transducer designs have been selected for manufacture.

7981-210, Poster Session

* Subsurface geo-applications of wireless signal networks

S. Yoon, E. Ghazanfari, L. Cheng, M. T. Suleiman, S. Pamukcu, Lehigh Univ. (United States)

Wireless Underground Sensor Networks (WUSNs) have abundant potential applications in monitoring subsurface geo-event. The key applications can be monitoring subsurface hazard and characterizing subsurface environments in real-time using WUSNs. However, it is difficult to monitor global subsurface hazard and characteristics due to the limited subsurface sensing capability of the sensor's equipments. With the concept and application of the wireless functional signals, the global subsurface monitoring in real-time can be achieved. The wireless functional signal uses the signal strength variation in the host medium (i.e., soil in this case) as the main indicator of an underground event or a physical change in soil properties. The target applications of subsurface hazards monitoring include landslide, earthquake, and active fault zone monitoring which involve a lot of perturbation of earth masses and are characterized by the localization of sensors which allows sensors to

estimate their locations using information transmitted by a set of seed sensors. Other potential applications of characterizing subsurface environments include monitoring of oil leakage from subsurface reservoirs, water leakage from underground pipelines, seepage in earth dams, and estimation of soil properties and conditions such as compaction, gradation, and salinity based on the received signal strength information. The target applications are experimentally evaluated by laboratory simulations and compared with theoretical estimations. In the theoretical analysis, an underground radio propagation model which is implemented in ns-2 network simulator and a geo-event classification model based on probabilistic decision theories are provided.

7981-211, Poster Session

Full-spectral interrogation of fiber Bragg grating sensors for damage identification

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In this study, we demonstrate a new in-situ measurement technique for monitoring damage progression in laminated composites during dynamic events. The measurements are based on high-speed, full-spectral scanning of the response of a FBG sensor, embedded in the laminate. This was achieved by extending the data acquisition rate for full-spectral interrogation of FBG sensors through a MEMs tunable filter interrogator in-situ damage identification. This measurement technique was applied to multiple, low-velocity impacts of two-dimensional woven laminates, at energies up to 14.5 J. During the impact events, both the strain components perpendicular and parallel to the lamina interface were measured. The strain acquisition was demonstrated at rates of 100 and 300 kHz, sufficient for the dynamic events tested. As a result of this high data acquisition rate, the maximum strain during impact was captured for all impact events. In the future, this measurement system could be applied to multiple FBG sensors, embedded at different depths and locations with the laminate, to better understand the spatial progression of damage in a structure. Even if only peak wavelength information is required, the resolution of the full-spectral response would also prevent errors due to "wavelength-hopping" or other spectral distortions previously limiting the application of embedded FBG sensors. The viability of the interrogator for future applications to in-flight structural health monitoring of aircraft frames in which strain fields must be identified in noisy environments is also discussed.

7981-212, Poster Session

Enhancing the sensitivity of semiconductor-based gas sensors on nanostructured surfaces

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The metal oxide semiconductor thin film gas sensors have been successfully fabricated on a nanospiked silicon surface formed with femtosecond laser irradiations, and nanospiked polyurethane (PU) polymer surface which is replicated by a low cost soft nanolithography method from the silicon nanospiked surface. The sensors show significant response to CO gas at room temperature. It is well-known that the C-O is polarized with positive charges on oxygen atom and negative charges on carbon atom. When the currents pass through the semiconductor sensitive layer, more electrons may accumulate on the tips of the nanospikes to maintain the same electric potential on the surface, which results in strong local electrical fields near the tips of the nanospikes. Then more CO molecules will be pulled onto the tips of the nanospikes and this will enhance the sensitivity of the sensor. The gate bias enhancement was studied on silicon/oxide layer/semiconductor architecture with the underlying silicon substrate as the back gate. The bias voltage applied on the gate can further enhance the sensitivities of

the gas sensors by alternate the electron (hole) concentration in the metal oxide semiconductor thin film.

7981-213, Poster Session

Advanced sensor-computer technology for urban runoff monitoring

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The paper presents the project team's advanced sensor-computer sphere technology for real-time and continuous monitoring of wastewater runoff at the sewer outfalls along the receiving water. This research significantly enhances and extends the previously proposed novel sensor-computer technology. This advanced technology offers new computation models for an innovative use of the sensor-computer sphere comprising accelerometer, programmable in-situ computer, solar power, and wireless communication for real-time and online monitoring of runoff quantity. This innovation can enable more effective planning and decision-making in civil infrastructure, natural environment protection, and water pollution related emergencies.

This research presents the following: (i) the sensor-computer sphere technology; (ii) a significant enhancement to the previously proposed discrete runoff quantity model of this technology; (iii) a new continuous runoff quantity model. Our comparative study on the two distinct models is presented. Based on this study, the paper further investigates the following: (1) energy-, memory-, and communication-efficient use of the technology for runoff quantity monitoring; (2) possible sensor extensions for runoff quality monitoring.

The proposed innovation also includes the server side technology for storage, update, retrieval, and applications of the sensor data streams produced by the sphere technology at multiple sources.

The paper presents important technical feasibility issues and lab test results involved with the functionality of the proposed technology. Based on the findings, the paper discusses the field applications, cost-efficiency, and scalability of the technology.

7981-214, Poster Session

Dynamic strain measurements with a luminescent photoelastic coating

J. P. Hubner, D. R. Gerber, The Univ. of Alabama (United States)

Over the past couple of years, the luminescent photoelastic coating technique has been extended to acquire principal strain measurements on static, three-dimensional structural components under load. The approach uses oblique incident excitation and digital imaging of the luminescence; subsequent analysis is performed on a three-dimension grid compatible with finite element analysis. These results were presented at the SPIE 2010 conference. This paper discusses the development of the technique for dynamically loaded specimens in which the excitation is strobed in synchronization with the load application cycle. The investigation started this summer and will continue through the fall and early winter. Full-field, phase-resolved measurements on a cantilever beam will be presented as well as the experimental technique and measurement set-up. Additionally, a point-wise investigation on smaller, higher frequency driven specimens will be discussed, assessing the dynamic response limit.

7981-217, Poster Session

Bio-inspired somatosensor with modeling of viscoelastic responses

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The human somatosensory system is composed of two major components. The first is responsible for detecting mechanical stimuli (light touch, vibration, pressure and cutaneous tension). The second broad component of the somatosensory system is responsible for detecting painful stimuli and temperature. This sensory transduction process transforms distant mechanical stimuli into an electrical signal that the brain can interpret. Two classes of mechanoreceptors are identified as (1) rapidly adapting receptors (FARs), and (2) slowly adapting receptors (SARs), as shown in the Figure.

These are the somatosensors that are responsible to human tactile sensing at different frequency ranges with different amplitudes of static responses. Based on the research study on the characteristics of viscoelastic biomedical materials, we discovered that the temporal responses of viscoelastic relaxation/creep curves also consistently show two time constants—one fast and the other slow, resembling the SARs and FARs of somatosensor. The presentation will present the analogy between human tactile sensory and this special temporal property of viscoelastic materials, as well as the development of a bio-inspired tactile sensor. Preliminary experimental results of a prototype sensor with different shapes of indenter, different locations of indentation, and different frequencies of indentation will be presented.

This research has been jointly supported by the joint grants between NSF (National Science Foundation) Grant CMMI0800241 and JST H19/299-1 (Japan Science and Technology Agency).

7981-59, Session 8a

Integrated impedance and guided wave based damage detection under temperature variation

Y. An, H. Sohn, KAIST (Korea, Republic of)

Electro-mechanical impedances and guided waves have been widely studied for detecting localized structural damages due to their sensitivity to small changes. In this paper, an integrated impedance and guided wave (IIG) based monitoring system is developed to improve the detectable capability of various damage types under varying temperature. First, a hardware system, called the IIG system, was designed to achieve simultaneous measurements of electro-mechanical impedance and guided wave signals. Then, the effects of temperature on guided waves and electro-mechanical impedances were compensated using the passive imaginary part of the impedance signal. Finally, an automated damage classification algorithm which incorporates temperature compensation was developed. To validate the proposed algorithm, experimental investigations were performed for the detection of crack and bolt loosening in metallic structures subjected to the temperature varying condition, in the range of -20 to 70°.

7981-60, Session 8a

Damage detection using time reversal imaging technique

S. Liu, F. Yuan, North Carolina State Univ. (United States)

A damage detection technique based on time reversal concept is proposed to detect and locate the defects in a plate structure. Time reversal imaging method is widely used as an advanced, robust data processing and imaging technique in structure health monitoring to detect the defects. Physically, it says that the time reversed signal will

retrace its original path precisely, which means that the signals will be refocused back on the source and defects after we record, time reverse and back propagate the wave signal experimentally or numerically. In this paper, a distributed actuator/sensor network is placed on a square homogeneous plate and utilizes piezoelectric as both actuators and sensors to generate and collect the guided wave signals in the plate. The time reversal technique is then used to interpret the physical meaning of the recorded data and image the defects in the plate. Both computer simulations and experiment are presented to illustrate the feasibility of the technique in this paper.

7981-61, Session 8a

Singularity analysis using continuous wavelet transform for EMAT ultrasonic measurement of lubricant film thickness

J. Jiao, Z. Qiang, W. H. Liu, C. He, B. Wu, Beijing Univ. of Technology (China)

The durability of mechanical structures such as gears, bearings and seals relies on the integrity of the lubricant film separating the contact surfaces. If the film fails, these surfaces contact and friction, wear and seizure can occur. Therefore it is necessary for the safe operation of mechanical structure to monitor the thickness of lubrication film. In conventional ultrasonic testing of a thin layer with thickness less than about twice the wavelength, successive echo signals become inseparable. In this paper, wavelet transform is applied to detect abrupt changes in ultrasonic signals detected by electromagnetic acoustic transducer (EMAT). In particular, singularity analysis across all scales of the continuous wavelet transform is performed to identify the location of interface-induced bursts in the ultrasonic signals. Through tracing on the modulus maxima of wavelet transform from large scale to small scale, the interface-related singularity points are highlighted and an intelligent algorithm is developed to automatically calculate the transmit time of ultrasonic waves in lubrication film. The ultrasonic experiments had been carried out in actual mechanical structures for lubrication film measurements; it was showed that the proposed method can be used for thickness measurement of lubrication film, and the results agreed well with the actual.

7981-62, Session 8b

Biofied building: interactive and adaptive building using sensor agent robots

A. Mita, Keio Univ. (Japan)

Evaluating and recording building conditions in a quantitative manner such as level of deterioration and level of safety has been recognized an important research area. Sensors are key devices for acquiring such necessary information, but in addition it is required that there be technology to extract only the relevant information from the tremendous amount of gathered data. The structural health monitoring (SHM) system, ascendant in civil engineering, has been studied and developed in our laboratory for many years. Our SHM system consists of a smart sensor network (for data acquisition), a database server (for data storage and data management), and a diagnosis and prognosis server. The SHM, however, can be extended to more novel roles -- detecting and recording the histories of environmental conditions of building structures and flexibly adapt to the environments.

Living matter has very flexible and smart adaptive mechanisms in nature as categorized into four, sensory adaption, adaption by learning, physiological adaption, and evolutionary adaption. We learn from these adaptive mechanisms to create biofied buildings. Among many potential approaches we are particularly interested in using robots as moving sensor agents, that we call sensor agent robots, to gather information of buildings and residents and interact with them. The information obtained by the sensor agent robots is used to record life phases of the environment relevant to buildings. We call this concept "biofied building" or "biofication of living spaces" and are working to integrate the concept.

This paper presents some aspects of the “biofied building” research conducted at our laboratory.

7981-63, Session 8b

Distributed neural computations for embedded sensor networks

C. Peckens, J. P. Lynch, Univ. of Michigan (United States); J. Pei, The Univ. of Oklahoma (United States)

Wireless sensing technologies have recently emerged as an inexpensive and robust method of data collection in a variety of structural monitoring applications. In comparison with cabled monitoring systems, wireless systems offer low-cost and low-power communication between a network of sensing devices. Wireless sensing networks possess embedded data processing capabilities which allow for data processing directly at the sensor thereby eliminating the need for transmission of raw data. In this study, the Volterra/Weiner neural network (VWNN), a powerful modeling tool for non-linear hysteretic behavior, is decentralized for embedment in a network of wireless sensors so as to take advantage of each sensor’s processing capabilities. The VWNN was chosen for modeling nonlinear dynamic systems because its architecture is computationally efficient and allows tasks to be decomposed for parallel execution. In the algorithm, each sensor collects its own data and performs a series of calculations on it. It then shares its resulting calculations with every other sensor in the network, while the other sensors are simultaneously exchanging their information. Because resource conservation is important in embedded sensor design, the data is pruned wherever possible to eliminate excessive communication between sensors. Once a sensor has its required data, it continues its calculations and computes a prediction of the system acceleration. The VWNN is embedded in the computational core of the Narada wireless sensor node for on-line execution. Data generated by a nonlinear steel framed structure excited by seismic ground motions is used for validation of the embedded VWNN model.

7981-64, Session 8b

Fly-ear inspired directional microphone: effects of air cavity

H. Liu, M. Yu, Univ. of Maryland, College Park (United States)

The superacute ear of the parasitoid fly *Ormia ochracea* has inspired the development of novel miniature directional microphones for sound source localization. However, the effects of the air cavity backing the eardrums have yet been studied. In most cases, its effects are assumed to be negligible without proof. In this article, a normalized version of our previous model of air-backed circular membranes is derived to study the conditions under which the air cavity can be indeed neglected. A transitional stage is thus identified in terms of non-dimensionalized parameters to establish the criteria. This model is then used to study the fly-ear inspired directional microphone, i.e. two clamped circular membranes mechanically coupled by a bridge. The simulation results will be compared with the reported biological findings. This article provides a theoretical guidance to the development of both air-backed pressure sensors in general and fly-ear inspired directional microphone.

7981-65, Session 8c

Finite element modeling of an optical fiber photoacoustic generator performance

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In recent years, the broadband ultrasound generation by ultrafast laser pulses attracts wide research interests due to its potential applications

in nondestructive testing and medical imaging. However, the conversion efficiency of photoacoustic generation is still very low, which limits the applications of photoacoustic ultrasound generators. An analytical or numerical modeling can give physical insights to the relationship among laser input parameters, film physical properties and generated ultrasonic waves. This paper presents a systematic numerical simulation of the photoacoustic process in our proposed optical fiber-based ultrasound generator.

A 2D-axisymmetric model was built up to simulate a 3-layer structure: optical fiber tip, light absorbing film, and surrounding water. Three equations govern the generation of ultrasonic waves: the heat conduction, thermal expansion and acoustic wave equations. Depending on the relationship between the film thickness and the light penetration depth, the photoacoustic generation is categorized into two regimes: “thin-film” regime and “thick-film” regime. In “thin-film” regime, the film is not thick enough to absorb the entire incident laser energy, then the majority of the energy is absorbed by the water; in “thick-film” regime, the majority of the energy is absorbed by the film and converted to vibrations, which excite ultrasound waves in the adjacent water. Three major conclusions were obtained from the simulation: 1) the “thick-film” generation has higher photoacoustic conversion efficiency than the “thin-film” generation; 2) Higher absorption and thermal expansion coefficients of the absorbing film lead to higher conversion efficiency; 3) the frequency spectrum of generated ultrasound is dominated by the laser pulse duration.

7981-66, Session 8c

Long term seismic response monitoring, finite element modeling and model updating of a concrete building

P. Omenzetter, F. Butt, The Univ. of Auckland (New Zealand)

This paper presents a study of the variation of natural frequencies and damping ratios of a reinforced concrete building identified from earthquake records during a period of four years. The four storey reinforced concrete building is instrumented with five tri-axial accelerometers, among which two accelerometers are at the base level, two at the roof level and one underneath the first floor slab. The accelerometers are configured to trigger on an event and had recorded many earthquakes of different intensities since its installation in early November 2007. The subspace state-space system identification technique was used to ascertain the natural frequencies and damping ratios considering 50 recorded earthquake response time histories. Correlations were developed between the peak ground acceleration at the base level and peak response acceleration at roof level with identified frequencies and damping ratios. It was found that modal characteristics of the building are sensitive to the level of excitation. A general trend of decreasing fundamental frequencies and increasing damping ratios were observed with increased level of shaking. To simulate the behavior of the building, a three dimensional finite element model (FEM) of the building was developed. To incorporate real in-situ conditions, soil underneath the foundation was modeled using spring elements and non-structural components (cladding, in-fills and partitions) were also included. The developed FEM was then updated using measured responses as basis. Two approaches for estimation of model updating parameters, one based on the pseudo-inverse method and the other on the weighted least squares method, were evaluated for their efficiency. It was concluded from the investigation that participation of soil and non-structural components is significant towards the seismic response of the building and these should be considered in models to simulate the real behavior.

7981-67, Session 8c

Study on finite element model updating of distributed structural health monitoring system

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The distributed structural health monitoring (SHM) system is an important renovation to the traditional centrally controlled system, however, the research on finite element model updating of the distributed SHM system was never conducted before. This paper investigates subgroup finite element model first and then constructs the new types of objective function relating to the calculated dynamical parameters and identified dynamical parameters of each single subgroup model. The problem defined by the objective function will be solved with genetic algorithm method. Then, the model updating strategy considering the reaction between two conjoined subgroups is studied. Furthermore, the systematic model updating strategy for the whole system is studied considering that more constraint conditions can be utilized in the distributed SHM system. The paper contributes meaningful idea on model updating field.

7981-68, Session 9a

Data analysis for long-term structural health monitoring on a continuous rigid frame bridge

L. Wang, Harbin Institute of Technology (China); D. Li, J. Ou, Dalian Univ. of Technology (China)

A series of bridges collapsed in China in recent years in earthquakes, floods or ship accidents. Also bridges are faced with fatigue problems caused by increased traffic demand, continued materials aging and deterioration, but are lack of maintenance. Sustainability of bridges is affected by environmental conditions such as traffic load, temperature, humidity, wind and so on. Long-term structural health monitoring (SHM) system has been developed to monitor the operational process of bridge structures, to estimate the bridge structural safety and serviceability by damage diagnosis, safety assessment and service life evaluation. Fiber Bragg grating (FBG) sensors are widely used in SHM to monitor environmental conditions, static and dynamic properties because of their high-durability. A mass of data is collected during the long-time monitoring; therefore methods for reducing data and prediction for future modal properties are main concerns in data analysis of SHM.

Dongying Yellow River Bridge is a continuous rigid frame concrete bridge with main span of 220 meter, which is implemented with 180 FBG sensors for temperature, 1688 for strain and 32 for acceleration. This paper analyses 5 months continuous monitoring data in year 2006. Because of abundant amounts of data, principle components analysis (PCA) method is utilized to reduce excessive information from raw data. The correlations between temperature and modal parameters and between strain and modal parameter are simulated by Support Vector Machine (SVM). The results show that PCA is an effective data deduce tool; with appropriate inputs for SVM, modal properties are predicted accurately and effectively.

7981-69, Session 9a

Monitoring system for the bolt joints on steel bridges

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The bolt joints on steel bridges are exposed to the possibility of damage, and thus, require intensive care. Usually, periodic inspections are

conducted at the cost of time and money; however, it is very difficult to check so many bolts carefully. The purpose of this study is to propose a system that can more efficiently monitor the tightness/looseness of these bolts. To develop this system, which is based on RFID/USN technology, studies on the loosening mechanism of bolts and nuts, development of data-gathering and application software, tests for the verification of a pilot system, and complementation will be conducted. And lastly, the application plan of an SOC structure monitoring system by using the RFID technology in the field will be proposed. The bolt tightness monitoring system is comprised of sensors that are attached to nuts and a data receiving terminal, which gathers information. The reed switch consists of two thin, metallic contacts enveloped in a glass tube and is an electrical switching sensor that is triggered ON or OFF by changes in the surrounding magnetic field. Indoor verification tests showed that bolt loosening can be effectively detected, proving the applicability of this system to the maintenance of the bolt joints of steel structures.

7981-70, Session 9a

structural performance assessment of Hongxing Bridge based on distributed long-gage sensors under ambient vibration

H. Wan, Z. Wu, C. Yang, Southeast Univ. (China)

In this paper, a typical application of distributed long-gauge FBG sensors to a prestressed box bridge is addressed, and a novel method is proposed to obtain the deformation distribution of large-scale structures based on distributed strain. The long-gauge FBG sensors are distributed in the middle span of the three spans. The bridges are statically and dynamically loaded with trucks on site. Firstly, the deformation distribution as an important static index of the bridge is obtained from strain distribution by conjugated beam method. Secondly, modal parameters, such as natural frequency and modal macro-strain (MMS) as an effective dynamic index for damage identification, are achieved as well. After the static and dynamic site-experiments, the FBG sensor network is left on the bridge for a long-term monitoring of the pre-stressed box bridge, and the data are taken at a certain frequency. Static and dynamic results show that distributed long-gauge FBG sensing technique can not only obtain the global information such as deformation, natural frequency of the structure but also the local parameters such as strain, modal macro-strain to detect damage of the bridge. It may therefore be concluded that structural health monitoring based on the proposed technique has great potential in maintenance of civil engineering structures.

7981-71, Session 9a

Health monitoring of prestressing tendons in post-tensioned concrete structures

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Currently 90% of bridges built in California are post-tensioned box-girder. In such structures the steel tendons are the main load-carrying components. The loss of prestress, as well as the presence of defects or the tendon breakage, can be catastrophic for the entire structure. Unfortunately, today there is no well-established method for the monitoring of prestressing (PS) tendons that can provide simultaneous information related to the presence of defects and the level of prestress in a continuous, real time manner. If such a monitoring system were available, considerable savings would be achieved in bridge maintenance since repairs would be implemented in a timely manner without traffic disruptions. This paper presents a health monitoring system for PS tendons in post-tensioned structures of interest to Caltrans. Such a system uses ultrasonic guided waves and embedded sensors to provide simultaneously and in real time, (a) measurements of the level of applied

prestress, and (b) defect detection at early grow stages. The proposed PS measurement technique exploits the sensitivity of ultrasonic waves to the inter-wire contact developing in a multi-wire strand as a function of prestress level. In particular the nonlinear ultrasonic behavior of the tendon under changing levels of prestress is monitored by tracking higher-order harmonics at ($n\omega$) arising under a fundamental guided-wave excitation at (ω). Moreover this paper also present real-time damage detection and location in post-tensioned bridge joints using Acoustic Emission techniques. Experimental tests on large-scale single-tendon PT joint specimens, subjected to multiple load cycles, will be presented to validate the monitoring of PS loads (through nonlinear ultrasonic probing) and the monitoring of damage progression and location (through acoustic emission techniques). Issues and potential for the use of such techniques to monitor post-tensioned bridges in the field will be discussed.

7981-72, Session 9b

Biomimetic ears for a sensor agent robot to localize sound sources

D. J. Marin, A. Mita, Keio Univ. (Japan)

Our current environment and architecture are mainly static even though our surrounding society is constantly changing. This is why the Biofication of Living Spaces field was created, to get more adaptive and suitable living spaces. On the other hand, human was naturally empowered with a lot of features responding to the environment. His 2 ears are powerful tools from which he can acquire a lot of information such as the source localization of a sound. Interaural (between both ears) time differences enable a lateral localization and this function can be technologically reproduced. However, the sound localization in the median plane of the head provided amongst others by our external ear called the pinna is yet to be imitated in robotics. The idea of this paper is to build some biomimetic ear prototypes and to analyze their influences on the transfer function called Interaural Transfer Function (ITF). The ITF is the Fourier transformed signal reaching one ear divided by the second ear's signal. This represents a relation between the sound source position and the signals recorded. Once achieved, attaching these prototyped ears to a sensor agent robot, we aim particularly at a sound localization in the median plane of the robot. However, we will have a quick look at the horizontal sound localization too. Finally, these "ears" on the sensor agent robot will be convenient to get as much accurate and useful information as possible with only 2 microphones and to use this agent for biofication of living spaces issues.

7981-73, Session 9b

Biofied room integrated with sensor agent robots to interact with residents and acquire environmental information

F. Sakurai, A. Mita, Keio Univ. (Japan)

Current smart buildings are based on scenarios, so not prepared for unexpected events. Additionally, people needs highly secured, more energy-efficient, and more comfortable space. Meanwhile, tools such as sensors and computers advance rapidly. Thus, using these new tools we would like to make living spaces safer and more comfortable. We focus our attention on living matters' high adaptability to environmental changes. "Biofication of Living Spaces" is the concept of creating safe and pleasant living environments using this high adaptability. Adaptability is the key element in Biofication of Living Spaces. Biofied room is integrated with sensor agent robots to interact with residents and acquire environmental information. In this research, we propose a highly adaptive algorithm to predict human behavior automatically for Biofication of Living Spaces. By incorporating interaction histories with residents and acquiring relevant environmental information, we can make the algorithm very flexible. As the first step in this research, we determine which functions to equip for the sensor agent robot. We mount camera, microphone, proximity sensor, laser range-finder (LRF) on the robot. Thus, we make a prototype of the sensor agent robot. As a sensor

agent robot follows the residents, it acquires environmental information, and records the interaction between the robot and human. Then these data are stored in the database, drawn up in a chronological order. We apply statistical processing to many time-series data, and extract feature quantity. We compare our method with the existing methods such as Hidden Markov Model, etc, to confirm the advantages of our method.

7981-74, Session 9b

Mimicking the human nervous system with a triboluminescence sensory receptor for the structural health monitoring of composite structures

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The human nervous system (HNS) provides one of the most advanced example of how to monitor the structural state of a complex system. In any attempt to mimic the HNS, a key component is the development of the sensory receptor. This paper reports on the development of a triboluminescence (TL)-based sensory receptor that converts mechanical energy from fatigue or impact loads and cracks propagation, into optical signals. This sensor system has potential for wireless, in-situ and distributed sensing (WID). The approach differs from existing fiber optic methods in that it does not require any external light source to function. The optical signal is generated through mechanical excitation of the highly triboluminescent ZnS:Mn. It is then transmitted through optical fibers to photomultiplier tubes (PMT) for detecting, quantifying and locating (with further analysis), intrinsic damage in critical engineering structures like concrete bridges.

The TL sensory receptor consists of a sensitized portion of a polymer optical fiber (POF) coated with epoxy containing ZnS:Mn crystals. The optical fibers were sensitized by removing the cladding mechanically. The sensory receptors were then incorporated into cementitious and polymer samples. Results from preliminary investigation showed that the TL sensory receptor gives repeatable responses under multiple impact loads. The triboluminescent intensity of the signal is directly related to the magnitude of the impact load. This paper discusses results from tests to characterize the new sensor's response under impact and flexural loading conditions when incorporated into different host materials. The sensor density required to attain distributed sensing will also be investigated.

7981-75, Session 9b

Decentralized simultaneous localization and mapping for robotic networks

R. Jaai, N. Chopra, B. Balachandran, Univ. of Maryland, College Park (United States); H. Karki, The Petroleum Institute (United Arab Emirates)

In the simultaneous localization and mapping (SLAM) problem, one addresses the problem of using mobile sensor platforms or robotic systems to map unknown environments while simultaneously localizing the mobile systems relative to the map. Applications include mapping in oil storage tanks, oil pipes, search and rescue operations, surveillance operations, exploration operations, and so on. In this effort, a previously proposed multi-robot localization algorithm is extended to implement SLAM. The decentralized algorithm is demonstrated to work in dynamic robot networks with unknown initial relative robot poses as well as unknown number of robots in the network. The algorithm allows a system of N agents to be split into subgroups and implement recursive filtering. Experimental and numerical studies conducted with multiple networked mobile platforms are also discussed to validate the analytical findings.

7981-76, Session 9c

Adaptive measurement selection for progressive damage estimation

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Noise and interference in sensor measurements degrade the quality of data and have a negative impact on the performance of structural damage diagnosis systems. In this paper, a novel approach for adaptive measurement selection (AMS) is presented to adaptively select measurements and use them intelligently for damage estimation. The proposed approach for noise suppression is related to the data association concept applied in tracking problems, where the measurements are either target-oriented or from clutter. In Lamb-wave based damage estimation scenarios, however, each sensor measurement generally includes both the damage related information and the clutter (such as the sample boundary) information, and the direct utilization of the data association events is not meaningful. The proposed AMS approach instead directly evaluates the "proximity" of the measurements to predictions made using past estimation history and then accordingly weights the estimates obtained using the measurements. Two approaches are considered to realize the AMS: the maximum likelihood (ML) method and the minimum mean-squared error (MMSE) method. The ML method selects the most likely measurement from the available measurements and uses it to estimate the damage state. The MMSE method weights the contributions of all the measurements for computing the damage state estimate. The AMS based progressive damage estimation method is implemented efficiently in a sequential Monte Carlo (SMC) setting using particle filtering. The noise suppression capability of the proposed method is demonstrated by an application to the problem of fatigue damage estimation in an aluminum compact tension (CT) sample using noisy PZT sensor measurements.

7981-77, Session 9c

Damage detection for plate-like structure using matching pursuits with chirplet atom

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Structural health monitoring (SHM) is an emerging technology which combines the advanced sensor technology with advanced signal processing technology to judge the health conditions of structure in real time. Lamb waves can propagate in beam-like, plate-like and shell-like structures with a long distance, and the damage monitoring method based on Lamb wave is considered as a promising active SHM method. The scattering signals are generated when Lamb wave interacts with defects. It can be achieved by the difference between the health signals and the damage signals. But the amplitude of the scattering signal is very small, and it is difficult to extract the damage information from the measured signals with strong noise. Hence it is necessary to study advanced signal processing methods to process the measured signals. The signal processing methods such as short time Fourier transform (STFT), wavelet transform and Hilbert-Huang (HHT) are used to process the Lamb wave signals successfully, but the time frequency resolution obtained by these methods may not be optimal, and they don't take into account of the dispersion characteristic. Compared to other time frequency signal processing methods, matching pursuits method have some advantages, such as high time frequency resolution, robustness to noise, lack of interference and computational efficiency. So matching pursuits method to process the monitoring signals was studied by many researchers.

In this paper, the matching pursuits method with chirplet atom is applied to handle the Lamb wave in plate-like structure. When Lamb wave interacts with boundary or damages, some modes of Lamb wave are generated due to the mode conversion, and it needs to distinguish the Lamb modes to determine the velocities of different modes of Lamb waves. In this research the relationship between the dispersion and

the chirp rate of chirplet atom is established to distinguish the modes of Lamb wave, such as A0 mode and S0 mode. A method for damage localization is developed based on the difference between the baseline signals and the damaged signals, which can resolve the overlapped signals reflected from several damages. The effectiveness and accuracy of the proposed method for identifying the modes and locating defects are demonstrated by the simulation and experimental results of isotropic plate structure and honeycomb sandwich composite structure.

7981-78, Session 9c

The use of matching pursuit decomposition for damage detection and localization in complex structures

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This work focuses on damage detection, localization and quantification in metallic plates using an array of sensors and an advanced feature extraction algorithm. In conventional approaches, the presence of damage is often identified based on the direct comparison between baseline and currently measured signals. Then the maximum change between two signals are determined and used to track possible damage locations. This type of approach will perform well in case the damage is located away from an actuator/sensor pair and acts only as a wave scatter. In general, however, measured signal contains different wave modes that are attenuated, scattered, or converted to due to damage. As a consequence, the performance of the sensing array can be limited without considering different types of wave interaction with damage.

To enhance the current capability of the sensing array, the use of matching pursuit decomposition (MPD) is proposed in this study. Using MPD, measured signals in the sensing array can be decomposed into multiple wave modes. By analyzing the individual wave modes, it is possible to better understand the cause of signal changes and locate the source. In addition, an effort is made to quantify the severity of damage by developing damage indices. The integrated use of damage indices and location information is expected to help in estimating the size of damage in different damage cases. Aluminum lug joint samples made of 6061 alloy, which are instrumented with piezoelectric transducers, are used for testing and validation of the proposed concept.

7981-79, Session 9c

* Damage classification using signal processing and machine learning in structural health monitoring

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Among the consecutive damage evaluation steps in the structural health monitoring systems, damage diagnosis and classification step can be very important since its result is the direct factor that has influences on estimating the remaining useful life of structures. In metallic structures, the first and second most frequent damages incurred are generally cracks and corrosions. The prognosis results can be significantly different because damage development phases for crack and corrosion have dissimilar patterns. In order to correctly diagnose and classify the damage types, all sensed signal information, such as time, amplitude, and frequency, are firstly processed through signal processing algorithms. Time-frequency representations based on the chirplet matching pursuit decomposition are utilized to study the differences between these damages under various damage conditions. The results from the representations are used for damage classification through an Adaboost machine learning algorithm. Adaboost enables to obtain accurate classification results with the advantages of better performance and simpler algorithms over other known classification algorithms. Through the matching pursuit decomposition and Adaboost, the overall damage information and the probabilities of damage types are obtained.

7981-80, Session 10a

Streicker Bridge: the impact of monitoring on decision making

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Structural monitoring has been recognized as a powerful information tool, yet bridge managers often make decisions based on their experience or on common sense, somehow regardless of the action suggested by instrumental damage detection algorithms. In fact, managers weight differently the outcomes of the monitoring based on their prior perception of the state of the structure and decide keeping in mind the possible effects of the action they can undertake. In this paper we propose a rational framework to include the impact of the issues mentioned on decision making, and we apply this to the Streicker Bridge, a new pedestrian which represents the entrance gate to Princeton campus. The bridge is equipped with various sensing systems designed to transform this structure into a multipurpose research and teaching laboratory in the field of Structural Health Monitoring and Theory of Structures. To quantify the benefit of health monitoring on Streicker Bridge, we use the concept of Value of Information (Vol), which in this case represents the cost the owner is willing to pay for any interrogation of the monitoring system.

7981-81, Session 10a

Streicker Bridge: a comparison between Bragg-gratings long-gauge strain and temperature sensors and Brillouin scattering-based distributed strain and temperature sensors

B. Glisic, J. Chen, Princeton Univ. (United States)

The Streicker Bridge at Princeton University campus has been equipped with structural health monitoring technology and has been transformed into an on-site laboratory for various research and educational purposes. Two fiber-optic sensing technologies are currently deployed: discrete long-gauge sensing, based on Fiber Bragg-Gratings (FBG), and truly-distributed sensing, based on Brillouin Optical Time Domain Analysis (BOTDA). The sensors were embedded in concrete during the construction. The post-tensioning of the bridge was performed about one week after the pouring. The early age measurements, including hydration swelling and contraction, and post-tensioning of concrete were registered by both systems and placed side by side in order to compare their performances. Aside from the usual behavior, an unusual increase in strain was detected by several sensors in various cross-sections. The nature of this event is still under investigation, but preliminary study indicates early-age cracking as the cause. The comparison between the two monitoring systems shows good agreement in the areas where no unusual behavior was detected, but discrepancies are noticed at locations where unusual behavior occurred. This discrepancy is attributed to the spatial resolution of the distributed monitoring system. In this paper, general background information concerning the Streicker Bridge project is given first. Then, the monitoring systems, their specifications and monitoring strategies are briefly presented. Finally, the monitoring data are analyzed and a detailed comparison between the two monitoring systems is performed.

7981-82, Session 10a

Development of structural health monitoring systems for railroad bridge testbeds

H. Park, J. Min, C. Yun, KAIST (Korea, Republic of); M. Shin, Korea Railroad Research Institute (Korea, Republic of); Y. Kim, Korea Infrastructure Safety and Technology Corp. (Korea, Republic of); S. Park, KM. Co. Ltd. (Korea, Republic of)

Recently a challenging project has been carried out for construction of a national network for safety management and monitoring of civil infrastructures in Korea. As a part of the project, structural health monitoring (SHM) systems have been established on railroad bridges employing various types of sensors such as accelerometers, optical fiber sensors, and piezoelectric sensors. This paper presents the current status of railroad bridge health monitoring testbeds. Emerging sensors and monitoring technologies are under investigation. They are local damage detection using PZT-based electro-mechanical impedances; vibration-based global monitoring using accelerations, FBG-based dynamic strains; and wireless sensor data acquisition systems. The monitoring systems provide real-time measurements under train-transit and environmental loadings, and can be remotely accessible and controllable via the web. Long-term behaviors of the railroad bridge testbeds are investigated, and guidelines for safety management are to be established by combining numerical analysis and signal processing of the measured data.

7981-83, Session 10a

Bridge condition assessment based on long-term strain monitoring

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In consideration of the important role that bridges play in transportation infrastructures, their safety, durability and serviceability have always been deeply concerned. Structural Health Monitoring Systems (SHMS) have been installed to many long-span bridges to provide bridge engineers with the knowledge needed in making rational decisions for maintenance. However, SHMS also confronted bridge engineers with the challenge of efficient use of monitoring data. Thus, methodologies which are robust to random disturbance and sensitive to damage become a subject on which many researches in structural condition assessment concentrate. In this study, an innovative probabilistic approach for condition assessment was proposed on the basis of long-term strain monitoring on steel girder of a cable-stayed bridge. Firstly, the composition of strain response of bridge components under operational loads was analyzed. Then, the time history of strain was decomposed using Wavelet technique. Thirdly, reliability assessment on load capacity and fatigue life were carried out based on the statistical characteristics of rain-flow cycles derived from the approximation signal. Finally, damage detection in the vicinity of monitoring point using strain-based indices was investigated. The research conducted indicates that the methodology proposed is qualified for structural condition assessment so far as the following respects are concerned: (a) capability of revealing structural deterioration; (b) immunity to the influence of environmental variation; (c) adaptability to the random characteristic exhibited by long-term monitoring data. Further examination of the applicability of the proposed methodology in aging bridge may provide a more convincing validation.

7981-84, Session 10a

Field load testing of long-span suspension bridge

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Field load testing is generally accepted as a most direct and effective approach for structural behavior investigation and quality checking of newly-built structures, especially for large-scale bridges. This paper is concerned with the field load testing of a long-span suspension bridge, Xihoumen Bridge, in Zhoushan Archipelago, China, which has the second longest span (1,065m main span) in the world. There are totally 20 major static loading cases conducted during the test to investigate the bridge behavior including bending, torsion and deflection. For most of loading cases, the planned loading effects of bridge control sections are about 85-98% of code-specified live (traffic) load demand. The structural parameters to be measured in the test include the deck profile, the stresses and displacements of steel box girder and towers, the forces of main cables and suspenders. Also, the initial equilibrium configuration

of the bridge under its self-weight is accurately measured. A three-dimensional hybrid finite element model of global-and sub-model is developed to verify the bridge responses. Results show that the bridge presents linear elastic characteristics under the planned testing load, and the measured bridge responses do not exceed the analytical values according to the design code, which indicated the bridge has a good integrity and an adequate load-carrying capacity.

7981-85, Session 10b

Pipeline monitoring using an integrated MFC/ FBG system

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This study proposes an integrated macro fiber composite (MFC) transducer and fiber Bragg grating (FBG) system for monitoring of pipelines. The integrated MFC/FBG system generates and measures guided waves using only a single laser source and optical cables. First, a tunable laser is used as the common power source for guided wave generation and sensing. This laser beam is transmitted through one optical fiber to actuate multiple MFC transducers and the other optical fiber is used with FBG sensors to measure the generated guided waves. The multiple MFC transducers can generate near-axisymmetric longitudinal and torsional modes by suppressing the excitation of several dominant flexural modes. The generated guided wave modes are incident on a structural damage and the interaction between the guided waves and the damage results in mode-converted flexural modes. This study focuses on the effects of wall thinning and longitudinal cracks on mode conversion. For analysis of the guided waves measured at the FBG sensors, a proper damage index is suggested to extract the mode-converted flexural modes for the robust identification of intact and damaged cases. The advent of the mode-converted flexural modes can clearly indicate the existence of the damage. The feasibility of the proposed system has been examined through finite element analysis and laboratory experiments.

7981-86, Session 10b

Structural health monitoring of wind turbine using fiber Bragg grating based sensing system

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As wind turbines become large, the early detection of structurally unstable condition becomes increasingly important for safety. This paper introduces the fiber Bragg grating based sensing system for use in multi-MW scale wind turbine as well as the result of preliminary field tests on dynamic strain monitoring. In this study, the Korea Institute of Energy Research (KIER) and the FiberPro developed wavelength and time division multiplexing (WTD) Bragg grating sensing system for high speed strain sensing in large structures. The linear array photo-detector with high-speed spectrometer allows sampling speed over 20kHz and four channels time division multiplexer expands the sensing capability up to 32 sensing points. This high speed Bragg grating sensing system showed good dynamic strain sensing performances during gearbox and tower monitoring in Woljeong wind turbine test field in Jeju island.

7981-87, Session 10b

Cable stretching construction monitoring based on FBG sensor

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The importance of real-time detection of cable force during stretching construction can hardly be overstated, especially in long-span space cable system. In this paper, some previous cable force measurement methods were presented and compared at first. As an alternative to the traditional methods, this paper aims to put forward a novel approach to monitor the cable stretching force using fiber Bragg grating (FBG) sensors. FBG sensing principle and sensor design were reviewed briefly, after which the cable force measuring principle was elaborated. The encapsulated FBG strain sensors were adhered onto the anchor to detect the strain variation of it, thereby indirectly measure the cable force. To get the cable force sensitivity coefficient, calibration tests were conducted prior to leaving factory, in which the linearity of cable force to wavelength was excellent. These calibrated cables were applied in monitoring the tensioning process of suspend-cable dome of Dalian Gymnasium under construction. The cable stretching process was monitored real-timely. During the stretching construction, some cable stretching force which hadn't meet the designed tension value were also detected and notified to the construction unit in charge. By cable force comparison of designed and measured value, an acceptable error rate less than 20% was calculated, in consideration of thermal influence, which is an unignorable factor that still needs to be further investigated. The monitoring results of stage stretching construction prove that this cable force monitoring method based on FBG sensors has advantages of easy installation, non-destruction to structure and high precision, showing promising potential in cable structure health monitoring.

7981-88, Session 10b

Lamb wave detection in prepreg composite materials with fibre Bragg grating sensors

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Lamb waves propagate in solid media and can therefore be successfully used for damage detection in composite plates. This paper will discuss the possibility of monitoring Lamb waves in CFRP prepreg material using Fibre Bragg Gratings (FBG)s for failure detection and production monitoring. FBG sensors are used in composite materials research, embedded or surface mounted, to perform structural health monitoring (SHM) in aerospace structures. This research focussed completely on the operational phase, when the composite material is used in its final application. Sensors that are embedded or surface mounted, might also be used immediately to detect production failures, to monitor the curing phase or to improve the non-destructive testing (NDT) phase. Lamb waves have been successfully detected by the authors in a one ply thick sheet unidirectional carbon fibre (UD-CFRP) material with a FBG sensor bonded to the surface in line with the fibre orientation.

Measuring Lamb waves in prepreg material is difficult as the bonding of the sensor is crucial. With the knowledge of measuring Lamb waves in prepreg, the authors also performed preliminary tests using piezoelectric transducer (PZT) sensors, to investigate the possibilities of that technique. This article will provide more detailed insight into the use of Lamb waves in UDFC as a monitoring technique during the production phase of the material. Furthermore, several detectable characteristics of prepreg material production will be investigated with PZT sensors and compared with FBG sensors.

7981-89, Session 10b

Life cycle strain mapping of composite airframe structures by using FBG sensors

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The purpose of this study is to develop structural health monitoring technology based on the strain mapping of composite airframe structures through their life cycles. First, the evaluation tests for damage detection in CFRP pressure bulkheads using FBG sensors were carried out, and the damage detection ability and accuracy of FBG sensors on various modes of damages and deformation were verified. As a result, damages could be detected as the changes in strain measured with FBG sensors. Moreover, the strain distribution changes due to damages measured by FBG sensors agreed well with numerical simulation. Next, the multifaceted filtering method using strain mapping for damage detection based on numerical simulations was investigated. As a result, the diagnostic indexes for damage detection from the analysis of deformation characteristics peculiar to each damage mode were shown. Moreover, strain changes which occurred near the bolted joints in assembling were measured with FBG sensors. These results demonstrated that FBG sensors could detect strain changes due to the correction of the thermal deformation in assembling and misalignment of bolt holes.

7981-90, Session 10c

Highly nonlinear solitary waves-based sensor for monitoring concrete curing

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This paper describes the application of a novel actuator/sensor technology for monitoring concrete curing. An automatic device is designed for generating and detecting the propagation of the highly nonlinear solitary waves (HNSWs) in a chain of steel beads. The reflections at the interface between the chain and a composite layer consisting of a thin aluminum plate and the concrete are observed. It was found that the wave speeds of HNSWs and the amplitudes of the reflected pulses depend on the boundary condition of the chain, so they change as the stiffness and strength of concrete develop during the curing process. Compared to the conventional method for determining the setting time of concrete by Vicat Needle which is widely used in practice, the presented technique is fully nondestructive, can be used for fresh concrete, and can be directly applied to the concrete specimens while the Vicat Needle determines the setting time of mortar.

7981-91, Session 10c

Damage identification under random dynamic loads based on long-gauge FBG sensors

Y. Tang, Z. Wu, Southeast Univ. (China); C. Yang, Southeast Univ. (China); G. Wu, L. Huang, Southeast Univ. (China)

In this paper, the performance of long-gauge FBG (Fiber Bragg Grating) sensors for identifying structural damage under random dynamic loads is investigated. At first, a three-storied pre-stressed reinforced concrete frame was prepared. To simulate the random loads, the specimen was set on a vibrating table loaded with three types of seismic waves and white noises. For getting the dynamic data, 20 FBG sensors with a special package at two different gauges, namely 10cm and 20cm, were bonded on the surface of one of the columns from top to bottom. Through analyzing the measured dynamic strain, the information about the modal strain, basic modal frequency and position of neutral axis of the column were abstracted at the same time, with which the damage can be identified. As well another new method in the time-domain zone is introduced and compared with the ways in the frequency-domain zone. Finally, the results have justified that the long-gauge FBG sensors can do a good job of damage identification under random dynamic loads together with the proposed methods in this paper.

7981-92, Session 10c

A distributed seismic damage sensing network using piezoceramic-based smart aggregates for RC building structures

S. Hou, Dalian Univ. of Technology (China)

The seismic damage mechanism remains murky due to the lack of the local response record during earthquakes, since the global response monitoring system fails to reveal the local failure modes owing to the high redundancy of building structures. Durable, stable, distributed, low power consumption and low cost are desirable features for the sensors of the structure local seismic damage monitoring, which can not be found in the inventory of conventional sensors. This paper proposed a distributed seismic damage sensing network using Piezoceramic-based smart aggregates for RC building structures, aiming to monitoring the structural local seismic response. The stress history and the crack patterns of the structure in the positions of interest are the two key items to be monitored. During the earthquake event, each smart aggregate of the network works in the way of load cell to record the internal stresses at the pre-designed positions. After the earthquake, each smart aggregate works as the actuator and exert stress wave in the concrete, and all the other smart aggregates receive the transmitted signals and indicate the damage along the wave propagation path by evaluating the wave energy attenuations. Thus, the crack pattern can be identified.

According to the seismic performance of building structures, prototype tests were conducted to verify the proposed method. The system for monitoring the stress and crack pattern was established. The ability of the smart aggregates in measuring the dynamic load was tested. The excitation frequency of the network for identifying the crack pattern was also optimized. By the preliminary work, it shows that the proposed system has the feasibility to unveil the seismic damage mechanism of building structures.

7981-93, Session 10c

Detection of damages in nonlinear reinforced concrete frames

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An objective of the structural health monitoring system is to identify the state of the structure and to detect its damages after a major event, such as the earthquake, to ensure the reliability and safety of structures. Innovative analysis techniques for the damage detection of structures have been extensively studied recently. However, practical and effective damage identification techniques remain to be developed for nonlinear structures, in particular nonlinear hysteretic reinforced concrete (RC) structures. In this paper, a smooth hysteretic model with stiffness and strength degradations and with the pinching effect is used to represent the dynamic characteristics of reinforced concrete (RC) frames. A system identification technique capable of detecting damages in nonlinear structures, referred to as the adaptive quadratic sum-square error (AQ SSE), is used to detect damages in nonlinear RC frames. The performance of the AQ SSE technique is also demonstrated by the experimental data.

Five identical 1/2-scale two-bay one-story RC frames have been designed and tested on the shake table at NCREC, Taiwan. Each RC frame was subject to different levels of seismic excitations followed by different levels of constant cyclic loads until failure. Test data were used to verify the capability of the AQ SSE technique in identifying structural damages. Experimental results demonstrate that the AQ SSE technique is quite effective in tracking the non-linear hysteretic parameters of RC frames with stiffness and strength degradations.

7981-94, Session 10c

Experimental demonstration of a damage detection technique for nonlinear hysteretic structures

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Many civil and mechanical engineering structures exhibit nonlinear hysteretic behavior when subject to dynamic loads, such as earthquakes. The modeling and identification of non-linear hysteretic systems with stiffness and strength degradations is a practical but challenging problem encountered in the engineering field. A recently developed technique, referred to as the adaptive quadratic sum-square error (AQSSSE), is capable of identifying parameters of nonlinear hysteretic structures. In this paper, the AQSSSE technique is applied to the parametric identification of nonlinear hysteretic reinforced concrete structures with stiffness and strength degradations, and the performance of the AQSSSE technique is demonstrated by the experimental test data.

A 1/3 scaled 2-story RC frame has been tested experimentally on the shake table at NCREC, Taiwan. The 2-story RC frame was subject to different levels of ground excitations back to back. The structure is firstly considered as a linear model with rotational springs, and the tracking of the degradation of the stiffness parameters is carried out using the AQSSSE technique. Then the same RC frame is considered as a nonlinear hysteretic model with plastic hinges following the Bouc-Wen model with stiffness and strength degradations. Experimental results show that the AQSSSE technique is quite effective for the tracking of: (i) the stiffness degradation of linear structures, and (ii) the non-linear hysteretic parameters with stiffness and strength degradations of RC structures.

7981-95, Session 11a

Structural integrity design for an active helicopter rotor blade with piezoelectric flap actuators

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In this paper, Active Trailing-edge Flap (ATF), which is one of the active control methods, is focused and examined. The rotor blade examined in this paper is called Seoul National University Flap (SNUF) blade.

SNUF blade is small scaled blade, and its cross section is composed of one spar. Thus, its cross section includes two cells. SNUF rotor blade will rotate at a quite high rotational speed, 1,528 RPM. And there are relatively heavy components in order to actuate the flap included at 65~85% span of the rotor blade. Therefore, concentrated loads will act upon that specific region. Thus detailed analysis is conducted to verify the structural integrity of SNUF blade. Structural analysis is conducted separately into 1-D beam analysis and 2-D cross sectional analysis. The cross section of the blade is designed by using a 2-cell thin-walled cross section analysis. And 1-D beam analysis is conducted based on the results of the cross sectional analysis. The stresses existing in each composite ply of the rotor blade under a certain rotation condition is computed to see if there is any failure in the material. Thus stress recovery is conducted for that purpose by using 2-D cross sectional analysis. After the blade design is completed by using 1-D and 2-D analysis, 3-D structural analysis will also be conducted. It is quick and sufficient to conduct the blade design by using 1-D beam and 2-D cross sectional analysis. However, more detailed results can be obtained by 3-D analysis, containing the effects of the flap actuation region.

7981-96, Session 11a

Simplified 2D modeling of power and energy transduction of piezoelectric wafer active sensors for structural health monitoring

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This paper presents an investigation of power and energy transduction in piezoelectric wafer active sensors (PWAS) for structural health monitoring (SHM). After a literature review of the state of the art, we developed a model of 2-D power and energy transduction of PWAS attached to structure. The model is an extension of our previously presented 1-D model. It allows examination of power and energy flow for a circular crested wave pattern. The model assumptions include: (a) 2-D axial and flexural wave propagation; (b) ideal bonding (pin-force) connection between PWAS and structure; (c) ideal excitation source at the transmitter PWAS and fully-resistive external load at the receiver PWAS (d) crested wave energy spread out. Frequency response functions are developed for voltage, current, complex power, active power, etc. Wave propagation method for an infinite boundary plate, electromechanical energy transformation of PWAS and structure, and wave propagation energy spread out in 2-D plate were considered. The parametric study of PWAS size, impedance match gives the PWAS design guideline for PWAS sensing and power harvesting applications.

7981-97, Session 11a

Embedded piezoelectric sensor-based real-time strength development monitoring during curing process of concrete

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Recently, novel methods to monitor the strength development of concrete during curing process have been reported based on electro-mechanical impedance measurement using piezoelectric sensors. However, the previous research works could not provide the information about the early age of strength development. In order to estimate the strength for early age of concretes, an embedded intelligent sensor system is developed in this study. To avoid the degradation of a piezoelectric sensor due to external and internal impacts and/or environmental variations, the piezoelectric sensor soldered with a lead wire is inserted into a small concrete block and then this block is embedded in larger concrete specimen. While the concrete is cured, the electro-mechanical impedance and guided wave signals self-measured from the embedded piezoelectric sensor will be changed because those are related to the material properties of the concrete such as the strength and the stiffness. Hence, the strength development of concrete can be monitored by analyzing the consistent variations in the measured impedance and guided wave signals. Specific equations to estimate the strength of the concrete are derived using a pattern analysis based on the features extracted from the signal variations. Finally, to verify the effectiveness of the proposed approach, a series of experimental studies using miscellaneous concrete specimens are conducted and further research issues will be discussed for real-world implementation of the proposed approach.

7981-98, Session 11a

Piezoelectric sensor for in-situ measurement of stress intensity factors

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Regular inspections of fatigue cracks in complex structures like aircraft structures or wind turbines are expensive. A prediction of crack growth on the basis of calculations often proves problematic. In particular, lack of

information on the usually stochastic load collectives causes inaccurate estimations of the growth rates of fatigue cracks.

A method for determining stress intensity factors using a thin piezoelectric ceramic material is presented in [1] and [2]. In [3] and [4], this method is extended for real time monitoring of fatigue cracks in thin-walled shell-structures using piezoelectric polymer films (PVDF). It allows a spatially re-solved measurement and the simultaneous determination of the crack tip location as well as the K-factors. From the measured electrical signals, the K-factors and the location of the crack tip can be determined by solving the resulting inverse problem. In earlier investigations KI and the position of the crack tip were determined with sufficient accuracy, in contrast to KII. The cause of the improper identification of KII could not yet be clarified. In a first attempt the concept was tested and verified at the example of a straight crack in an infi-nite plate under mixed-mode loading conditions. The results led to significant improvements of the sensor layout. First experiments could be successfully carried out on cracked aluminum specimen.

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7981-99, Session 11a

Development of a nano-textured nonporous Pt/Ti bottom electrode for sol-gel derived lead zirconate titanate (PZT) thin films

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Lead Zirconate Titanate Oxide ($\text{PbZr}_x\text{Ti}_{1-x}\text{O}_3$ or PZT) thin films have received increasing attention for their potential applications in piezoelectric micro-sensors and actuators. For PZT thin films fabricated via sol-gel processes, Pt/Ti bi-layer is the most common choice for bottom electrodes. Before the PZT film is deposited, Pt/Ti bi-layer must be annealed at high temperature (e.g., 800°C) to obtain a condensed structure with a rough micro surface texture. A condensed Pt/Ti structure prevents delamination of the bottom electrode, while a rough micro surface texture ensures PZT thin films anchored firmly into the bottom electrodes. Although the annealing process is necessary, its high temperature causes Pt/Ti bi-layer to become porous, thus degrading electrical and ferroelectric properties of the PZT thin films.

In this paper, we present a novel Pt/Ti bottom electrode that is nonporous yet with the desired micro surface texture for PZT thin films. The new electrode is made via a two-step E-Beam evaporation and annealing process. To evaluate the new electrode, we measure leakage current density J of PZT thin film samples with porous and nonporous Pt bottom electrodes for comparison. In the experiments, an HP4155B semiconductor parameter analyzer generates an electric field across the PZT thin films. While the electric field steps from 0 kV/cm to 150 kV/cm with a resolution of 0.5 kV/cm, a corresponding leakage current density J is obtained via J-E curve. Experimental results show that the leakage current density J for PZT thin film samples with porous and nonporous Pt bottom electrodes are 3.73×10^{-7} A/cm² vs. 2.03×10^{-8} A/cm² at 2V. This indicates that our novel nonporous Pt/Ti bottom electrodes has reduced the leakage current by an order of magnitude and improves performance of PZT thin films.

7981-100, Session 11b

Study on the temperature characteristics of distributed optical fiber sensors

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In this paper, based on the distributed optical fiber strain sensing technology of pulse-pre-pump Brillouin Optical Time Domain Analysis (PPP-BOTDA), the temperature characteristics of three types of optical fiber sensors, i.e. single mode optical fiber with jacket (Type-A), optical fiber with UV resin coating (Type-B) and a novel optical fiber with improved strain sensitivity (Type-C), were studied at a given temperature amplitudes. Experimental results show that there exists linear relation between the measurements of all the three types with temperature variation. But Type-B and Type-C, with better linearity and stability than Type-A, are more suitable for the temperature monitoring of infrastructure. Moreover, temperature compensation methods corresponding to these types of optical fibers were talked about to consider the temperature effect to structure and realize the separation of temperature and strain.

7981-101, Session 11b

A monitoring of breathing using a hetero-core optical fiber sensor

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A multi purpose monitoring system has been developed as a commercially available standard using the technique of optical fiber sensor, for the purposes of human health monitoring human vital activities and body motions. Especially, a monitoring human breathing has been seen as an important source of factor for vital status for emergency medical service. The monitoring of breathing has been tested and evaluated in a possible breathing condition of a person to be monitored. A hetero-core optical fiber humidity sensor was developed for in order to monitor relative humidity (RH) in a medial mask. A light intensity characteristics of sensor for RH was examined the performance to changing RH, and to clarify RH influences in terms of a sensitive range and a stability. Elements for determent breathing condition were extracted from the light intensity changing at some human breathing condition, which were Breath-depth, Breath-cycle, Breath-time and Check breathing based on threshold level. It is found that the elements had differences relative to normal breathing, for instance, the Breath-depth 1.51V (light intensity) of deep breathing is higher than 1.32V at normal breathing by mouse. A real-time monitoring for breathing was experimented and it successfully observed the actually given breath by means of measuring the light intensity using a PD and differences of some breath condition calculation based using an opticalmultimeter. The breathing condition value was experimented using a simple measuring system and found clear difference from extracting some factors which are used evaluating breath condition in emergency medical care.

7981-102, Session 11b

* Investigation of miniature fiber optic surface-mountable Fabry-Perot pressure sensor built on 45° angled fiber

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We present a surface-mountable miniature Fabry-Perot (FP) pressure sensor that exploits the total internal reflection at a polished 45° angled fiber end face to swerve the optical axis by 90°. Optical analysis of the sensor system is performed based in ABCD method in terms of intensity of the beams reflected from each mirror and visibility of the sensor compared to conventional sensor system. One unique feature of the surface-mountable sensor is that it can be directly mounted on a structure surface or embedded in a shallow channel to measure

pressure with minimum intrusiveness to the system. By using the fiber as a waveguide, as well as an inherent mask for photolithography, a self-aligned FP cavity is constructed on the sidewall of the fiber. A polymer-metal composite diaphragm is employed as a deflection diaphragm for pressure sensing which enables achieving higher sensitivity and low-cost fabrication over silicon diaphragm. The sensor exhibits a good linearity over the designed pressure range. Fiber Bragg grating is embedded in the vicinity of the pressure sensor to measure the temperature of the system and compensate the effect of it. The problem of cross sensitivity between pressure and temperature is resolved by integrating two sensors in one fiber and measuring pressure and temperature simultaneously. This sensor is expected to impact many fronts where temperature effect should be considered to perform reliable and accurate pressure measurement with minimum intrusiveness.

7981-103, Session 11b

Transformer winding temperature estimation based on tank surface temperature

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Electrical grid is a critical part of the infrastructure. Power transformers are among the most valuable assets in the electrical grid. Many power transformers fail each year around the world for various reasons. Some of the failures are related to winding insulation damage caused by high temperatures.

Recently, fibre optic temperature sensors become a viable solution for direct winding temperature measurement. However, a fibre optic temperature sensor could only be installed at the manufacturing stage. For operating transformers without fibre optic temperature sensors, winding temperature estimation based on the conventional methods, such as by using winding temperature indicators, would require measured top oil temperature. For transformers where oil temperature measurement is not easily available, tank surface temperature may be used as an alternative, as it offers the potential to monitor and detect abnormal winding temperature without modifying the transformers. This paper shows how surface temperature may be utilised for this purpose. The data used in this paper are acquired using a special test transformer designed for research purposes. The surface temperature is measured using thermocouples. Winding temperature estimated based on measured surface temperature is validated against winding temperature measured using embedded fibre optic sensors.

7981-104, Session 11b

Measurement of a tree growth condition by the hetero-core optical fiber sensor

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Condition and growth of forests are considered to be important in monitoring global circulation with heat and water, additionally growth of trees are affected by CO₂ and air pollutants. On the other hand, since growth of plants is affected by surrounding climates, it is expected real-time monitoring of crop plants growing makes us quantitative agricultural management.

In this study, we proposed the dendrometer for measuring radial growth of a tree and the stretching sensor for measuring extension growth of a relatively-small plant using hetero-core optical fiber whose characteristics of optical loss for bending a sensor portion is monotonic and sensitive. The sensors are suited for long-term, remote and real-time monitoring with wide area such as forest because the hetero-core optical fiber sensors are independent from temperature fluctuation and weather condition in addition to advantages of an optical fiber such as thin and light cable, no electromagnetic interference and resistance to corrosion.

In our experiment, it was demonstrated the sensor was capable of measuring the differences of tree growing trend period of different seasons such as one tree have grown up 2.081mm in spring-summer and 0.213mm in autumn-winter, respectively. Additionally, it was suggested

that the sensor was capable of monitoring tree growing condition changes due to high resolution, automatically, short interval measuring.

The experiments performed on the hetero-core optical fiber show a new implication that the monitoring system could realize using for forest health monitoring and agricultural control.

7981-105, Session 11c

Applications of embedded capacitance sensors in layered polymer structures

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The theory of parallel plate capacitance can be used in a layered polymer structure to allow continuous structure health monitoring. Capacitive sensors have a wide field of applications for measuring changes to layered polymer structures that are the result of a change in an external parameter, such as pressure, or are the result of a structural failure within the layered polymers themselves. While the theory for the embedded capacitance sensor is the same for each application, the implementation of the sensor is unique. Each application has different parameters, both internal and external, that need to be identified and calibrated. This sensor type has the ability to be used either intermittently or continuously for health monitoring or as part in a larger closed loop control.

This type of sensor measurement is driven by the physical properties in the parallel plate capacitance equation. The general equation for parallel plate capacitance is shown in (1). "C" is the capacitance; "κ" is the dielectric constant of the material between the plates; "ε₀" is the permittivity of free space; "A" is the area of the plates; and "d" is the distance that separates the plates.

$$C = (\kappa \cdot \epsilon_0 \cdot A) / d$$

In normal applications, ε₀ is assumed to be constant, so capacitance can be varied due to a physical change in four ways. Capacitance is affected by a change in the overlapping area of the electrode plates, a change in dielectric material, or due to a change in the distance between the plates. When applied to layered polymer structures the changes in capacitance have a direct correlation to changes in the overall structure. Area of the plates can change from plate deformation due to applied loads or plate displacement. Changes in dielectric material can occur due to delamination or seepage of the environment between the layers. Distance between conductive plates can change due to delamination of the layers or deformation of the sandwiched dielectric material.

The sensor itself is created from two integrated layers of conductive polymers separated by a polymer layer which has a high dielectric constant. This paper is an overview of current research into the application of this type of sensor. When incorporated into a hydraulic hose, it was found that capacitance measurement of the sensor increased in a linear manner as pressure inside the hose increased. The sensor was used in on-highway tires to successfully monitor pressure and predict possible catastrophic tire wall failure in a laboratory setting. This type of capacitance sensing was also incorporated into material testing for human lumbar disc replacements. Results from the research showed a correlation between capacitance measurements and amount of damage sustained by the ultra-high molecular weight polyethylene (UHMWPE) test material. Additionally, this type of embedded capacitance sensing has been researched in hydraulic o-ring seals. Again, there is a correlation between the capacitance measurement and initial squeeze on the o-ring, the operating pressures on the o-ring in the hydraulic system, and the structural integrity of the o-ring.

7981-106, Session 11c

Regularization of pattern formation in metal/SMP bi-layer structures

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Wrinkling metal thin films on compliant substrates can lead to interesting applications such as sensor skins, stretchable circuits, electronic muscles and so on. Wavy patterns can be formed in metal thin film/compliant substrate structures via a heating or cooling process. However, the compressive-stress induced patterns resulting from the thermal expansion (CTE) mismatch in the bi-layer structure are usually isotropic - that is, they have no preferred orientation. This randomness hinders the advanced application of integrated devices. In this paper, we use pre-programmed shape memory polymer (SMP) as the substrate in the bi-layer structure. By heating the hybrid structure above the SMP's shape recovery temperature, the substrate expands because of positive CTE in one direction, while in the perpendicular direction it shrinks due to shape memory effect overpowering thermal expansion. Consequently, the metal thin film is subjected to an orthogonal stress field and forms unidirectional wavy patterns.

7981-108, Session 11c

Sensing performance of electrically conductive fabrics and dielectric electro-active polymers for parachutes

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The performance of a parachute is dependent on physical properties of the parachute canopy such as porosity, geometry, and air vent openings. The ability to change these physical properties will greatly expand the performance and maneuverability of parachutes. In order for the variables to be controlled during flight, an intelligent network of sensors must be instrumented to acquire data throughout the duration of the drop. Relevant data includes strain, load, and pressure. Ideally, a parachute would make adjustments to the geometry or porosity of the canopy utilizing intelligent actuators based on feedback from strategically placed sensors. Additionally, the sensing technologies could provide a quantifiable measurement of the maximum strain or load during a drop. This information is important to ensure the structural integrity of the parachute was not compromised during a drop and to assist in understanding the physical dynamics of parachute opening and steady state flight.

This paper quantifies the sensing capabilities of novel smart materials in an effort to improve the performance, better understand the physics, and enhance the safety of parachutes. Based upon a recent review of actuation technologies for parachute applications, it was shown that the actuators reviewed could not effectively alter the drag or lift (i.e. geometry, porosity, or air vent openings) of a parachute during flight. However, several materials showed potential for sensing applications within a parachute, specifically electrically conductive fabrics and dielectric electro-active polymers. This paper introduces several new conductive fabrics and provides an evaluation of the sensing performance of these smart materials based upon test results using mechanical testing and digital image correlation for comparison.

7981-109, Session 11c

Unidirectional strain sensing properties of conductive composite with anisotropic piezoresistivity

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Piezoresistivity of conductive composites was usually utilized for strain sensing. In this paper, a tunnel effect theory-based piezoresistivity model was proposed to predict the strain-sensing property of conductive composite. The proposed model indicated that piezoresistivity of a randomly dispersed conductive composite is multi-axial dependent. In other words, we want to use the composite to measure the strain in x axis, however, the change in resistance may be caused by the strain in y axis or z axis. Therefore, to make the piezoresistivity unidirectional sensitive, the conductive network in composite should be structured.

Experimental study was conducted on the polymer-based composites. As motivated by the structured conductive network for unidirectional piezoresistivity, the conductive particles were aligned during curing. The size of specimen was 10×10×36mm. DC electrical resistance measurement was made in the longitudinal axis, using the four-probe method. Compressive testing was performed on a 10×10mm side of each specimen (longitudinal pressure) and on a 10×36mm side of each specimen (transverse pressure), respectively. During loading process, DC electrical resistance measurement was simultaneously made. For the specimens with uncontrolled conductive networks, 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 multi-axial stress dependent. For the specimens with structured conductive networks, the resistance was found only sensitive to the longitudinal pressure, suggesting that unidirectional piezoresistivity can be achieved by controlling the conductive networks in composite.

7981-110, Session 12a

Characterising fatigue damage in train structures based on nonlinearity of acousto-ultrasonic signals

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Envisioning rapid development of railway networks worldwide but envisaging threats to the safe operation of networks due to continuous ageing of train structures, there has been increasing interest in developing cost-effective and practical structural health monitoring (SHM) solutions to in-service trains. Majority of existing ultrasonics-based SHM has been developed and validated for linear macroscopic damage, by canvassing linear properties of waves such as attenuation, transmission and mode conversion. However real damage in train structures initiates from microscopic fatigue damage under cyclic loading, which is a sort of nonlinear damage, presenting highly nonlinear features. Complicated working environment and operational variability of railway network bring on additional difficulties to signal interpretation. In this study, a SHM technique targeted at fatigue damage in typical train structures was developed by exploring extracted nonlinearities of higher-order acousto-ultrasonic wave signals, including (i) the second-harmonic wave generation (effect of second-harmonic generation by acousto-ultrasonic wave is highly sensitive to fatigue damage) and (ii) spatial reciprocity of signals (nonlinear damage causes nonlinear wave propagation behaviour, breakings spatial reciprocity). A diagnostic sensor network was designed and integrated to train structures to activate and capture acousto-ultrasonic signals. A signal processing technique was developed to facilitate extraction of nonlinear signal features. A probability-based diagnostic imaging approach based on data/image

fusion was introduced to visualise damage, whereby health status of train structures can be estimated in a quick and straightforward manner. The feasibility of the proposed technique was experimentally evaluated, and results showed satisfactory monitoring accuracy for fatigue damage in train structures.

7981-111, Session 12a

A PZT nanoscale active fiber composites acoustic emission sensor for structure health monitoring

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The integration of smart materials into civil engineering structures, such as bridges, dams, towers and roads, can allow one to monitor or actuate them for different purposes. Active fiber composites (AFCs) based AE sensors have demonstrated a number of advantages in comparison with conventional acoustic emission (AE) sensors, such as low weight, flexibility, anisotropic sensitivity. However, they are still too thick to be embedded in composites structures. Here we present a self-powered nanoscale active fiber composite (NAFCs) based AE sensor with high sensitivity. The aligned lead zirconate titanate (PZT) nanofiber, with a diameter and length of approximately 60 nm and 500 μm , was electrospun on a silicon substrate. The interdigitated electrodes were deposited on the PZT nanofibers and packaged by spinning a thin soft polymer layer on the top of the sensor. The sensor was imbedded in the epoxy structure and the measured output voltage under the periodic impact of a grounded steel bar was over 0.2 Volt. The PZT NAFCs AE sensor show promising application in monitoring the structures by integrated into composites.

7981-112, Session 12a

Frequency steerable acoustic sensors for SHM

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Structural health monitoring (SHM) is an active research area devoted to the assessment of the structural integrity of critical components of aerospace, civil and mechanical systems. Guided wave methods have been proposed for SHM of plate-like structures using permanently attached piezoelectric transducers, which generate and sense waves to evaluate the presence of damage.

This paper illustrates the equations that govern sensing of elastic waves (Lamb waves) through surface mounted piezoelectric patches. The case of a piezo patch of arbitrary shape is illustrated as a general framework for the subsequent illustration of the principles of directional sensing through properly shaped patches.

In essence, the transducers act as spatial filters, which preferentially sense directions corresponding to wavenumbers defined by the spatial arrangement of their elements. Through the dispersion relation of the elastic substrate the sensing wavenumbers can be associated to frequencies. Waves direction of arrival can thus be determined from the sensed frequency.

At the same time, the transducers can be used in actuation with frequency dependent directional characteristics, which allow beam steering through a sweep of the excitation frequency.

The concept has the potential to enable in-situ monitoring of critical components through strongly focused sensing (and/or actuation) and directional scanning capability, which may be achieved with very limited hardware requirements, leading to a robust and single channel control device suitable also for wireless applications.

Performances of the transducers have been evaluated numerically and a virtual approach using a laser doppler vibrometer has been developed to perform a preliminary experimental validation of their capabilities. Very promising results has been obtained.

7981-113, Session 12b

Ultra low-power corrosion-enabled sensor node

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Structural health monitoring incorporates sensing, data management, and statistical modeling to measure the performance of a host structure. Sensing systems play a lead role in this paradigm by performing actuation, data acquisition, and communication in order to enable the implementation of a health monitoring strategy. In many applications power provision can become a limiting factor, as the conventional strategy for wireless networks is a battery. However, batteries require replacement as their power capacity often does not exceed the intended long-term sensing requirements of their host structures.

Energy harvesting has emerged as a class of potential powering solutions whereby one form of energy available on the structure is harvested and converted to useful electrical energy. The objective of this work is to investigate the harvesting of energy from galvanic corrosion that naturally occurs in many structures. Specifically, this initiative considers the design of a sensor node to manage energy harvested from galvanic corrosion between magnesium and graphite rods encased in a concrete structure immersed in seawater. The sensor node makes use of high-efficiency switching converters and low-power microprocessors to reduce the power demands on the energy harvester. This investigation also considers the correlation between the output power of the corrosion-based energy harvester relative to the pH levels of the electrolyte.

7981-114, Session 12b

Temperature compensation of piezoelectric energy harvesters using shape memory alloys

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Energy harvesting from ambient vibrations in civil and mechanical structures has been given a growing attention in recent years. Converted electrical energy is typically used as a power source for sensors' networks for health and usage monitoring. The longevity, and hence the efficacy, of these sensors are severely limited by the levels of generated power. Piezoelectric vibration harvesters have been widely used given their energy conversion ability and relatively high mechanical to electrical coupling properties. Several techniques can be applied to improve these properties and to cancel external environmental effects such as temperature variations. These techniques include the optimization of the piezoelectric material itself, the alteration of the electrode pattern and system configuration, the use of matching networks to increase the power transfer, and most importantly, the tuning of the harvester's resonant frequency to match the fundamental frequency of the base insuring a maximum response,

In this paper, the alteration of the energy harvesting characteristics of a bimorph cantilever PZT piezoelectric beam, through a combination with shape memory alloys, is studied. A mathematical model, based on one-dimensional linear piezoelectricity equations and one dimensional constitutive behavior of shape memory alloys, is derived. The model describes the effect of temperature deviations on the theoretical harvestable energy levels and the natural frequency of the piezoelectric device. An experimental analysis is also performed. Voltage transfer functions of a piezoelectric scavenger for different temperature values are measured and compared to predictions from the theoretical model.

7981-115, Session 12b

Multi-functional self-powered sensor for long-term ambient vibration monitoring

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Unlike conventional energy harvesting sensors, self-powering sensors scavenge energy for sensing, computation and storage from the signal being sensed. In this paper, we demonstrate the feasibility of a self-powered sensor that can monitor multi-functional attributes of vibration signals without the aid of batteries or remote powering. At the core of the sensor is our previously reported piezo-floating-gate (PFG) technology which facilitates long-term monitoring at fundamental limits of energy scavenging. We extend the core design to simultaneous self-powered monitoring of strain-levels, strain-rates and temperature.

The mathematical model for multi-functional monitoring is presented which is further validated using measured results. Using prototypes fabricated in a 0.5 micron standard CMOS process, we demonstrate that a micro-scale sensor can sense, compute and store level-crossing statistics of the multi-functional attributes while consuming only 35nA per channel.

7981-116, Session 12c

Decentralized SHM system based on substructure parameter identification

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A new decentralized structural health monitoring (SHM) system based on substructure dynamical parameter identification method is proposed in this paper, which is designed for embedding on smart sensors with a vibration sensor and a processor for decentralized computing.

Recent technological advancements in low-cost and compact sensing and networking devices enable the SHM system to be a decentralized system with high system scalability and redundancy. However, unlike in conventional centralized systems, the processing jobs of sensing data in such a decentralized system should be proficiently divided into small pieces and assigned to each sensor node.

In this paper, a decentralized SHM system using Kalman filter algorithm and substructure parameter identification method is proposed, which can be executed in parallel in each smart sensor. The proposed system is flexible for sensor placement, so we can place smart sensors only in the locations of interest, such as seismic isolation storey or around vibration absorption dampers. And also, the method consists of online recursive algorithm, so it can detect structural nonlinearity for damage detection. To show the advantages of the proposed decentralized SHM system, some identification processes are demonstrated using the data sets of both numerical simulations and seismic observation data of a real building.

7981-117, Session 12c

An optimal sensor configuration strategy for decentralized structural damage detection

M. Jayawardhana, X. Zhu, R. Liyanapathirana, Univ. of Western Sydney (Australia)

Due to the variety of challenges that Civil structures face in their life time such as environmental, service and accidental actions, Structural Health Monitoring (SHM) and damage detection techniques have become vital to maintain safety and integrity of structures, to increase their life span and to reduce costs of maintenance and repairs. Owing to these facts SHM has become a key area of interest for researchers and Structural engineers. The disastrous failures of bridges around the world occurred in the recent past such as the I-35W highway bridge over the Mississippi River in Minneapolis, Minnesota, US, 2007; emphasize the need to develop an effective, real-time and cost-effective SHM and damage detection system. This is imperative in protecting the structure as well as preserving human lives, and developing an economic infrastructure asset management scheme. With the advancements of telecommunication technologies and smart devices, Structural health monitoring is no longer a concept limited only to theory and research. It is now being used to monitor structures in real world with successful results. Wireless Sensor Networks (WSNs) have rendered the task of SHM more cost effective

and convenient as opposed to conventional Wired Networks, making the deployment of SHM systems practically realisable and manageable. These actual applications have brought the attention of engineers and researchers to many new areas and issues related to SHM. Distributed structural damage detection is one such area with high potential for development. In the light of development of sensor nodes as intelligent devices, distributed computing strategy for structural damage detection has proved to significantly reduce the power consumption of the system while giving more robust and accurate results with increased efficiency. Efficient power management and optimal sensor configuration are some issues that have been identified with regard to WSN based SHM systems.

Being a local phenomenon, structural damage detection gives better results when more sensors are deployed in a structure. An SHM system with densely distributed sensors similar to the neuron network in human body can be used to easily identify and localize damages. But this will not be an efficient and effective system as in the case of human body, since it will unnecessarily increase the cost of the system and power consumption as well. This is where optimal sensor configuration comes into picture. It has proved to be a significant part in designing an SHM system in the recent research work. Inefficient sensor configuration may result in wastage of investment and in an extreme case it may also lead to fatal disasters due to poorly equipped structural monitoring systems. Telecommunication related factors such as sensing range, wireless communication properties as well as Structural Engineering factors such as model of the structure and construction specifics affect the decision of sensor configuration. In this paper an improved sensor configuration strategy for distributed structural damage detection using WSNs is presented. First the existing sensor placement strategies are discussed and their drawbacks with regard to distributed structural damage detection are identified. Changes that are required in the existing strategies to achieve optimal damage detection results for distributed systems are briefly discussed. An efficient sensor placement method is developed to maximize the network lifetime by optimally determining locations and number of sensors for a structure, activity schedules and energy consumption of deployed sensors and data flow routes. This strategy is first implemented in a simulation environment and the successful results are presented. Then it is implemented in a laboratory, in a simply supported beam structure and the resulting outcome is compared. The results show that the efficient SHM can be achieved through the optimization of sensor configuration.

7981-118, Session 12c

Decentralized modal analysis using stochastic subspace identification

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Wireless sensors have been recognized as a promising technology for structural health monitoring. Its cost-effectiveness and maintainability enable massive deployment of sensors that are required for larger-scale civil infrastructures. Despite the advances in the technology, power consumption is still a challenge in real applications. The idea is to exploit the on-board computation capacity of wireless sensors to reduce data communication, and then reduce power consumption. The paper proposes a new decentralized processing technique for modal analysis based on stochastic subspace identification (SSI). The SSI method uses some robust numerical tools such as the singular value decomposition (SVD) to process measured data, which makes the algorithm efficient and reliable. It is also applicable for multi-input and multi-output cases, which makes it a promising technique for wireless sensors networks with various topologies. In the proposed technique, measurements from one sensor node are transmitted to the other sensor nodes as reference data, then the SSI is performed in the others sensors. The identified state-space model or modal parameters are then transmitted to base stations for centralized data aggregation. Special network topology is not required and the total data to be transferred can be significantly reduced. Finally, the performance of the proposed technique is demonstrated using numerical examples.

7981-119, Session 12d

Physics-based model for predicting the performance of a miniature wind turbine

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A miniature wind turbine (MWT) has received great attention recently for powering low-power devices. In this paper, a comprehensive physics-based model for predicting the performance of the MWT was developed. The turbine rotor performance was measured and an approximation of the power coefficient of the turbine rotor was made. Incorporation of the approximation with the equivalent circuit model which was proposed according to the principles of the MWT, the overall system performance of the MWT versus the resistive load and ambient wind speed was predicted. To demonstrate the predictive modeling capability, the MWT system comprised of commercially available off-the-shelf components was designed and its performance under different wind and resistive load condition was tested experimentally. To get a low start speed, the MWT blade was composed of a 7.6 cm thorgren plastic propeller rotor with four blades. The system efficiency of the MWT reach 7.5% at the wind speed of 6m/s. The predicted output voltage, power and system efficiency are matched well with the tested results, which imply that this study holds promise in estimating and optimizing the performance of the MWT. When the incoming wind speed is 3.5 m/s, the generated power of the MWT is about 7 mW which can be used to power some low power wireless sensors. The airflow at 3.5m/s speed is very common in the natural world and also can be provided by heating, ventilating, and air-conditioning (HVAC) systems. Moreover, when the MWT operates at high wind speed condition such as the high speed wind tunnel or hurricane environment, it can get much higher output power and apply for multiple uses.

7981-120, Session 12d

Smart actuation of inlet guide vanes for miniature turbine engine

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This paper focuses on the feasibility of a smart, compact actuation mechanism for Inlet Guide Vanes (IGV) in miniature turbine engines. Existing hydraulic actuators change the angle of attack of variable-geometry IGV in response to changes in operating conditions. IGV have been used in large-scale gas turbine engines since the 1970's. Due to an increase in UAV usage worldwide, there is a need to develop small-scale jet-engines, and implicitly small IGV actuation mechanisms.

The current paper studies the feasibility of a light, compact smart-material based actuation for IGV. The preliminary design parameters were provided by a turbine engine manufacturer to the authors. The preliminary IGV were designed to have a 1.2-inch-interior diameter and 3 inch-exterior diameter. Preliminary flow conditions assumed a range of trailing edge exit flow angles varying from 350 to 450 for an inlet Mach number of 0.4. Computational fluid dynamics calculations were performed to validate initial control-volume calculations of force, moment and angular displacement needed for blade actuation through a range of angles of attack. The actuation force and moment calculations were performed parametrically for an IGV stage that contained from 10 to 20 blades. The initial design of the actuation mechanism (based on crank-slider), was performed. Several smart material-based actuation methods, including piezoelectric inchworm motors, were investigated.

7981-121, Session 12d

Wind turbine gearbox health monitoring using time-frequency features of signals

J. Tang, Y. Lu, Univ. of Connecticut (United States)

Due to wind energy's increasing contribution to the electricity supply, maintenance of wind turbines emerges as a critical and challenging issue in the engineering society. Because of the remote nature of those turbines, autonomous health monitoring techniques are necessary. Gearbox, as the core component for each wind turbine, is the natural focus in such development. In this research, we collect time domain signals from a gearbox testbed which can simulate different fault conditions by changing gears, adjusting clearance, or programming motor and brake parameters. The signals are then processed and time-frequency domain features can be extracted for further diagnosis. The feature extraction and diagnosis process may be implemented onto a wireless sensor node and a PC separately, with a balance between computational capability and power consumption.

7981-122, Session 13a

Development of hybrid type pneumatic vibration isolation table by piezo-stack actuator and filtered-X LMS algorithm

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Recently, vibration requirements are getting stricter as precise equipments need more improved vibration environment to realize their powerful performance. While the passive pneumatic vibration isolation tables are frequently used to satisfy the rigorous vibration requirements, the specific vibration problem, especially continuous sinusoidal or periodic vibration induced by a rotor system of other precise equipment, a thermo-hygrostat or a ventilation system, is still left. In this research, the application procedure of Filtered-X LMS algorithm to pneumatic vibration isolation table with piezo-stack actuators is proposed to enhance the isolation performance for the continuous sinusoidal or periodic vibration. And the experimental results to show the isolation performance of proposed system are also presented together with the isolation performance of passive pneumatic isolation table.

7981-123, Session 13a

Semi hardening and snap-through mechanism system for smart vibration generators

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We proposed a novel mechanism system named 'Semi Hardening and Snap-Through (SHST) Mechanism System' for vibration generators. This mechanism system combines dynamics characteristics of the nonlinear hardening mechanism by adopting fixed-fixed beams and the nonlinear snap-through mechanism by introducing attractive magnetic forces. Existing nonlinear dynamics vibration energy harvesting devices have been experimentally proved to be able to effectively expand the operational frequency range well compared with the narrow bandwidth of linear resonators. However, because of the additional nonlinear stiffness term introduced by nonlinear vibration devices, the response amplitudes of these devices are lower than that of linear resonators within the frequency range between the response start point and the frequency response curves cross point under the same input acceleration. It could be observed that the stiffness of SHST mechanism system is significant lower than nonlinear hardening mechanism system which is primarily

adopted by existing nonlinear vibration devices by the static analysis of the relationship between displacement and stiffness. Through numerical simulations for both systems with the same device volume and input vibration criteria, SHST mechanism system could increase the response amplitudes by over 20% and expand the operation frequency range by over 5% compared with nonlinear hardening mechanism system. Besides that, due to the nonlinear snap-through mechanism characteristics of SHST mechanism system, the travel of the mass between the two maxima is speeded up. Therefore, SHST mechanism system would be suitable for both piezoelectric vibration generators and electromagnetic vibration generators.

7981-124, Session 13a

Sensitivity vector fields in embedded coordinates

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Identifying variations in system parameters is essential in diagnostic engineering applications ranging from damage detection to mass sensing. Vibration-based methods that measure resonant frequency shifts are often used for this purpose. However, frequency-shift methods may be ineffective under certain circumstances: when the system has a low quality factor, when it is insensitive to the parameters of interest, when it is significantly nonlinear, or when multiple simultaneous parameter changes need to be distinguished. One alternative metric is the sensitivity vector field (SVF), a means of quantifying changes in the morphology of a system attractor resulting from parameter variations. SVFs have proven to be a reliable means of identifying parameter variations and remain effective even in cases where frequency-shift methods fail. Properly designed nonlinear feedback can be used to enhance or reduce the sensitivity of SVFs to parameter variations of interest.

Previous research on SVFs focused on simulations and experiments where it was possible to access a full set of state variables. In all but the simplest real systems, this kind of knowledge is not possible; as the dimensionality of the system increases it becomes increasingly difficult to measure the full state and to densely populate the state space with data. Often, we have access to only a single time-series: a sequence of scalar data points measured at successive times. When this is the case, it is still possible to reconstruct the state space of the dynamical system using embedded coordinates. The most common form of embedding is a delay reconstruction where vectors consisting of individual observations separated by a fixed delay time are used.

In this paper, we discuss how to practically implement SVF in embedded coordinates. The problem is fundamentally a prediction problem: starting at an initial condition in the state space we want to predict two states in the future, one state for the system having nominal parameters and a second state for the system under some perturbation. The difference between these states is an embedded sensitivity vector. Making these predictions requires us to construct local models that fit a neighborhood of nearby points for both the nominal and perturbed data sets while insisting that both models share a nearly coincident initial condition. We discuss the challenges in local modeling including how to ensure coincident initial conditions, how to choose an appropriate neighborhood size, how to reject neighborhoods that will result in incorrect SVs, and how to deal with noise. We also discuss error estimation. We then present an algorithm that computes embedded SVFs when given a time series.

Our algorithm is applied to various simulated time series, including a series generated by a Duffing oscillator and a series generated by the Lorenz attractor. We also apply the algorithm to an experimental time series taken from a vibrating cantilever beam to which various amounts of mass can be added. These examples highlight the reliability of the algorithm and show that SVFs are an appropriate metric to measure system variations, even for higher dimensional systems where only some state variables can be recorded.

7981-125, Session 13a

Bending vibration of simply supported beams with anchored constrained viscoelastic layers

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VE materials are commonly used to control vibration-induced fatigue in airframes and for general vibration suppression. The use of VE materials in sandwich structures increases their dissipative character and the energy dissipation is generated mainly by their shearing effect. This study investigates the effect of different configurations of anchored constrained VE layers on the bending vibration of simply supported beams. Emphasis was given to formulating the analytical solution for bending vibration of a simply supported beam with VE layers anchored at one-end as well as at both-end. First, the equation of bending vibration of the beam was formulated based on analytical approach. The responses due to externally applied excitation for different configurations of the anchored constrained VE layers were obtained in the form of acceleration ratio based on steady state analysis. The acceleration ratio was defined as the ratio between response acceleration of the beam and externally applied acceleration, i.e. excitation. The effects of VE layer thickness as well as beam thickness on the bending vibration of simply supported beams were also investigated. It was observed that a VE layer with both-end anchorage is more effective than that of the other configurations and that VE layer with smaller thickness is more effective than that of the larger thickness. It was also observed that, for a given configuration and thickness, the VE layer is more effective for flexible structures. This new technique is expected to be very useful for vibration suppression, particularly in civil, mechanical and aerospace structures.

7981-126, Session 13b

A minimax optimal sensor placement approach for damage detection in composite structures

A. Vanli, L. L. Chen, C. Zhang, B. Wang, The Florida State Univ. (United States)

This paper proposes a new method to find the best placement and the number of sensors to maximize the effectiveness of sensor networks in detecting damages in composites. A minimax approach is employed which minimizes the maximum (worst) probability of non-detection. It is shown that a minimax approach can more efficiently place the sensors on complex geometries, compared to existing placement methods that consider average probability of detection. The method accounts for the characteristics of the sensors by assuming that the effectiveness of each sensor decreases with its distance from the damage via an experimentally determined sensor detectability function. The formulation also enables to account for the nonuniform likelihood of having damages on the structure due to loading condition or material properties by using a damage probability density function which can be obtained numerically by finite element simulation. A sequential quadratic programming method has been adopted to solve the minimax problem. The method is illustrated by sensor network design problems involving 8 to 16 sensors. Computational difficulties of the solution are discussed and alternative optimization algorithms are suggested as future work.

7981-127, Session 13b

a nondestructive experimental study on damage progression in woven glass-epoxy composites

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Little is known about the damage mechanisms in composite materials, especially woven composites. The purpose of this study is to develop

a better understanding of the damage progression in woven composite materials undergoing tension and bending-compression, while pushing the boundaries on measurements to identify material damage. Several SHM methods are used to detect the types of damage that are observed in each test. A Digital Image Correlation system is used to measure the surface strain throughout the test and also the residual strain after each loading cycle. The surface strain and residual strain is compared to the damage size and type seen with the Micro XCT system to determine if it can be used as an indicator for the presence of damage in the structure. Piezoelectric wafer active sensors (PWAS) are bonded to the composite material and are used to detect damage using Electromechanical Impedance Spectroscopy (EMIS). The EMIS method analyzes the changes in the structural resonances and anti-resonances. The Electrochemical Impedance Spectroscopy (ECIS) method is also used to detect damage. This method uses the impedance of the structure to determine the state of the structure. As the damage progresses in the composite, the impedance across the thickness will change. These SHM methods are compared to find how well each one detects the types of damage that are found. The damage progression is also studied using a Micro XCT system. The size, type, and location of the damage are found.

7981-128, Session 13b

Condition-based prognosis of composite structures under multiaxial random loading

Y. Liu, Arizona State Univ. (United States)

The assurance of structural reliability remains a critical issue in the use of composites in aerospace and other applications. Damage in anisotropic material systems is complex and multiscale in nature. Thus it is important to address these issues while developing a structural management framework (SHM) for composite structures. In this paper a condition based prognosis model is developed to forecast the damage state and assess the remaining useful life (RUL) of composite structures subject to random amplitude fatigue loading.

The prognosis framework includes an on-line damage state estimation model and an off-line predictive model. In the on-line damage state estimation model, the previous loading conditions are included in the kernel matrix to estimate the current damage state. In the off-line predictive model, the kernel matrix is updated with the latest damage state information and the loading conditions. The future unknown loading (with known probability) is also introduced to calculate the RUL. A recursive method is used to address the problem of estimating prognostic likelihoods of damage states. Confidence intervals are used to manifest the uncertainty of the model, and establish the prediction horizon of life estimation. Estimations of RUL with confidence intervals provide a more confident maintenance procedure. The proposed methodology is experimentally demonstrated using composite cruciform specimens subject to biaxial random fatigue loading. Piezoelectric based sensors are used for the damage detection of braid carbon fiber composite structures. Experiments are conducted using a MTS bi-axial/torsion test frame.

7981-129, Session 13b

Optimal sensor placement in a guided wave based active sensing framework for composite wing structures

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Structural health monitoring (SHM) is an integral aspect of fleet maintenance in the aerospace industry. It allows the operators to perform part replacement and maintenance on an as needed basis as opposed to the scheduled based procedures currently being followed. This could lead to immense cost savings and reduced down time for aircraft. Deployment of sensor arrays on service structures has so far been limited to metallic components. For composite structures, research

is still focused on flat plates and simple geometries due to complexities associated with ply orientation and the combination of damage modes that can occur. The research proposed in this paper focuses on optimizing sensor placement on a composite wing.

The composite wing will have a uniform cross section based on the NACA0012 airfoil. The wing is constructed using unidirectional carbon fibers in a [0/90]_{2s} configuration. The wing planform has a rectangular cross section with a 12" chord length and 38" span. The test specimen will be fixed in a cantilever position and weights may be added to simulate its static loading. Piezoelectric transducers will be used as the sensors and actuators in this optimized sensor network because they are cheaper and light weight compared to conventional transducers.

Experiments will be carried out to quantify the attenuation of a 4.5 cycle burst wave at 150 kHz as a function of direction on the composite plate. The optimal sensing radius as a function of position on the wing will also be studied.

Next, a simulated annealing algorithm will be developed that takes the information about the sensing radius and the sensor sensitivities at every point and maps out the optimal location of sensors on the structure for sufficient overlap and sensor redundancy.

7981-130, Session 13c

Damage detection for health monitoring of ground vehicle through active probing of vehicle response

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While semi-active suspension systems have been shown to be effective in the real-time optimization of vehicle ride and handling, these systems also present a means for system interrogation and damage detection. This research will demonstrate the ability to monitor the condition of a ground vehicle by utilizing a semi-active suspension system to systematically alter the suspension parameters in order to probe the system response. By modulating the suspension parameters at a particular corner of the vehicle, or combinations of corners, selected operational modes of the sprung and unsprung masses can be probed providing an increased ability to detect and locate damage. Additionally, the ability to measure the system response at known incremented levels of damping increases the sensitivity and accuracy of the damage prediction.

Often times it is necessary to analyze operational data based on comparisons to large historical databases. However, the creation of such databases for ground vehicles is time consuming and costly due to the large number of vehicle models and variations. Another major benefit of the active probing method described is that the associated damage index is based only on one specific vehicle's response over time. A massive database of historical data from similar vehicles is not required.

The active probing method also benefits from the transducers already integrated for control of the semi-active suspension system. Benefits of an on-board health monitoring system can be realized with minimal added cost, by adding only a small number of additional sensors. The ability to detect vehicle damage during operation can be extremely advantageous in terms of safety and condition-based maintenance.

7981-131, Session 13c

Localized damage detection in a large-scale moment connection using a strain gauge sensor network

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In order to maintain healthy structures, it is important to find means of Structural Health Monitoring (SHM) that are effective, economical, and easy to implement. A localized damage detection algorithm based

on measured data from a densely clustered sensor network has been previously presented. This method has been validated using both wired and wireless accelerometers applied to a small-scale idealized beam-column connection. However, to progress towards real-world implementation, there is a need to verify that this algorithm is effective and applicable for full-scale structures with unknown progressive damage. Moreover, it is important to verify the use of other commonly used sensor types, in this case strain gauges, which represent different response parameters. In this paper, the performance of the damage detection algorithm is evaluated for a large-scale steel moment connection constructed at the ATLSS Center at Lehigh University, which was being tested for use in an earthquake-prone structure. This test specimen was instrumented with strain gauges and cyclically loaded to failure. The strain responses from four separate tests are analyzed using the local damage detection algorithm. Furthermore, a Bayesian framework is applied to detect the occurrence of statistically significant damage to a 95% confidence level. The results from these hypothesis tests are compared to the amount of visible damage and performance level to both determine the point of earliest detection and to verify the locations of the damage. By successfully implementing this local damage detection algorithm using strain gauges instrumented on a large-scale structure, the versatility of this method is demonstrated.

7981-132, Session 13c

Comparative study of two element modal strain energy based damage identification methods

H. Wu, Tongji Univ. (China) and East-China Jiaotong Univ. (China); L. Sun, Tongji Univ. (China)

Damage identification still remains a challenging task in structural health monitoring and condition assessment though many algorithms have been proposed in the past decades. Among them, methods based on element modal strain energy (MSE) change between pre- and post-damage are promising ones owing to their precision and robustness according to the studies conducted in the literature. Stubbs damage index method and modal strain energy change ratio (MSECR) method are two popular ones, though based on totally different assumptions, and get more attention thus being continuously improved by researchers. In this paper, these two methods are compared in detail when they are performed in various incomplete and noisy "test" conditions. The effects of different modal expansion methods, number of sensors, and noise level on damage localization and quantification are discussed.

7981-133, Session 13c

The proposed damage model and mechanical behaviors of damaged short suspenders in arch bridges

Y. Li, Q. Zhang, Tongji Univ. (China)

The proposed damage model and mechanical behaviors of deteriorated wires of damaged short suspenders in arch bridges are suggested in this paper. From a monotonic tensile test and numerical simulations, a new damage model and the bilinear approximation of damaged suspenders are developed, which is cumulative and capable of combining the real constitutive relations of wires, strength, stiffness, ductility, corrosion, and loading history. According to the damage model, the static and dynamic stresses of damaged suspenders caused by local temperature and vibration of deck are identified by numerical analysis, assuming the suspenders fixed at the connections with the ribs and the deck. The non-uniform stress distribution and the range of the enhancement coefficient of stress of short suspender are illustrated based on engineering project. The influences of vehicle speed, vehicle frequency, driving frequency with shift, etc., are examined as well. Moreover, this paper investigates the stress condition for each wire in a short suspender with various levels of damage. The comprehensive simulation of the cross-sectional stress

distribution of damaged suspenders may be helpful to the maintenance and safety of the hangers and the arch bridges during their service life.

7981-134, Session 13d

Monitoring thermal stresses and incipient buckling of continuous-welded rails: results from the UCSD/BNSF/FRA large-scale laboratory test track

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Most modern railways use Continuous Welded Rail (CWR). A major problem is the almost total absence of expansion joints that can create buckling in hot weather and breakage in cold weather due to the rail thermal stresses. In June 2008 the University of California, San Diego (UCSD), under the sponsorship of a Federal Railroad Administration (FRA) Office of Research and Development (R&D) grant, began work to develop a technique for in-situ measurement of stress and detection of incipient buckling in CWR. The method under investigation is based on ultrasonic guided waves, and the ultimate goal is to develop a prototype that can be used in motion. A large-scale full rail track (70 feet in length) has been constructed at UCSD's Powell Structural Laboratories, the largest laboratories in the country for structural testing, to validate the CWR stress measurement and buckling detection technique under rail heating conditions well controlled in the laboratory. This paper will report on the results obtained from this unique large-scale test track to date. These results will pave the road for the future development of the rail stress measurement & buckling detection prototype.

7981-135, Session 13d

Auto-Gopher: a wireline rotary-hammer ultrasonic drill

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Developing technologies that would enable NASA to sample rock, soil, and ice by coring, drilling or abrading at a significant depth is of great importance for a large number of in-situ exploration missions as well as for earth applications. Proven techniques to sample Mars subsurface will be critical for future NASA astrobiology missions that will search for records of past and present life on the planet, as well as the search of water and other resources. A deep corer, called Auto-Gopher, is currently being developed as a joint effort of the JPL's NDEAA laboratory and Honeybee Robotics Corp. The Auto-Gopher is a wireline rotary-hammer drill that combines rock breaking by hammering using an ultrasonic actuator and cuttings removal by rotating a fluted bit. The hammering mechanism is based on the Ultrasonic/Sonic Drill/Corer (USDC) that has been developed as an adaptable tool for many of drilling and coring applications. The USDC uses an intermediate free-flying mass to transform the high frequency vibrations of the horn tip into a sonic hammering of a drill bit. The USDC concept was used in a previous task to develop an Ultrasonic/Sonic Ice Gopher. The lessons learned from testing the ice gopher were implemented into the design of the Auto-Gopher by inducing a rotary motion onto the fluted coring bit. A wireline version of such a system would allow penetration of significant depth without a large increase in mass. A laboratory version of the corer was developed in the NDEAA lab to determine the design and drive parameters of the integrated system. The design configuration, lab version of the design and fabrication and preliminary testing results will be presented in this paper.

7981-136, Session 13d

Experimental analysis of fretting related acoustic emission signals

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In structural connections involving rivet and bolt connections, the mating parts close to the connections are often subject to relative movement on the order of micrometers, causing fretting. Fretting is a process involving small amplitude cyclic relative displacement between mating parts. Beyond bolted connections, mechanical elements like gears and bearings are subject to relative movement which causes surface degradation.

In structural health monitoring, detection of crack growth is of keen interest. One method which enables us to investigate the crack growth is acoustic emission (AE) technique. These techniques record and analyze the AE waves generated during the formation of new surfaces. However, these signals are subject to "false positives", i.e., signals coming out from other sources, such as fretting between surfaces. Thus, it is important to differentiate the "false positives" in the signals from crack growth acoustic emissions.

In the area of machinery condition monitoring, the acoustic emission associated with relative movement between contacting surfaces can provide information on the surface conditions of those surfaces. Examples of such situations include bearings, transmission assemblies etc. AE signals may potentially be useful for the prognosis of critical parts of machinery that are in service.

The objective of this research is to characterize fretting acoustic emission signals using experimental methods. A test fixture for different contact geometries is developed. The signals released during relative movement between fretting pads and test specimen are recorded and analyzed. Acoustic emission occurrence and parameters such as amplitude, frequency, and others are investigated. These experimentally observed acoustic emission signals were compared with the results of fretting process obtained through numerical simulations.

7981-137, Session 13d

Modified Brinson model as an equivalent one-dimensional constitutive equation of SMA spring

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Shape Memory Alloy (SMA) spring has great potential as a component of compact actuating system. Trade-off between recovery force and deformation range due to phase transformation is possible through the control of spring design parameters such as spring diameter to overcome the shortage of SMA, small phase transformation strain. Actuation force of SMA spring is sufficient to satisfy design requirement of actuator in spite of the trade-off because recovery force of SMA is almost 1GPa. Deformation behavior of SMA spring is a complicated function in three-dimensional space because it is a combination of torsion, bending and stretching. Therefore, three dimensional analysis of SMA spring is most accurate simulation procedure. However, development of efficient computing scheme to simulate SMA spring is essential procedure to optimize actuator system because three dimension analysis of it requires extremely expensive. Over whole deformation behavior of SMA spring can be reduced to tension and compression, it is possible constructing equivalent one-dimensional constitutive equations of SMA spring. With the equivalent one-dimensional constitutive equation, optimization of arrangement of SMA spring can be handled in much cheaper computing cost. In this paper, experiments of SMA wire for the construction of three-dimensional constitutive equation of SMA are performed. Using the constitutive equation, dimensionless analysis and parametric study of SMA spring at various temperature conditions are presented. Based on these studies, modified Brinson model for SMA spring is constructed.

Finally, experiments of pseudo-elastic behavior of SMA is proposed model are illustrated for the verification of numerical simulation.

7981-138, Session 14a

High-sensitivity fiber loop ringdown evanescent-field sensors

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The evanescent field (EF) sensing mechanism has been widely implemented in the development of fiber optic sensors for physical, chemical, and biomedical sensing. Challenges in the development of EF fiber optic sensors include the enhancement of the sensor's sensitivity and implementing on-line high precision control in the fabrication of a sensor head to allow the desired strength of the EF to be excited in the interface. We incorporate the EF sensing mechanism into the fiber loop ringdown (FLRD) sensing scheme to create fiber loop ringdown-evanescent field (FLRD-EF) sensors and demonstrate their initial applications in high-sensitivity, fast response, and low cost index sensing. The multi-pass nature of the ringdown technique enables the detection sensitivity of the fiber loop ringdown-evanescent field index sensors to be enhanced by more than one order of magnitude. A detection limit for an optical index change of 3.2×10^{-5} (RIU) is demonstrated in initial sensors, in which no chemical-coating, delicate fiber components, and/or sophisticated architecture are utilized at the sensor head. A potential detection limit can be on the order of 10^{-6} RIU. Universal applications of the FLRD-EF sensors in chemical and biomedical sensing will also be discussed.

7981-139, Session 14a

Data acquisition and interpretation in order to anticipate the behavior of a resident for biofication of living spaces

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Current smart buildings are designed based on prescribed scenarios so that they cannot deal with unexpected events. Moreover, they do not evolve by themselves. "Biofication of Living Spaces" is the concept which we aim to make living spaces safer and more comfortable by embedding autonomous mechanisms in the living spaces. The key technologies for biofication are sensor networks to acquire information and data-processing technologies for effective utilization of information. As a first step towards the realization of "Biofication of Living Spaces", a system for acquisition and storing information must be developed. In this research, we will propose a system to control a comfortable space. First, we suggest a data model and a database for biofication. Secondly, we acquire information of residents and rooms, such as temperature, humidity and luminance. We use a sensor agent robot to collect data, because it can follow residents and acquire data at any point. Next, by using collected data and data mining, we analyze the relationship between human behavior and environment. This relationship differs in each person, thus we suggest an algorithm to capture the conditions of human and environment and to control environment accordingly. Finally, we control home appliances using an infrared remote control instrument on the robot based on the anticipated behavior of the resident. Thus, the living space adapts to changes of the environment.

7981-140, Session 14a

Integrated casing and directional antenna: initial design and validation

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This paper presents an effort that addresses two problems in structural health monitoring of concrete/prestressed concrete highway roads and bridges: poor wireless signal transmission and low real-world survivability of wireless sensors. Our proposed product is called "Integrated Casing and Directional Antenna" (ICDA). This unit is designed and manufactured to improve the wireless performance and protect an off-the-shelf wireless sensor that is installed on a road surface or concrete/prestressed concrete highway bridge deck. The overall height of the ICDA does not exceed 6.5 inches given the minimum depth of a common-designed deck, the drilling requirement for its installation calls for the utilization of easily obtainable 6- and 9-inch drilling cores.

The selection of the wireless components of the ICDA, the antenna(s) and optimizing circuitry, is a key factor of the design. Several electromagnetic field numerical simulations including finite difference time domain models and power spectrum measurements are conducted for that purpose. Also, the selected antennas designs are carefully chosen to allow survivability and flexibility of installation and deployment. They also provide a good range of communication with a stable connection to overcome the harsh wireless conditions found on concrete/prestressed concrete bridges.

Protecting the wireless sensor and all other components is the other important goal in this study. To accomplish this, a recommendation is made on the installation location to minimize the loads that would be accidentally applied to the ICDA unit in a real-world environment. Following this, basic structural analysis is exercised to obtain an enclosure design that tends to optimize the load-carrying capacity given the design constraints. All materials used in the manufacturing of the enclosure have low electrical conductivities making them wireless communication friendly. Off-the-shelf components are utilized as often as possible to minimize the overall cost and expedite the manufacturing process.

A prototype of the ICDA has been built and is currently undergoing a series of systematic experimental investigations. This paper discusses the design requirements, approaches, details and some initial test results. This is the first step by this team to design and manufacture a comprehensive and robust product to address the aforementioned two practical issues to implement wireless structural health monitoring. Future work is identified.

7981-141, Session 14a

Optimal design of MPD based fiber optic strain sensors and comparison of power-meter and CCD camera based architectures

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In this work, we consider optimal Modal Power Distribution (MPD) based fiber optic sensor design problem and compare power-meter and CCD camera based techniques for strain measurements. MPD is a sensitive and low-cost fiber optic sensing technique which uses spatial intensity modulation in two dimensional setting. MPD based sensors can be classified into two groups: CCD camera and power-meter based. Most of the power-meter based sensors reported in the literature are based on the use of a single photo-detector. There is one research result reported in the literature where a sensor is built from two photo-detectors, but the main goal was simple normalization, and no optimization was considered for measurement location selection. In a power-meter based fiber optic sensor, light intensity is measured at one or more points, and selection of these points is usually very critical in sensor design. Single point based sensors are not usually very successful, because of the time varying feature of a laser source output intensity. Measurement location selection problem and the associated optimization problem are addressed in this work. It was shown that, by optimal measurement location selection, strain sensor sensitivity can be increased by more than a factor of two. We also analyzed the relationship between power-meter and CCD camera based fiber optic strain sensors, and showed that power-meter based sensor measurements can be estimated from CCD camera images with an average error of less than 4%. This equivalence greatly simplifies optimal sensor design, and eliminates time consuming test

measurements by placing the power-meter at various different locations. Because of its cheap and lightweight nature, the proposed sensor architecture presents an improved effective and economical way for monitoring smart structures.

7981-142, Session 14a

Design and construction of a novel bionic imaging polarization navigation sensor

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Navigation sensor plays a key role in exploration, emergency, precision-guided weapons, ship and aircraft navigation and satellites positioning system. The hot issues of current research of navigation technology include: optimization of single navigation sensor performance, multiple sensors information fusion, novel principle navigation sensor exploitation. The perfect navigational capabilities of some insects afford us plenty of technology reference on novel navigation sensor research. Inspired by the polarization sensitivity mechanism for navigation of desert ants (*Cataglyphis*), a novel imaging polarization navigation sensor system is designed. The work principle of bionic imaging polarization sensor for navigation is discussed in detail. A novel heading solution algorithm for imaging polarization navigation is designed, which implements precise navigation angle extraction by means of main polarization direction selection, polarization direction line character detection and polarization direction image center checkout. The new heading angle solution method can improve sensor polarization sensitivity, spatial solution and navigation performance robustness effectively. Based on the work principle of the new imaging polarization sensor, the prototype machine which integrates CMOS image detector and multi-tier thin film micro polarizer array is built up. Due to this function architecture design, the volume and power consumption of navigation sensor is decreased greatly, and the overall navigation performance is enhanced obviously. The imaging polarization sensor character is calibrated in the dark field and uniform non-polarization light field, and several possible sensor error causes are analyzed. And the polarization heading angle output error within $\pm 0.15^\circ$ is achieved under different skylight condition. Outdoor experiments indicate the novel bionic imaging polarization navigation sensor is feasible and robust.

7981-143, Session 14b

A miniature batteryless health and usage monitoring system based on hybrid energy harvesting

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The cost and size of the state-of-the-art health and usage monitoring systems (HUMS) are determined by capacity of on-board energy storage which limits their large scale in-field deployment. In this paper we present a miniature low-cost mechanical HUMS integrated circuit (IC) based on the concept of hybrid energy harvesting where continuous monitoring is achieved by self-powering, where as the programming, localization and communication with the sensor is achieved using remote RF powering. The self-powered component controllable hot electron injection on floating-gate transistor as an ultra-low power signal processor. We show that the HUMS IC can seamlessly switch between different energy harvesting modes based on the availability of ambient RF power and that all the necessary initialization, floating-gate programming and communication functions can be remotely performed without physically accessing the HUMS device. All the measured results presented in this paper have been obtained from prototypes fabricated in a 0.5 micron standard CMOS process and the entire system has been successfully integrated on a 2.2cm x 1.6cm package making it one of the smallest HUMS reported to date.

7981-144, Session 14b

Monitoring fatigue crack growth in narrow structural component using Lamb wave technique

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Fatigue is a progressive and localised damage that occurs when a material is subjected to cyclic loading. Historical cases shown that undetected fatigue cracks often leads to catastrophic failure, including loss of lives and assets. It is therefore important to have a robust Structural Health Monitoring (SHM) technique to detect and monitor these cracks. The Lamb Wave technique for SHM is promising due to its ability to interrogate a large area of the structure from only a few locations. The use of surface bonded piezoelectric materials also translates to achieving consistent measurements as compared to the conventional large transducers. The feasibility of fatigue crack detection in wide specimens, where the effect of boundary reflections is not significant in the signal processing and damage quantification process, have been investigated by other researchers. However, in a narrow structural component, where the width is smaller than the actuator-sensor range, the boundary reflection has a significant role in the sensor signal and the damage quantifier from available literatures cannot be applied readily.

The main focus of this study is to investigate the feasibility of monitoring fatigue crack growth in a narrow structural component using the Lamb Wave technique. Experimental study conducted on lab-sized aluminium beam found that as the crack propagates the amplitude of the sensor signal decreases. A damage index is proposed, and a linear relationship between the damage index and the crack length is identified. With the proposed damage index, a crack length can be estimated from the acquired sensor signals through a correlation factor.

7981-145, Session 14b

Multiplexing wireless antenna sensors for crack growth monitoring

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This paper presents an unpowered wireless sensor array for crack monitoring at multiple locations. The sensor array can be interrogated wirelessly and simultaneously by multiplexing the antenna sensors based on the principle of frequency division. The structure under monitoring forms the ground plane of the antenna sensor array. Crack presence in the ground plane of an antenna sensor causes the resonant frequency of the corresponding antenna sensor to decrease. Thus by monitoring the resonant frequencies of each antenna sensor, the crack growth at different locations can be monitored. Compared to the single antenna sensor we presented before, the antenna sensor array enables us to track the status of cracks at different parts of the metallic structure at the same time.

To demonstrate the capability of the antenna sensor array for crack monitoring, the antenna sensor array was bonded to a pre-cracked Compact Tension (CT) subjected to cyclic loadings. The resonant frequencies of each antenna sensor were measured at different crack lengths. The antenna sensor array can be wireless interrogated using a mono-static radar system and a single impedance-switching circuit implemented at the sensor array. An interrogating horn antenna, placed at a far-field distance from the specimen under test, irradiates the antenna sensor array with a chirp signal generated by a VNA. Detailed experiment setup, data processing algorithm and measurement results will be presented.

7981-146, Session 14b

Detecting crack orientation using antenna sensor

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The diagnostics of cracks in structures has been gaining importance in recent years. In the past decade, numerous sensors were developed to detect and monitor the crack propagation, such as Meandering Winding Magnetometer sensors, Comparative Vacuum Monitoring sensors, ultrasound sensors etc. But still, very few sensors can extract quantified information of crack such as its size and orientation with high sensitivity. Recently, we have presented a passive wireless antenna sensor that can detect sub-millimeter crack growth when the crack is parallel to one edge of the antenna patch. This paper will be focused on studying the effect of crack orientation on the sensor frequency. Based on the principle of microstrip patch antenna, an antenna sensor with a rectangular radiation patch radiates at two resonant frequencies. Cracks in the ground plane of the sensor with different orientations influence these two resonant frequencies in two different ways. Thus by monitoring the changes in both resonant frequencies of the patch antenna, quantitative information about the crack orientations can be obtained.

The resonant frequencies of the antenna sensor were first simulated using an EM simulation tool by modeling the crack as a 1 mm wide slot on a thin metal sheet at various angles. Simulation results confirmed that the resonant frequency of the antenna sensor is sensitive to the crack orientation. Subsequently, the antenna sensor's capability to detect crack orientation was experimentally validated by fabrication an antenna sensor with a thin metal sheet as the ground plane. A mini-milling machine was employed to produce cracks in the ground plane at different angles. The resonant frequencies of the antenna sensor were then measured to study the effect of crack orientation and length on both frequencies of the antenna sensor. The principal of operation will be discussed first followed by detailed descriptions on the specimen design, preparation, sensor fabrication, experimental setup, procedure and results.

7981-147, Session 14b

The research on embedded shock signal storage measurement system

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It is the important research field to measure and record the shock load signal in the environmental test. To acquire the dynamic impact load acceleration signal conveniently and reliably, the embedded storage measurement and testing technique has been adopted, that is integrating the sensor, signal acquisition, signal adaption, datum storage into a small size datum recorder, which is installed inside the tester following the tester to do some environmental tests as the penetrating or drop test with high impact load and shock signal, and is reclaimed to read and to reappear the datum of impact load acceleration signal by computer after the experiment. In the paper, for the sake of satisfying some special demands in the drop test, such as the system applicability under the high impact load condition, system reliability, miniaturization, low power consumption, low cost price and so forth, an embedded shock load storage measurement system has been designed and developed. The overload acceleration signal can be recorded perfectly by the system based on fully integrated mixed-signal system-on-chip MCU C8051F340 with full speed USB flash and a good deal of merit. It has small bulk and built-in dry battery, so many practical problems in the drop test using traditional outer wiring measurement method were solved, for example the experimental signals easily were interfered by shaking wires and the device was inconvenient to install because of the long leads of transducers.

In the introduction of the paper, the research background is recommended firstly; the domestic and international research status, the development and application of research are also put forward.

Henceforth the paper is expanded from the three aspects. In the first section, the operation principle, the circuits of central modules, and the software design scheme are simply enumerated, as a result the main structure of the system can be understood easily; the characteristics of the primary hardware components are introduced too; to resist the high overload, the encapsulating materials and embedding technology are studied to protect the printed circuit board assemblies. In the second section, the static and dynamic calibration methods and instruments are presented. The static method is used to detect the electrical performance of system when the different measuring range is chosen, such as linearity, sensitivity, and accuracy and so on, at the same time the coefficient of correction can be calculated from that the voltage is converted into the impact load. Here the system has a sampling frequency of 100 KHz, 5 second sampling length, 100000g measuring range, and it can resist at least high overload of 60000g through the dynamic calibration experiment using Marshall Hammer machine. In the third section, the system was assessed by the 22m drop test and the experiment result curve was offered. From that we can check that the system has some engineering practicability. Lastly in the conclusion of the paper, we summarize some aspects that deserve making further efforts to study. If the sensor and adapter are replaced, the system can be used to measure the strain, temperature, displacement and so on, so the design has some referenced value to measure the other transient signals by storage testing method.

7981-148, Session 14c

Structural damage detection with insufficient data using transfer learning techniques

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The effective detection of damage in complex structures is an important task in structural health monitoring (SHM) systems. Conventional information processing techniques rely heavily on statistical modeling machinery that requires large amounts of training data (used for computing model parameters). Unfortunately, the cost and complexity of conducting too many experiments to collect, store and process data can be prohibitive. Performance of conventional techniques is generally poor under these data-scarce conditions.

However, in many SHM scenarios a modest amount of data may be available from a few different but related experiments. In this paper, a new structural damage detection method is proposed that makes use of statistics from a related detection task to improve performance on a data set with insufficient training examples. The approach is based on the transfer learning (TL) framework which provides an information transfer mechanism between related learning tasks. This transfer of information from one experiment to another significantly alleviates the problems incurred from data-hungry modeling and boosts overall learning performance.

The utility of the proposed method is demonstrated on fatigue damage detection in an aluminum lug joint. Data is collected in the form of Lamb wave measurements using four surface-mounted piezoelectric sensors. The TL based damage detection method is utilized to detect fatigue induced crack damage in the case when enough (statistically significant) training data is available from only one sensor and insufficient training data is available from the other sensors. Our results show a significant improvement in damage detection performance, with correct detection rates increasing from 26% to 77% in our application.

7981-149, Session 14c

Bayesian anomaly detection in monitoring data applying relevance vector machine

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Many structural health monitoring systems have been installed in buildings recently. The enormous amount of data collected by the systems, however, could include some anomalous data due to sensor malfunction, impacts of human activities, and so on. Such anomalous data have been checked and removed manually, which is getting more and more difficult as the amount of the collected data is increasing explosively.

Therefore we develop a method for automatically classifying the monitoring data into two categories, normal and anomaly, applying the relevance vector machine (RVM) to a probabilistic discriminative model with basis functions and their weight parameters whose posterior PDF (probabilistic density function) conditional on the learning data set is given by Bayes' theorem.

The proposed framework is applied to actual monitoring data sets containing some anomalous data, collected at two buildings in Tokyo, Japan. We consider three feature quantities and by combining all or some of them set four kinds of feature vectors each of which specifies a model class set. The evidence (marginal likelihood) in two model class sets maximized during the learning process has almost equally the largest values, which shows these two model class sets should be chosen.

We use another data sets to investigate the generalization ability of the trained models, which shows that both MAP (maximum a posteriori) models in the selected two model class sets discriminate anomalous data from normal data very clearly, giving high probabilities of being normal to normal data and low probabilities of being normal to anomalous data.

7981-150, Session 14c

Stochastic subspace identification for output-only modal analysis: accuracy and sensitivity on model parameter estimation

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For output-only system identification techniques for civil structures under ambient vibrations, in this study, mainly focused on the Subspace System Identification (SSI) based algorithms. SSI technique was proved by several researchers to be numerically stable, robust to noise perturbation and suitable for conducting non-stationarity of the ambient excitations although its stationary assumption is violated. Besides, the estimation of damping is shown to be poor. Therefore, the accuracy and sensibility of the identified modal parameters under different scenarios by using SSI technique, which include: The measured quantity, Non-stationarity effect, Level of noise in the measurements, and Presence of some non-linear behavior on the structure is needed.

A numerical simulation will be performed to determine the accuracy and sensibility of the identified modal parameters under different proposed scenarios by using SSI method. Secondly, identification task of the real large scale structure: Guangzhou New TV Tower (GNTVT), a benchmark problem for structural health monitoring of high-rise slender structures will be carried out, for which the capacity of each identification algorithm will be demonstrated.

7981-151, Session 14c

Damage identification of full scale four-story steel building using multi-input multi-output models

H. T. Hien, A. Mita, Keio Univ. (Japan)

Earthquakes have caused many serious damages; that is why it is needed to study the health of buildings after these earthquakes. After a large earthquake, evaluation of damage of structures is an important task for health assessment. Vibrations of buildings give us valuable information on it. Among the representative structural characteristics, natural frequencies provide the global information. However they are relatively simple, accurate to measure and easy to obtain. Besides, the changes in frequencies must be considered to identify a damage of structures. This study will consider the frequencies shifts with various levels of seismic excitations. The excitations are represented by different intensity levels of the 1995 Hyogoken Nanbu Earthquake that are obtained in JR - Takatori Station. The acceleration data of E-defense tests on full scale 4-story steel building will be analyzed. This will allow us detecting structural damage as well as evaluating the structural performances. The changes in frequencies are achieved from multi-input multi-output models. Those will be compared so as to get the results with reasonable accuracy. The aim of this paper is to propose a damage identification method in order to give correlation between the models and real damage of a steel building using real-size shake table tests.

7981-152, Session 14c

Probabilistic analysis of structural condition properties based on SHM

Z. Min, Tongji Univ. (China)

In the process of structural health monitoring (SHM), the structural condition features were not only affected by the structural condition, but also influenced by some random factors, such as the environmental factors, measurement noise and analysis errors. The traditional structural condition assessment methods, which were based on the deterministic theories, cannot apply in this condition. So a probabilistic analysis method of structural condition properties based on SHM is proposed in this paper. At first, these structural condition features, which characterized the structural safety, serviceability and durability properties respectively, were extracted from the SHM data. The environmental factors, which affected the structural features, were identified and the analysis model of the environmental factors effects was established. After that, the structural abnormal condition can be identified based on the probability and statistics approaches, such as hypothesis testing and novelty detection. Finally according to the monitoring data of the extreme environmental factors and the structural boundary condition, the change of the structural condition can be correctly determined. The framework of the probabilistic analysis method and some approaches, which may be used in the method, were discussed respectively in this paper.

7981-153, Session 14d

Adaptive backstepping based MR damper monitoring for structural applications

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Magnetorheological (MR) dampers are intrinsically nonlinear devices, which make the modeling and design of a suitable control algorithm for MR damper monitoring an interesting and challenging task [1]. To evaluate the potential of magnetorheological (MR) dampers in control applications and to take full advantages of its unique features, a mathematical model to accurately reproduce its dynamic behavior has to be developed and then a proper control strategy has to be taken that is implementable and can fully utilize their capabilities as a semi-active control devices.

To this day most widely used MR damper model is Bouc-Wen hysteretic model [2]. The parameters of the hysteretic model are identified through various pseudo-dynamic testing of the damper. Therefore, dependence of the parameters on damper dynamics (i.e., displacement and velocity) is neglected. Recent studies have shown that this negligence is not minor and could lead to a catastrophe especially for large MR dampers [3].

The present paper focuses on both the aspects. The proposed paper will develop an MR damper control algorithm based on adaptive backstepping approach, which will provide a stable nonlinear voltage monitoring for MR dampers based on system feedback. The advantage is the voltage-change in MR damper is gradual and all voltages in the minimum to maximum voltage range can be used. Another important advantage of the proposed technique is that it directly monitors voltage required to control the structure. The force to voltage map and force feedback for MR dampers are not needed in the proposed method. The efficiency of the proposed technique has been shown taking a single degree of freedom structure under earthquake excitation.

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Note: This paper was accepted in SPIE NDE 2010, but the authors could not participate in the conference due to visa problems. The full paper is ready and this time authors want to participate and present the paper in the conference.

7981-154, Session 14d

Estimation of dynamic characteristics of a medium-height office building with passive dampers considering vertical seismic response

M. Ishikawa, A. Mita, Keio Univ. (Japan)

In this paper, dynamic characteristics of a medium-height office building with passive dampers is investigated. After the Great Hanshin-Awaji earthquake and the recent construction scandals, the safer mechanism of structures has attracted a keen attention of the general public. The mechanism has been widely recognized and has become often used for buildings these days. However, it is still unclear whether these buildings will act properly against large earthquakes or not.

Many examples of analyzing real structures have been reported so far. However, most of them are only targeted at horizontal seismic response, and there are few analytical examples on vertical seismic response. Thus, we focus on the vertical components to know the real performance of buildings.

The building considered here is equipped with two kinds of passive dampers, that are viscous vibration control walls and low yield point steel-based buckling restraint braces. Eleven accelerometers are installed on basement, 1st, 5th, 10th, 14th floors. Two displacement meters for measuring the response of dampers are installed. The dynamical behaviors of the building under several earthquakes are analyzed using multi-input and multi-output models of modal analysis. Using acceleration responses of multiple observation points, the dynamic characteristics are estimated more precisely. The estimation errors of modal parameters are obtained simultaneously. Applying the method, we estimate the damping ratios of vertical direction and investigate the reliability of the estimated values quantitatively.

7981-155, Session 14d

Design of modern monitoring systems for efficient control and management of technological processes

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Proliferation of new and upgrade of existing industrial technologies is impossible without the development of efficient systems and algorithms of automatic control of technological processes that rely on modern monitoring approaches.

Typically, the monitoring tools, which include various sensors and other devices, have to be tightly integrated with automatic control systems of industrial processes to reduce service expenses and down time, increase capacity and optimize production as a whole.

While designing technological and automation lines, it is necessary to carefully select parameters to be monitored such that optimal operation is achieved.

At the same time, every step of industrial production has to be monitored to assure that each particular process is properly executed and resources are utilized in an efficient manner.

An example presented in this paper is based on an ac electric drive equipped with control and monitoring systems.

The result of a properly designed monitoring system is a simplified architecture of the control devices.

The overall method can be implemented on the basis of a microprocessor, which offers several advantages including the possibility of designing intelligent control loops, expanding the fault-tolerant range of operation, extending the resource of operation, and coordinating interaction between different systems.

7981-157, Session 14d

Theoretical and experimental study of vibration suppression for stayed cable

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The objective of this study is to develop a numerical model of a stayed cable interacted with deck, and to examine the vibration suppression of the stayed cable subject to external loading. First, a numerical model based on the finite difference method and the finite element method has been developed to simulate the effects of the bending stiffness and its sag-extensibility characteristics of the cable. Accurate vibration mode shapes and modal frequency of the stayed-cable and deck interaction are examined. For the vibration control of cable, a MR-damper is used as control device. This damper can be achieved either the passive control strategy or the semi-active control strategy employing linear quadratic Gaussian (LQG) control or decentralized sliding-mode (DSM) control. To verify this study, a scaled-down cable structure is designed and constructed in NCREE, Taiwan. A small shaker is designed and mounted onto the cable to generate the sinusoid excitation with different amplitudes and frequencies. Dynamic characteristics of the cable-deck system are identified. Through model updating technique the system model is developed for control purpose. The decentralized sliding mode control algorithm using MR damper was studied to reduce the cable vibration under different excitation frequencies.

7981-158, Session 15a

Sensor for direct measurement of the boundary shear stress in fluid flow

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The formation of scour patterns at bridge piers is driven by the forces at the boundary of the water flow. In most experimental scour studies, indirect processes have been applied to estimate the shear and normal stress using measured velocity profiles. The estimations are based on theoretical models and associated assumptions. However, the turbulence flow fields and boundary layer in the pier-scour region are very complex. Direct measurement of the boundary shear and normal stress and their fluctuations are attractive and challenging alternatives. The authors designed and fabricated a prototype miniature shear stress sensor including an EDM machined floating plate and a high-resolution laser optical encoder. Tests were performed both in air as well as operation in water with controlled flow. The sensor sensitivity, stability and signal-to-noise level were measured and evaluated. The detailed test results and a discussion of future work will be presented in this paper.

7981-159, Session 15a

A self-sensing structure with printed sensors

H. Yoon, Tennessee Technological Univ. (United States)

Recently, printed electronics have received growing attention as a potential method to produce low-cost large-area electronics on flexible substrates. Much of the current research relies mainly on an inkjet printing technique to deposit electrically functional material solutions onto plastic substrates in order to fabricate various electronic components such as resistors, capacitors and transistors. In this paper, we propose to apply the printed electronics technology to the development of self-sensing structures. For this purpose, we have developed an aerosol printing system that exhibits a better performance in printing on various types of substrates. The system consists of a moving platform, two pressure regulators, and a fluid atomizer. Using the system, we demonstrate that conducting wires can be printed directly onto a metallic substrate. An aluminum substrate is prepared by printing a polymer-based dielectric material in the area where conductor will be printed. Then, a water-based silver nano particle solution or a conducting polymer solution is printed to form wires using the same aerosol printer. Finally, another dielectric material is printed on top of the conducting wire to protect it from environmental influences. The result of this research will serve as a critical step toward the fabrication of structures with printed sensors and accompanying electronics.

7981-160, Session 15a

Photonic crystal fiber heat sensors

R. M. Wynne, J. Coomson, A. Colalillo, S. Twigg, Villanova Univ. (United States)

A sensing configuration based on commercially available triple-core photonic crystal fibre (PCF) for the image based collection of thermal information is presented. Detection of thermal phenomena on the micro and nano scale is important for monitoring thermodynamic processes including cooling mechanisms for industry and basic research in both civil and mechanical systems. The thermal characteristics of the PCF combined with coupled-mode theory principles are used to construct a three core PCF with a 1-D core arrangement to simultaneously measure heat flux and temperature. The PCF sensor demonstrated high detection sensitivity ($<1^{\circ}\text{C}$) and fast response times ($<30\mu\text{s}$), which is a significant improvement to current commercial standards.

PCFs are specialty optical fibers contain carefully spaced micron-sized cavities that provide extraordinary waveguide characteristics not demonstrated by standard optical fiber. The three core PCF has a core diameter of $2\mu\text{m}$, outer diameter of $132.5\mu\text{m}$ and varied inter core spacing. A single mode fiber is fusion spliced with the multicore PCF such that the optical field is confined and launched into the PCF. The output end of the fiber is inspected and imaged with a CCD camera. An 1 inch section of the PCF is surrounded by a guarded hotplate configuration to control the thermal conditions for sensor characterization. Evanescent wave coupling occurs whereby power is transferred from the central core to a neighboring core. Minimum detection sensitivities of 0.2 Celsius were recorded. Theoretical sensitivities on the order of 10^{-2} Celsius are possible. Experimental results agreed with coupled-mode theoretical results with errors $<4\%$.

7981-161, Session 15a

Low-frequency high-sensitive tunable mechanical monolithic horizontal sensors

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This paper describes an optimized version of the mechanical version of the monolithic tunable folded pendulum, developed at the University of Salerno, configurable both as seismometer and, in a force-feedback configuration, as accelerometer. Typical application of the sensors are in the field of geophysics, including the study of seismic and newtonian noise for characterization of suitable sites for underground interferometer for gravitational waves detection. The sensor, shaped with precision machining and electric-discharge-machining, like the previous version, is a very compact instrument, very sensitive in the low-frequency seismic noise band, with a very good immunity to environmental noises. Important characteristics are the tunability of the resonance frequency and the integrated laser optical readout, consisting of an optical lever and an interferometer. The theoretical sensitivity curves, largely improved due to a new design of the pendulum arms and of the electronics, are in a very good agreement with the measurements. The very large measurement band (10^{-6} Hz - 10 Hz) is coupled to a very good sensitivity (10^{-12} m/sqrt(Hz) in the band 0.1 - 10 Hz), as seismometer. Prototypes of monolithic seismometers are already operational in selected sites around the world both to acquire seismic data for scientific analysis of seismic noise and to collect all the useful information to understand their performances in the very low frequency band (10^{-6} - 10^{-3} Hz). The results of the monolithic sensor as accelerometer (force feed-back configuration) are also presented and discussed. Particular relevance has their sensitivity that is better than 10^{-11} m/s²/sqrt(Hz) in the band 0.1 - 10 Hz. Finally, hypotheses are made on further developments and improvements of monolithic sensors.

7981-162, Session 15a

A tele-gait monitoring system with an inertial measurement unit and smart shoes

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A treadmill has been widely used in gait rehabilitation treatments. The gait rehabilitation treatment on a treadmill makes it easy for physical therapists to observe their patients' gait motions and to control the treatment settings such as the walking speed and inclination. However, many researchers have found that walking motions on a treadmill are different from those on the ground due to the lack of the transition motions of the center of body weight. Also, the treadmill does not fully realize arbitrary environments in daily lives (e.g., ascending/descending stairs), which limits the effect of rehabilitation treatment.

To enable the observation of walking motions with more natural settings, a mobile gait monitoring system (MGMS) was proposed in our previous

works. The MGMS measures ground reaction forces (GRFs) by force sensors embedded in Smart Shoes. However, although the GRF patterns measured by MGMS provide useful information for the diagnoses of patients' walking motions, the Smart Shoes did not measure the position of feet, which is necessary for a complete diagnosis of walking motions.

In this paper, an inertial measurement unit (IMU) is used in addition to the force sensors in Smart Shoes for a complete observation of walking motions. By analyzing the signals measured by the IMU and the force sensors of Smart Shoes, it is possible to thoroughly diagnose the patient's walking motion including the trajectory of joints, the walking distance, the length of a stride and the foot attitude. Moreover, a wireless network is accompanied with the proposed gait monitoring system such that physical therapists can monitor their patients' status anywhere at anytime.

7981-215, Session 15a

Multicore photonic crystal fiber force meters

R. M. Wynne, Villanova Univ. (United States)

A silica based three core photonic crystal fiber (PCF) force meter with fast response times ($<30\mu\text{s}$) for low wind speed detection is presented. Results are provided for PCF structures containing cores with varied lattice spacing. Force meters with high spatial resolution (sample regions $\leq 10\text{cm}$) specially outfitted for extreme environmental conditions are of interest to both industry and basic research institutions. The featured PCF force meter exhibited sensitivities that agreed with theoretical predictions resulting in the detection of minimum displacements for wind speeds $<30\text{m/s}$. The results of this investigation are relevant to civil engineering applications including urban sensing technologies that involve air quality monitoring.

The deflection of the PCF detection interface was measured as a function of the applied force (e.g. wind speed). The three core PCF has a core diameter of $2\mu\text{m}$, outer diameter of $132.5\mu\text{m}$ and varied inter core spacing. A 10cm length of the PCF is attached to the surface of a thin metal beam. One end of the PCF section is fusion spliced to a single mode fiber (SMF) at the fiber input. The remaining fiber end is coupled to a CCD camera with a lens at the PCF output. The applied force deflects the supported PCF such that the intensity distribution of the optical field for the multiple cores changes as a function of displacement. Wind tunnel tests were employed to measure wind speed with the PCF force meter device. Experimental results are in agreement with coupled-mode theory and simple beam deflection theory models.

7981-163, Session 15b

Development of a multi-scale monitoring and health assessment framework for levees in New Orleans

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This project includes the development of a new health assessment framework to monitor, manage and ensure the safety of levees and other systems of a flood-control infrastructure. The framework provides a comprehensive multi-scale monitoring and analysis for real-time health assessment of this infrastructure. More specifically, the project develops and implements: (1) multi-scale (global and local) sensing and optimal monitoring strategies, (2) a hierarchy of multi-scale data-reduction and identification tools of geosystems, and (3) model-based tools for fusing and mining of observational and computational data to assess the health of these systems so that their safety can be more effectively managed. A suite of fully-integrated instrumentation and observation techniques will be developed and employed to monitor a system of flood-control (water-retaining) levees. These long term continuous monitoring techniques are minimally-intrusive and relatively inexpensive. They include: (1) satellite-based interferometric synthetic aperture radar (InSAR) measurements, (2)

a new high resolution GPS sensor with millimeter level accuracy, and (3) a new high resolution shape-acceleration-pore pressure (SAPP) arrays for below the ground monitoring. These measurements and sensors will be integrated into a smart network to monitor the response of flood-control levees on multiple scales ranging from the global to the local levels.

7981-164, Session 15b

Verification of a multi-level damage detection approach using a full scale structure

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In this paper a multi-level damage detection scheme is applied and verified on a large-scale, complex structure. To determine the modal properties of the structure the Natural Excitation Technique (NExT) in conjunction with Eigensystem Realization Algorithm (ERA) is applied to the sensor data acquired from a full scale highway sign truss structure. In the multi-level scheme only one node is active in each region for the first level and for the second level additional nodes are activated in the damaged region to localize the damaged element. The proposed multi-level damage detection scheme considers the structure under two types of structural behavior. In the first level damage detection, the structure is assumed to behave like a beam and the Angle between String-and-horizon (ASH) flexibility method is applied to detect the damaged region. For the second level damage detection, refined mode shapes are constructed using the additional nodes in the damaged region. The substructure is assumed to behave like a truss and Axial Strain (AS) flexibility method is applied to detect the damaged element. The experimental verification of the ASH and AS damage detection algorithms were performed on two independent damage scenarios of a 57.5-ft, 10 bay structure.

7981-165, Session 15b

Application of data compression method using K-SVD to experimental ambient vibration data

H. Y. Noh, A. S. Kiremidjian, Stanford Univ. (United States)

In this paper, a data compression method using K-SVD algorithm is developed and applied to experimental ambient vibration data. Many damage diagnosis algorithms using system identification require vibration measurements of multiple locations, thus it is necessary to transmit long threads of vibration measurements. In wireless sensor network for structural health monitoring, however, wireless data transmission is often a major source of battery consumption. Therefore, reducing the amount of data to transmit can significantly lengthen the battery life and reduce the maintenance cost. K-SVD algorithm is originally developed in the field of information theory for data compression. This algorithm creates an optimal set of bases, referred as dictionary, from the data using singular value decomposition (SVD), and represents the data as linear combinations of these bases. Since ambient vibration data are stationary, they can be segmented, and each segment can be represented as a linear combination of the bases. Then only the dictionary and the vectors of the coefficients need to be transmitted wirelessly for restoration of the original data. This method is applied to ambient vibration data measured from Taiwanese benchmark structure. The primary results show that this method can compress the data efficiently and we can restore the data with very small error.

7981-166, Session 15b

Analysis of high rise building lifespan monitoring data using Bayesian logic

D. Zonta, Univ. degli Studi di Trento (Italy); B. Glisic, Princeton Univ. (United States); M. Pozzi, Univ. degli Studi di Trento (Italy); J. M. Lau, C. C. Fong, Housing & Development Board (Singapore)

Permanent monitoring of civil structures is a typical situation involving large amounts of data and uncertainties, including measurement noise, uncertain model and inaccurate prior information. Bayesian inference is possibly the most rational way to combine information stemming from sources of different nature. Above all, Bayes' principle lets us handle the qualitative information normally known as 'common sense' or 'engineering judgment' - information which very often has a critical role in the owner's ultimate decision. In this contribution, we use a Bayesian approach to analyze the data from a 19-story building block, which is part of the Punggol EC26 construction project undertaken by the Singapore Housing and Development Board in the early 2000s. The building was instrumented during construction with interferometric fiber optic average strain sensors, embedded in ten of the first story columns during construction. The philosophy driving the design of the monitoring system was to instrument a representative number of structural elements, while maintaining the cost at a reasonable level. The analysis of the data, along with the prior experience, allowed the owner to recognize at early stage an ongoing differential settlement of one base column. We show how the whole cognitive process followed by the owner can be reproduced using Bayesian logic. Particularly, we discuss to what extent the prior knowledge and potential evidence from inspection, can alter the perception of the building response based solely on instrumental data.

7981-168, Session 15c

Dynamic performance and fatigue properties of shear viscous damper for stay cable vibration control

M. Liu, G. Zhang, H. Li, Harbin Institute of Technology (China)

At present, viscous oil dampers have been successfully implemented to stay cables vibration control and achieved effective control efficacy. However, the viscous oil dampers with squeezing pressure, which have been installed at in-situ cable-stayed bridges, have some shortcomings due to oil leaking, lots of maintenance service et al. In this paper, a new type of shear viscous dampers was developed to mitigate the stay cable vibration. The shear viscous dampers consist of inserted plates and slots which hold much thick oil with high dynamic viscosity coefficient. Based on the designed and manufactured shear viscous damper, dynamic performance tests were carried on. Utilizing the dynamic performance testing results, mechanics model of the shear viscous damper was proposed by using parameter identification method. Using the proposed mechanics model, numerical investigations on the stay cable vibration control attached with the shear viscous damper with different parameters were conducted to demonstrate the control efficacy and the increasing damping ability. The universal design method of the stay cable vibration control installed with the shear viscous damper was also developed on the basis of the numerical analysis. Finally, for the purpose of investigation on the damper's fatigue properties and durability, fatigue experiments of the shear viscous damper were done. Effects of parametric factors on the damper's durability were investigated based on the fatigue experiments of the shear viscous damper. Investigations on the dynamic performance and fatigue prosperities of the shear viscous damper show that the dampers with simple building and stable dynamic performance can effectively reduce the stay cable vibration by increasing the damping of the stay cable, and have superior durability for the in-situ stay cable vibration control.

7981-169, Session 15c

Structural vibration control by tuned mass damper using central pattern generator

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This paper proposes a new control method for an active mass damper using Central Pattern Generator in the vibration mitigation. The active mass damper (or active dynamic absorber) has been applied to structural vibration control of high-rise buildings, bridges and so on. In this case, the mass of the active mass damper might be moved as an appropriate phase in relation to the control object, and the damper has been designed by linear control theory, pole placement method, optimal control method or H infinity control method, and all the rest. On the other hand, on walking of animate beings like mammals or insects, both side feet have appropriate phase relations, moreover, it is possible to keep moving on irregular ground. That is, an algorithm for the walking would be embedded into the animate beings to control the complicated and redundant body with ease and robustness. In biological study, what Central Pattern Generator in body plays a significant role in the walking has been learned over the last few decades, and some studies say that some animate beings control their feet by using the generator without their brains in the walking. Moreover, the mathematical models of the pattern generator have been proposed, and some researchers have been studying to realize walking of biped-robots using the pattern generator embedded in a computer. In this study, the algorithm is installed into the controller for the active mass damper; furthermore, validation of the controller is performed by numerical simulation.

7981-170, Session 15c

Low-frequency seismic noise acquisition and analysis with tunable monolithic horizontal sensors

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In this paper we describe the scientific data recorded mechanical monolithic horizontal sensor prototypes located in the Gran Sasso Laboratory of the INFN. The mechanical monolithic sensors, developed at the University of Salerno, are placed, in thermally insulating enclosures, onto concrete slabs connected to the bedrock, and behind a sound-proofing wall. The main goal of this experiment is to characterize seismically the sites in the frequency band 10^{-4} - 30 Hz and to get all the necessary information to optimize the sensor.

7981-171, Session 15c

Vibration control and motion control of a micro-actuator for the hard disk drive using self-sensing actuation

M. Sasaki, S. Ito, H. Tamagawa, Gifu Univ. (Japan)

In this paper, vibration control and motion control of a micro-actuator for the hard disk drive using self-sensing actuation are presented. A suspension assembly in hard disk drive (HDD) can be excited by airflow generated from high speed rotating magnetic disk, a non-circular track motion of the head/slider which is caused by the resonance vibration modes of components, and other external disturbances. Active control of these problems and vibration of components requires additional vibration sensors and actuators. Many researchers have proposed adding extra vibration sensors and actuators. This paper describes a suspension driving type micro-actuator. The micro-actuator uses a PZT actuator pair, installed on the assembly of the suspension. The self-sensing micro actuator can be used to form a combined actuation and sensing mechanism. Feedback control results of direct velocity feedback

(DVR) and direct position feedback (DPF) and positive position feedback (PPF) are presented and compared. And the two-degree-of-freedom control system is comprised of a feedforward controller and a feedback controller. Two controllers are designed for the two-degree-of-freedom control system, one for the inverse dynamic model for the feedforward controller and one for the feedback controller using self-sensing signal. The feedback controller can realize the self-sensing signal. The objective of the experiments are to verify the feasibility of these self-sensing approaches as a vibration suppression control and a position control of the micro-actuator.

7981-172, Session 15c

A multi sensor based control system for self-preserving smart energy harvesting civil infrastructure system

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The traditional approach for ensuring resistance of the transportation infrastructure system against fluctuations of temperature has been through the use of energy intensive and expensive chemicals such as polymers in construction materials. A radically different concept is proposed, in which wireless sensors embedded in road and airport vehicles and pavements will be used to trigger an embedded system to heat or cool pavements as required. This approach will enable the pavement system to self-monitor temperatures, dampen temperature fluctuations, prevent weakening of its condition, and hence prevent failures and costly repairs. The incident solar energy is available for powering sensors. A conceptual design approach is proposed for an active energy harvesting pavement system, through the integration of conventional pavement systems, tubes, sensors, actuators, and controllers. Fluid flowing through tubes inserted within pavements is used as heat exchangers. The temperature of water collected from sensors is used as the indicator of efficiency of heat capture. A multi-input, multi-output (MIMO) optimal control system is developed to extract maximum amount of energy and maintain the ideal temperature in pavements - it is formulated as a multi-objective optimization problem. The optimal distribution of the sensors in a decentralized system is found using intelligent optimization techniques. Finite element model, test results and design procedure of the MIMO optimal controller are presented.

7981-173, Session 15d

Model-free modal flexibility-based damage detection strategy for in-service highway bridges

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Long-term structural health monitoring of bridges has been underway in Connecticut since 1997, when the University of Connecticut and the Connecticut Department of Transportation began the implementation of permanent structural health monitoring (SHM) systems on a variety of bridge types across the State. The objective of the long-term structural health monitoring has been to develop techniques to identify global changes in the bridges' behavior over multiple years using ambient vibrations on in-service highway bridges.

Recently, SHM algorithms based on the modal flexibility matrix has drawn significant attention. This method has been shown to be more effective in damage localization than other methods such as using natural frequencies or mode shapes alone. However, not many of these algorithms are directly applicable for in-service highway bridges. Many studies that are done on highway bridges use SHM algorithms that require known excitations. Other studies require the use of a finite element model to implement the flexibility approach.

In this paper, a model-free modal flexibility based SHM algorithm is developed to identify structural damage considering variations in modal properties due to temperature fluctuations. A damage index is proposed for providing compact information on damage from the modal flexibility matrices before and after damage. The algorithm in conjunction with the damage index is first validated using a laboratory scale girder bridge under constant temperature. Finally, the efficacy of the SHM algorithm is verified using data collected under ambient loading conditions on an in-service highway bridge.

7981-174, Session 15d

Material property assessment and crack identification of recycled concrete with embedded smart cement modules

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In this study, the material property assessment and crack identification of concrete using embedded smart cement modules are presented. Both the concrete samples with recycled aggregates (RA) and natural aggregates (NA) were prepared. The smart cement modules were fabricated and embedded in concrete beams to serve as either the actuators or sensors, and the elastic wave propagation-based technique was developed to detect the damage (crack) in the RAC beams and monitor the material degradation of RAC beams due to the freeze/thaw (F/T) conditioning cycles. The damage detection results and elastic modulus reduction monitoring data demonstrate that the proposed smart cement modules and associated damage detection and monitoring techniques are capable of identifying crack-type damage and monitoring material degradation of the RAC structures. Both the RAC and NAC degrade with the increased F/T conditioning cycles. Though the RAC shows a lower reduction percentage of the modulus of elasticity (MOE) from both the dynamic modulus and wave propagation tests at the given maximum F/T conditioning cycle (i.e., 300 in this study), the RAC tends to degrade faster after the 180 F/T cycles. As observed in this study, the material properties and degradation rate of RAC are comparable to those of NAC, thus making the RAC suitable for transportation construction. The findings in development of damage detection and health monitoring techniques using embedded smart cement modules resulted from this study promote the widespread application of recycled concrete in transportation construction and provide viable and effective health monitoring techniques for concrete structures in general.

7981-175, Session 15d

Full-scale decentralized bridge health monitoring using wireless smart sensors

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Wireless Smart Sensor Networks (WSSN) facilitates a new paradigm to structural health monitoring (SHM) for civil infrastructure. Conventionally, SHM systems employing wired sensors and central data acquisition have been used to characterize the state of a structure; however, widespread implementation has been limited due to difficulties in cabling, high equipment cost, and long setup time. WSSNs offer a unique opportunity to overcome such difficulties. Recent advances in sensor technology have realized low-cost, smart sensors with on-board computation and wireless communication capabilities, making deployment of a dense array of sensors on large civil structures both feasible and economical. Wireless smart sensors have shown their tremendous potential for SHM in recent full-scale bridge monitoring examples. However, structural damage identification in WSSNs, a primary objective of SHM, has yet to reach its full potential. This paper presents a full-scale validation of the decentralized stochastic dynamic damage locating vector (SDDL) method on the Imote2 sensor platform on a historic steel truss bridge. The SHM application for WSSN developed in the previous research is further combined with continuous and autonomous monitoring

application. In total, 144 sensor channels and one base station have been deployed on the bridge for damage localization. Various power options are considered to explore long-term power options including batteries, AC-power, and solar panels. The measured data, results of damage localization, and brief evaluation of the deployed SHM system will be provided.

7981-176, Session 15d

Real-time health monitoring of bridge structures using a reference-free damage detection algorithm

S. Lee, G. Yun, S. Shang, The Univ. of Akron (United States)

The recent advanced structural health monitoring systems are gradually adopting remote, real-time and continuous monitoring features, being integrated with wireless sensors, GPS technology, information technology, advanced data analysis tools such as statistical mechanics, and artificial intelligence techniques, etc. To this end, we present a prototypical remote and real-time monitoring system which consists of two servers (NI-DAQ server and Web server). In NI-DAQ server, data acquisition and analysis tools are implemented into a NI-LabView VI program. A remote front panel associated with the VI program is web-published and embedded into a public web page so that remote users can access to the data and run analysis programs, interacting with NI-DAQ server. For a demonstration, a laboratory-size 3D truss structure is instrumented with wired accelerometers. The real-time health monitoring system is tailored for demonstrating a reference-free damage detection algorithm. As a damage indicator, the relative wavelet entropy (RWE) is implemented in the data analysis VI program using measured acceleration data. The proposed damage index is found to be suitable for detecting damage locations without knowing data from undamaged structures. It is notable that repetitive geometric and structural design of components in bridges enables the reference-free damage detection. To realize the real-time feature, discrete wavelet transformation is used for its fast computation time. Damage scenarios were made by loosening bolts in gusset plates. Finally, the damage locations in the bridge are successfully identified in real-time at a remote site.

7981-177, Session 15d

Stochastic Galerkin model updating of randomly distributed parameters

G. Yun, K. Nizamiev, K. Sett, S. I. Hariharan, The Univ. of Akron (United States)

Uncertainties arise everywhere in civil infrastructure systems due to a variety of reasons. They include structure variability due to the quality of constructions and discrete nature of construction processes particularly for RC bridge structures, measurement noises, degradations of materials due to environmental changes, natural variability of soil deposits, and randomness of loadings. Most deterministic model updating methods assume that parameters are discrete. However, they are spatially varying distributed random variables in actual structures. In this paper, we present a new stochastic model updating methodology to identify spatially varying material properties based on experimental data. This data is typically obtained from ambient or forced vibration measurement. For this purpose, linear elastic properties are modeled as random variables using the Karhunen-Loeve expansion (KLE). Covariance kernels of the parameters are decomposed in spectral domain by numerically solving the homogeneous Fredholm integral equation. Equation of motion is formulated using the Galerkin method. Parameters are updated using multiple sets of eigenvalues and mode shapes of structures until an error function of modal properties between the model and experiments is minimized. Synthetic data are generated in such a way that they have appropriate marginal probability distribution functions. Correlations between them are also taken into account. Our results are compared with the ones using Monte Carlo simulations for the corresponding deterministic model.

Conference 7982: Smart Sensor Phenomena, Technology, Networks, and Systems IV

Monday-Wednesday 7-9 March 2011

Part of Proceedings of SPIE Vol. 7982 Smart Sensor Phenomena, Technology, Networks, and Systems 2011

7982-01, Session 1

Fibre optic sensors in smart structures: achievements, challenges, and prospects

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This paper will seek to establish a critical perspective on the achievements and prospects offered by fibre optic sensors in Smart Structures. There have been numerous trial installations in structures ranging from wind turbine blades to bridges to tunnels and pipelines. Furthermore such installations have largely now evolved from interesting demonstrators into feasible prospective product with substantial apparent potential. However fibre optic sensors have still to progress into the "technology of choice" despite the demonstrations and apparent benefits. The paper will endeavour to establish why, by examining not only the considerable data which such systems can acquire but also the engineering prospects which this data may realise. This leads into the interpretation of continuous monitoring sensor data. Standards and acceptance criteria through which an unambiguous definition of sensor system performance may be established and communicated inevitably follow.

Most of the work to date has used one form or other of silica optical fibre. However geo- textiles, synthetic ropes, biomedical systems and similar applications require the significantly greater flexibility afforded through plastic optical fibres. Interest in POF transducer elements has recently increased as the optical performance of the materials themselves (exemplified in terms of attenuation and dispersion) has improved. POF sensors do however require different interrogation system techniques and measurement philosophies to accommodate the sensing characteristics of the fibres and the measurements they are intended to undertake. We shall present examples.

Many other emerging technologies may influence the application of fibre sensors in Smart Structures. These inevitably include processes through which the data acquired may be turned into decision making information. In parallel new optical technologies - photonic crystal fibres and techniques such as slow light, squeezed light and frequency combs - also facilitate new measurement modalities. These will be explored briefly. There are also prospects for combining fibres with other sensing techniques, most notably ultrasonics.

The opportunities for fibre sensors in Smart Structures appear to be significant at the technological level. There remains the recurrent need for the sensor enthusiast to clearly relate prospects offered to user needs. Perhaps this continues to be the greatest challenge of them all?

7982-02, Session 1

Active fiber sensor array for cryogenic environments

K. P. Chen, Univ. of Pittsburgh (United States)

Cryogenic fuels, such as liquid hydrogen, oxygen, and liquefied natural gas, are often considered as major energy alternatives to replace fossil fuel. To ensure safe storage and transfer of liquefied fuels, safe and reliable sensor networks are required for on-demand, real-time fuel management in cryogenic environments.

Fiber Bragg gratings (FBG) are key components for optical sensing. FBGs coated with Palladium (Pd) can be used for hydrogen gas leak detection. However, the sensor sensitivity degrades rapidly due to the diminishing Pd-Hydrogen absorption at low temperatures.

In this paper, a new sensor design is described that enhances the low-temperature performance of fiber sensors. FBGs inscribed in high

attenuation fiber (HAF) are used to absorb in-fiber power light to raise the local sensor temperature in the cryogenic environment. When in-fiber power light is turned off, FBG sensors can serve as passive sensors to gauge temperature and stress in the cryogenic system. When the in-fiber power light is turned on, the heated sensors can be used to rapidly gauge fuel leaks.

A hydrogen gas sensor array is demonstrated to detect hydrogen concentrations well below the 4% explosion limit simultaneously at different cryogenic locations. Hybrid metal-oxide nano-composite layers were coated on FBGs to protect the sensors from contaminants such as SO₂ and H₂S to avoid sensor poisoning. Device sensitivity, longevity, and response time were studied and optimized as function of nano-coating composition, thickness, and laser heating power. The paper presents an active sensing technique that can effectively function at the cryogenic environment with an excellent selectivity.

7982-04, Session 1

Memorization and detection of an arrested crack in a foam-core sandwich structure using a crack arrester with embedded metal wires and FBG sensors

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A crack arrester was recently developed to suppress crack propagation along the interface between the facesheet and the core in a foam core sandwich structure. The crack arrester is a semi-cylindrical stiff material inserted into the interface. The crack arrester decreases the energy release rate at the crack tip by suppressing local deformation around the crack. If the arrested crack can be instantaneously detected, the damage tolerance of foam-core sandwich structures can be dramatically improved. This study establishes an innovative crack detection technique using metal wires and fiber Bragg grating (FBG) sensors embedded at both edges of the arrester. The change in strain distribution in the arrester induced by arresting the interface crack is first memorized by the metal wire and the consequent residual strain distribution after unloading is then picked up by the FBG sensor as a damage signal. This study began by simulating sensor responses to evaluate the feasibility of the proposed technique. Elasto-plastic finite element analysis was conducted and the obtained residual strain in the sensor was then utilized to estimate changes in the reflection spectrum from the FBGs. Finally, a verification test was conducted, confirming that the spectral change of the FBG can clearly indicate the propagation direction and the tip location of the arrested crack. The proposed technique enables an effective application of the crack arrester and significantly improves the reliability of foam-core sandwich structures.

7982-05, Session 1

Embedded optical fiber Bragg gratings for in-situ measurement of residual stress in Al cold sprayed magnesium parts

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Magnesium alloys are opening their ways into various industries such as automotive due to their light weight, good machinability, and high damping characteristics. However, magnesium is an electrochemically active element and is prone to galvanic corrosion. In this regard,

Cold Spray (CS) process is used to coat the surface of magnesium parts with aluminum to protect it from corrosion. In the CS process, the magnesium surface is bombarded by micron-size Al particles accelerated to speeds of 300-1200 m/s by a supersonic gas stream. The CS process causes the formation of residual stress in the magnesium parts which can affect their fatigue behavior. This paper is concerned with the embedding of a network of Fiber Bragg Grating (FBG) sensors for in-situ monitoring of the residual stress and nondestructive testing of the magnesium parts. Finite element modeling of the CS process has shown that the magnitude of the residual stress decreases with a large gradient from the CS'ed surface down to the bulk of magnesium. As a result, the placement of the FBG sensors is a critical issue affecting their sensitivity. This issue is mainly addressed in this paper. In this approach, FBG sensors are embedded in micron-size holes drilled at the proximity of the CS'ed surface. By capturing the optical response of the embedded FBG, the strain components in the FBGs are obtained which are then related to the induced residual stress. To calibrate the sensors and evaluate their performance, the residual stress measurements are performed by X-ray diffraction.

7982-06, Session 2

FDM (frequency division multiplexing) and TDM (time division multiplexing) BOTDA for long sensing length

X. Bao, Univ. of Ottawa (Canada)

In long distance sensing range, fiber loss is major limiting factor, although the Brillouin gain can compensate some of the fiber loss, the compromise is the signal to noise ratio of the sensor system, hence the spatial resolution and the measurement accuracy of the Brillouin frequency shift, namely, temperature and strain resolution. To overcome this difficulty, we need to increase the Brillouin gain over the effective length instead of entire sensing length, so that long sensing length can be obtained with high spatial and strain resolution. We proposed and demonstrated frequency-division-multiplexing (FDM) and time-division-multiplexing (TDM) based BOTDA technique for long sensing length.

In both TDM and FDM based BOTDA, the gain control and optimization is very crucial to achieve high performance over the long sensing length. No inline amplifier is used within 75km and 100km sensing length and 1m spatial resolution at 100km and 0.5m spatial resolution at 75km have been achieved. Such a long sensing length can be used for pipeline and power line monitoring.

7982-07, Session 2

Distributed fiber optic sensor testing, data interpretation, and evaluation for monitoring in the geotechnical field

M. R. Iten, D. Hauswirth, A. M. Puzrin, ETH Zurich (Switzerland)

In this paper, an overview of optical sensor testing and evaluation from several geotechnical monitoring projects performed by the authors is given. Additionally, data interpretation for the tested sensors is addressed.

As distributed fiber optic sensing (BOTDA/BOTDR and others) is increasingly applied for monitoring in the geotechnical field, it is crucial to understand the behavior and the limitations of the sensor itself. This sensor can be a bare single mode fiber, but usually the fiber is protected by one or more layers above the fiber, and due to these layers, particularities for each sensor cable exist. So far, no standards and guidelines for fiber optic strain sensing cables are available. In some projects, the selected sensors do not meet the requirements, are inadequate or even break before completion of the integration process. Yet, with a non-ideal sensor, reasonable results can be obtained by suitable data interpretation.

For this paper, the sensor testing consists of straining a section of the

sensor to different strain levels and acquiring at each level distributed optical strain data besides independent load and displacement measurements at the sensor cable tip. The optical strain sensing technologies used are BOTDA (Brillouin Optical Time Domain Analysis) and BEDS (Brillouin Echo Distributed Sensing). While BOTDA allows for strain measurements over 1m spatial resolution, the spatial resolution of BEDS is 0.05m. This enormous increase in spatial resolution permits to capture sensor inhomogeneities (e.g. slippage of the fiber within the sensor cable) and therefore, the quality of the sensor evaluation is dramatically improved. For the data interpretation, several known models are summarized and an additional model which includes the above stated slippage is developed. The problems and methods discussed in the paper, as well as the authors approach to testing and data interpretation are expected to be of use for engineers confronted with a fiber optics distributed strain sensing problem.

7982-08, Session 2

Research on SRSI method of selecting valid measuring points

P. Gong, X. Zhao, Y. Liu, J. Lu, Dalian Univ. of Technology (China)

In recent years, the distributed BOTDR technique has been widely applied into the field of structural health monitoring (SHM) because of its advantages, such as durability, distributed measurement ability, anti-interference in electromagnetism, etc. Traditionally, distributed BOTDR technique can be utilized to monitor temperature, stress and strain in the field of SHM on the large scale. Nevertheless, if the sensing gauge is relatively small, the number of measuring points along the fiber will be quite limited, sometimes even only 3 to 5 points due to the restrictions of the minimum spatial resolution and sampling interval of the BOTDR analyzer. Therefore, how to select monitoring data from only a few measuring points becomes a key to apply distributed BOTDR technique into the field of small-scale monitoring successfully. This paper presents the concepts of valid measuring points and invalid measuring points, proposes the selecting method of the valid measuring points considering spatial resolution and sampling interval (SRSI Method) of the BOTDR analyzer, and analyzes the test data by the SRSI Method and the selecting method of the valid measuring points by peaks (Peaks Method) in the temperature sensing test, strain sensing test and BOTDR corrosion monitoring test. In the above tests, different spatial resolutions or sensing lengths of the fiber were set for comparison with each other. The test results reveal that SRSI Method, which can improve the accuracy of the test results effectively, is the better selecting method of the valid measuring points than Peaks Method, especially when the number of valid measuring points is rather small.

7982-09, Session 3

Analysis of fiber Bragg grating spectral features for in-situ assessment of composites

K. J. Peters, North Carolina State Univ. (United States)

Embedded sensors provide a high sensitivity to sub-surface damage due to their proximity to the damage features. In particular, fiber Bragg gratings (FBG) are easily embedded into laminates with a minimum of perturbation to the surrounding material microstructure. In this paper we summarize some recent advances derived from full-spectral interrogation of FBG sensors for structural health monitoring and damage identification in composites. In particular we will present signals from the FBG reflected spectra that have been correlated to stress concentrations near crack tips, curing conditions during processing of composite laminates and the progression of delamination due to multiple low-velocity impacts in woven composite laminates and foam-core sandwich composites. We also discuss recent advances in interrogation systems for these sensors which have permitted dynamic evaluation of these parameters. Finally, spectral distortion can lead to errors in the interpretation of strain values from the peak wavelength measurement when peak waveforms are assumed. This distortion is highly dependent upon the

local microstructure surrounding the sensor and therefore cannot be compensated a-priori through a calibration factor. We demonstrate that full-spectral interrogation can provide sensor specific error compensation for these measurements. These results demonstrate the richness of information that can be obtained from full-spectral interrogation of FBG sensors in a complex, multiple stress component environment.

7982-10, Session 3

Noise propagation in a 3x3 optical demodulation scheme used for fiber Bragg grating interrogation

M. D. Todd, Univ. of California, San Diego (United States)

This work presents a model of an exact transfer function and its associated probability structure for intensity noise propagation through a digital fiber optic demodulation scheme used with fiber Bragg grating sensor systems. It is generalized to any input noise probability structure and includes the possibility of full or partial correlation among the demodulation input channels. For the case of Gaussian intensity noise, the work shows explicit interferometer phase influence on output noise statistical moments, which are important for signal-to-noise predictions. The demodulator's nonlinear transfer function is shown to induce output bias as well as either attenuate or amplify output variance, depending upon the signal phase. Experimental data are provided to validate the model.

This work shows that the probability density function of the output noise may be written very generally as a joint probability density function of two variables a and b that may be shown to be linearly related to the input noise on the three input channels. Approximate probability density functions have been presented in some different configurations, usually for nonlinear phase noise in differential phase-key shifting systems, in the past, but these approaches typically modeled combined signal and noise on the output. This approach models the input/output noise only, since the structure and propagation of noise is of great interest in distributed sensing applications. This work thus considers, given the probability and correlation structure of any noise on the three demodulator input channels, what the output noise characteristics are such that performance metrics may be explicitly computed for fiber Bragg grating sensing systems.

7982-11, Session 3

Evaluation of the internal strains and stresses produced in a plate by propagating Lamb waves through the use of fibre optic sensors

G. J. Thursby, B. Culshaw, Univ. of Strathclyde (United Kingdom)

Lamb waves are frequently used in structural evaluation and for the determination of materials properties, but they are invariably detected either by non-contact methods or via a transducer mounted onto the sample surface. In this paper we will look at ways of experimentally detecting the different stress and strain patterns within the thickness of a plate through which Lamb waves are propagating. Experimental analysis shows that particle motion, and hence strains and pressure, varies with depth through a plate in differing ways according to the type of mode propagating. This is particularly noticeable when comparing the symmetric (S0) and antisymmetric (A0) modes. The difference should be greatest near the neutral axis of the plate and least near the surface. In order to study this difference, two types of fibre optical sensor were used, fibre Bragg gratings and polarimeters, both of which were embedded into an 8 ply carbon composite plate. One of each type of sensor was placed at the centre of the plate, one just below the surface and one on the surface. It was anticipated that the FBGs would be primarily sensitive to longitudinal strains whilst the polarimeters would have greatest sensitivity to pressure. The two types of sensor were therefore located orthogonally, with the FBGs aligned parallel to the direction of ultrasound propagation and the polarimeters normal to it. Ultrasound was launched by electrically exciting a PZT bonded to the plate surface with 4.5 cycle tonebursts.

It will be shown that broad agreement has been reached between the theoretical model and the experimental results and ongoing work will be described that should provide a more detailed description of the mechanisms involved

7982-12, Session 3

Full-spectral interrogation of fiber Bragg grating sensors for damage identification

S. C. Webb, K. J. Peters, M. Zirky, North Carolina State Univ. (United States); S. L. Chadderdon, T. Vella, R. H. Selfridge, S. M. Schultz, Brigham Young Univ. (United States)

In this study, we demonstrate a new in-situ measurement technique for monitoring damage progression in laminated composites during dynamic events. The measurements are based on high-speed, full-spectral scanning of the response of a FBG sensor, embedded in the laminate. This was achieved by extending the data acquisition rate for full-spectral interrogation of FBG sensors through a MEMs tunable filter interrogator in-situ damage identification. This measurement technique was applied to multiple, low-velocity impacts of two-dimensional woven laminates, at energies up to 14.5 J. During the impact events, both the strain components perpendicular and parallel to the lamina interface were measured. The strain acquisition was demonstrated at rates of 100 and 300 kHz, sufficient for the dynamic events tested. As a result of this high data acquisition rate, the maximum strain during impact was captured for all impact events. In the future, this measurement system could be applied to multiple FBG sensors, embedded at different depths and locations with the laminate, to better understand the spatial progression of damage in a structure. Even if only peak wavelength information is required, the resolution of the full-spectral response would also prevent errors due to "wavelength-hopping" or other spectral distortions previously limiting the application of embedded FBG sensors. The viability of the interrogator for future applications to in-flight structural health monitoring of aircraft frames in which strain fields must be identified in noisy environments is also discussed.

7982-13, Session 3

Multi-signal integrated optical fiber sensors based on ROTDR and FBG

J. He, Z. Zhou, Dalian Univ. of Technology (China); M. Huang, Harbin Institute of Technology (China); J. Ou, Dalian Univ. of Technology (China)

Strain and temperature are the two most important simultaneous parameters for the structural health monitoring for infrastructures. In field applications, there is lack of effective and low cost methodology to separate the stress and the temperature. In this paper, a novel multi-signal integrated optical fiber sensing technique by using Raman optical time domain reflectometry (ROTDR) temperature sensor and fiber Bragg grating (FBG) strain sensing technique is proposed, named ROTDR-FBG multi signal-integrated system. In this ROTDR-FBG system, the FBG sensors can be used for either stress or the temperature while ROTDR can take the full-scale temperature along the sensing line, and the temperature measured by ROTDR at the FBG positions can be used for the temperature compensation for strain measured by FBG. The strain and temperature can be separate simultaneously in one sensing line based on ROTDR-FBG technique, which greatly reduces the layout cost of SHM and has widely application value.

7982-14, Session 3

Damage detection in FRP structures using fiber Bragg grating dynamic strain sensing systems

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Fiber optic sensors have become widely-used for structural health monitoring in recent decades. The aim of this research is to characterize the dynamic failure signals (such as acoustic waves) emitted in FRP (Fiberglass Reinforced Panels) using FBGs (Fiber Bragg Gratings) and two types of interferometric demodulation systems, namely Michelson interferometer and Two-Wave Mixing (TWM) interferometer for detection. One of the main advantages of TWM interferometer is its ability to multiplex. Two channels of FBGs are used with the TWM interferometer to track damage in coupon-size FRP samples. Due to its one-dimensional form, only one FBG and the Michelson interferometer are used for damage monitoring in an FRP cable under various types of loading. It is interesting to note that beyond a 2mm static stretch, chirping is observed in the FBGs mounted on a coupon-size FRP sample under tensile loading. However, the FBG returns its original profile after static deformation is released and subsequent damage detection is still possible using the same FBG. In this paper, we will present results for damage detection in these FRP structures through static and dynamic strain sensing as the structures were loaded to failure.

This research work is part of an international collaborative effort funded by the US National Science Foundation, where the materials were supplied and experiments were conducted at Harbin Institute of Technology, China, using the TWM and Michelson demodulators developed by Northwestern University, USA.

7982-15, Session 4

Twenty five years of structural health monitoring using fiber optic sensors

E. Udd, Columbia Gorge Research (United States)

This paper describes work in the area of fiber optic smart structures performed by the authors and his colleagues at McDonnell Douglas, Blue Road Research and Columbia Gorge Research over the past 25 years. It is intended to provide an overview of some of the developments in the field and how it evolved over this time span. Application areas that will be addressed include aerospace, civil structures and composite materials. The paper will address underlying philosophies and approaches to smart structures and how these methods have been implemented in the field.

7982-16, Session 4

Condition assessment of a bridge superstructure using diagnostic performance indicators

M. V. Gangone, Clarkson Univ. (United States); M. J. Whelan, The Univ. of North Carolina at Charlotte (United States); K. D. Janoyan, Clarkson Univ. (United States)

With nearly one quarter of today's highway bridges rated as structurally deficient or functionally obsolete, it is ever more important to quantify the safe level of performance using in-situ structural health monitoring techniques. This paper discusses the experimental testing of a single simply supported span composite superstructure under various controlled progressive damage cases. The single span is part of a three span bridge located in northern New York. Using strain transducers mounted at the midspan and support locations, changes in load distribution factors and neutral axis locations are calculated to detect changes in load shedding behavior and structural capacity of the bridge span as diaphragm connections were severed and support conditions were altered to different levels. The results of the testing show that changes in the bridge response can be tracked as damage is introduced to the superstructure. The measurements are used to identify the diagnostic load testing parameters that can be used as structural health indicators that can in turn be used to complement current inspection protocols. Furthermore, the measurements also help provide a basis for future development of a performance index to be used in conjunction

with existing condition rating measures for improved bridge condition assessment.

7982-17, Session 4

Printed resistive strain sensors for monitoring of light-weight structures

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In this paper we present the design and test of printed strain sensors, which can be integrated in light-weight structures for monitoring purposes. We focus on composite structures consisting of metal substrate as well as insulating and conductive ink layers for sensing normal strain at the surface. Both, inkjet and screen printing technology are used to realize resistive topologies that can be evaluated using a Wheatstone bridge configuration.

In a first step, we analyzed electrical properties of functional inks: electrical impedance and breakdown electrical field strength in case of insulation inks, resistance in case of conducting inks. A silver and a PEDOT:PSS based suspension were used. To determine the resistance change due to deformation of the metal substrate in a forming process, tensile tests were performed up to 30% strain and subsequent resistance change was measured.

In a second step, the sensing effect of printed conductive structures was investigated. Resistive sensing topologies were designed for detecting longitudinal and transverse normal strain. Meander structures, which form single resistors as well as bridge configurations, were printed on test specimens and analyzed in a four-point bending set up. Performing loading and unloading cycles, gauge factor, cross sensitivity, nonlinearity and hysteresis error of the sensors were measured. To test creeping, the test specimens were stressed with constant load for four hours and the change of the output voltage was evaluated.

First measurements showed that the measured gauge factor is lower than the expected value. One reason could be the low Young modulus of the insulation layer which causes a lower strain transmission.

7982-18, Session 5

Overview of applications and industrial trends of fiber optic sensing in structural health monitoring

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Over the past decade, optical fiber sensors have seen increased acceptance and widespread use in different fields and industries for a variety of applications ranging from structural sensing and health monitoring of materials and structures; 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 biomedical patient devices-to name just a few.

Optical fiber sensor operation and instrumentation have become well understood and developed, and a broad variety of commercial discrete sensors and instruments-based on Fabry-Perot (FP) cavities and fiber Bragg gratings (FBGs), as well as distributed ones based on Raman and Brillouin scattering methods-are nowadays readily available. However, some technical hurdles and market barriers remain and need to be overcome in order for fiber sensing technology to gain more commercial momentum and achieve faster and broader market growth compared to conventional sensing technologies.

This talk will provide an overview on the diverse structural health monitoring (SHM) applications of fiber sensing technologies-such as civil infrastructure test and monitoring, wind turbine blade monitoring, pipelines, vessels and cargo ships, to name a few-and its associated commercial status, as well as its future prospects and market outlook. The main goal is to contrast the issues and progress made on the R&D side against the trends on the industrial and commercial fronts.

7982-19, Session 5

Robust diagnostics for Bayesian compressive sensing with applications to structural health monitoring

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In structural health monitoring (SHM) for civil structures, signal compression is important to reduce the cost of huge data transfer and storage. Compressive sensing is a novel data compressing method whereby one does not measure the signal directly but rather related measurements. The length of the required compressive-sensing measurements is typically much smaller than the original signal. Recently, a Bayesian formalism has also been employed for optimal compressive sensing, which adopts the ideas in the relevance vector machine (RVM) as a decompression tool, such as the automatic relevance determination prior (ARD). Recently publications illustrate the benefits of using the Bayesian compressive sensing (BCS) method. However, none of these publications have investigated the robustness of the BCS method. We show that RVM lacks robustness when the number of measurements is a lot less than the length of the signals because it can produce sub-optimal signal representations, and so BCS is not robust when high compression efficiency is required. This induces a tradeoff between efficiently compressing data and accurately decompressing it. Based on a study of the robustness of the BCS method, diagnostic tools are proposed to investigate whether the compressed representation of the signal is optimal. With reliable diagnostics, performance of BCS method can be monitored along with a potential "healing algorithm" that can be applied in the case that a sub-optimal compressed representation is detected. The numerical results show that robustness is enhanced by the proposed diagnostics. Finally, data collected from a SHM system is used to validate the method.

7982-20, Session 5

Monitoring dispersion, strain, and damage in multi-phase composite materials using electrical resistance methods

A. Paipetis, S. Grammatikos, G. Gkikas, Univ. of Ioannina (Greece)

The electrical properties of fiber reinforced polymers (FRP's) offer the ability of strain and damage monitoring. This is performed via electrical resistance and electrical potential measurements. Since Carbon Nanotubes (CNT's) were invented, they proved to be an efficient additive to polymers and matrices of composites with respect to structural enhancement and improvement of the electrical properties. The induction of CNT's in signal, as far as they transform matrix into conductor. The key issue of the structural and electrical the insulating matrix increases the capability of the obtained properties optimization is the dispersion degree of the nano-scale phase in the polymer phase. Well dispersed CNTs provide an electrical network between the insulating matrix and the fibres which acts as an inherent sensor the composite structure, since every invisible crack or delamination is manifested as an increase of the electrical resistance. The scope of this work is to further exploit the information provided by the electrical properties with a view to characterise dispersion quality via real time resistance measurements, identify strain variation and global damage via bulk resistance measurements and investigate the possibility of localised damage monitoring (either artificial or service induced via scanning or topography techniques). The aforementioned techniques were employed to monitor dispersion, strain and damage either global or localised in polymers reinforced with conductive nanofillers as well as in fibre reinforced composite laminates.

7982-22, Session 6

Influence of sensor placement on operational modal analysis of steel girder bridges

M. J. Whelan, The Univ. of North Carolina at Charlotte (United States); M. V. Gangone, K. D. Janoyan, Clarkson Univ. (United States)

With the advent and development of low-cost wireless structural health monitoring systems, the task of routinely assessing the in-service condition of highway bridges is an increasingly feasible component of bridge safety and management practice. Bridge monitoring encompasses placement of often a limited number of distributed sensors across a relatively large and complex structural system. Consequently, the selection of proper sensor locations is imperative for extracting the most value from the recorded measurements. An experimental investigation of ambient vibration monitoring on a three-span in-service highway bridge is presented wherein the measured response from sensor placement on the superstructure girders is contrasted to the measured response on the surface of the bridge deck. The effect on the dataset richness, as evidenced by the modal content, is investigated and conclusions regarding optimal placement for this structure type are drawn. In particular, the study highlights the influence of sensor placement on either accentuating or attenuating localized element behavior within the context of the common reinforced concrete deck on multi-girder structure type. To affirm the plausibility of the observed responses and conclusions drawn, a finite element analysis is also performed on a model developed from the as-built drawings.

7982-23, Session 6

RFID-based displacement field monitoring system

M. Huang, Harbin Institute of Technology (China); Z. Zhou, Dalian Univ. of Technology (China) and Harbin Institute of Technology (China); J. He, Dalian Univ. of Technology (China); J. Ou, Harbin Institute of Technology (China) and Dalian University of Technology (China)

In this paper, a novel displacement field monitoring method is proposed based on the radio frequency identification (RFID) technique. A smart block is configured by embedding the RFID smart tag with the identities (ID) into the natural or artificial rock, which can be effectively identified and located by the RFID readers in real-time. Herein the displacement measuring method was firstly derived in detail from the conventional identified and located principle of the RFID technique, and further smart rocks were designed and fabricated. A prototype displacement field monitoring system was set up with three RFID readers to identify the smart rocks and further measure their displacements in the laboratory, and the experimental results show that the proposed system identified the smart rocks and further monitored their displacements effectively. The proposed system can be widely applied to monitor the displacement field in real-time, and further provide direct information for assessing the potential damages in the structural health monitoring.

7982-24, Session 6

Node cooperation based support vector machine localization algorithm in mobile wireless sensor networks

Q. Guo, T. Tang, Harbin Institute of Technology (China)

This paper considers the problem of security in Wireless Sensor Networks (WSNs). We only focus on the malicious attacks such as Wormholes, Sybil, Hello, Flood, monitor location information, Replay, and so on. Suppose that two types of sensors, anchors and unknown,

are randomly and uniformly distributed in the static WSN with two-dimensional space. The base point is deployed in the center of the WSN field and it can communicate with all the sensors. The base point with an adaptive array antenna (AAA) is perfectly safe with high processing capacity and sufficient energy.

There are two steps in the NCBLV algorithm: information collection from the anchors and malicious node verification by base point. In the first step, the information of ID and position from the neighbor nodes (unknown nodes and anchors) are respectively gathered by the node S. Then these information will packet to the base point, and we call this packet as Packet 1. In the second step, the base point calculate the angle of node S, and form the beam with beam width angle using AAA. Then we can find all the nodes in this area. Also the information is packeted as Packet 2. Compare Packet 1 & Packet 2, then we can obtain the plausibility.

We conduct simulation experiments to evaluate the performance of this algorithm by varying the communication range and the antenna beam width angle. Results show that NCBLV algorithm has high probability of successful malicious nodes detection and probability of false nodes detection.

7982-25, Session 7

FOS standards and testing method to validate fibre optic strain measurements

W. R. Habel, V. G. Schukar, Bundesanstalt für Materialforschung und -prüfung (Germany)

In the second part of the presentation, a newly developed method and facility to evaluate, calibrate and validate all kinds of surface-applied strain sensors (fibre optic and resistance ones, extensometers, ...) under combined thermal and mechanical loading will be presented. Usually, applied fibre optic strain sensors are calibrated against attached high-quality strain sensors. The developed method uses, in contrast, an application-independent calibration procedure for observation and evaluation of the strain development in/around the applied strain sensor. It is therefore suitable for the reliable validation of the strain sensor characteristics. Selected results provided by this facility will be exemplified, e. g. experimental investigations on the strain transfer characteristics of fibre Bragg grating patches - in conformity to the new guideline. Comparison between patches and resistance strain gauges during tensile tests and combined temperature and tensile loading revealed there are partial disagreements between the manufacturer's specifications and the observed characteristics, for instance, in strain gauge factor and temperature sensitivity of the strain gauge factor. The developed methodology is therefore recommended for verification and confirmation of technical data of commercially available sensors.

In the third part, ongoing standardization activities and new European networks related to fibre optic sensors will be given. The new guidelines and recent discussions are considered as basic activities on the way to further IEC fibre optic sensor standardisation documents. Cooperation activities with SAE standardisation groups such as AS3-C2 committee will also be considered. The outcome of these activities for interested users becomes evident.

7982-26, Session 7

Multi-use D-fiber sensors

R. H. Selfridge, Brigham Young Univ. (United States)

Optical fiber sensors have formed an integral part of the structural health monitoring and smart sensor communities from their early beginnings. Particular benefits have been derived from both the mechanical and optical properties of the optical fibers. In particular, they are lightweight, small, and can be integrated in the structures they are designed to monitor. Also, optical fiber sensors are generally immune from electromagnetic interference. These properties have been exploited in a wide range of applications in civil structures, aerospace, and electronics.

Applications range from body armor and bomb detection to monitoring bridges and oil wells. This paper reviews the value of D-type optical fibers (D-fibers) in measuring a variety of important parameters. In standard optical fibers the light propagation is confined tightly to the core of the fiber and only interacts with the physical structure of the fiber itself. The principal advantage of the D-fiber is that it allows for interaction with light traveling in the core of the fiber materials and materials or structures placed in contact with the fiber. This allows for stimulus sensitive materials to be placed on the D-fiber to interact with the light in the core of the fiber. This presentation shows that this feature of D-fibers can be used to form alternatives to sensors formed in standard optical fibers for measuring temperature, strain, and shape change. In addition, D-fiber sensors have been created to measure chemical concentrations, electric and magnetic fields. The results of a range of D-fiber devices will be given during the course of this presentation.

7982-27, Session 7

Electro-optic polymer electric field sensor

D. T. Perry, S. L. Chadderdon, B. Schreeve, S. M. Schultz, R. H. Selfridge, Brigham Young Univ. (United States); W. C. Wang, R. A. Forber, IPITEK, Inc. (United States); J. Luo, Univ. of Washington (United States)

Modern electronics are often shielded with metallic packaging to protect them from harmful electromagnetic radiation. In order to determine the effectiveness of the electronic shielding, there is a need to perform non-intrusive measurements of the electric field within the shielding. The requirement to be non-intrusive requires the sensor to be all dielectric and the sensing area needs to be very small. The non-intrusive sensor is attained by coupling a slab of non-linear optical material to the surface of a D shaped optical fiber and is called a slab coupled optical fiber sensor (SCOS). The sensitivity of the SCOS is increased by using an organic electro-optic (EO) polymer.

One of the biggest advantages of EO polymer over inorganic materials is its lower dielectric constant. Several technical challenges were overcome in order to take advantage of the lower dielectric constant. These challenges are (1) development of an EO polymer material that has a high electro-optic coefficient and is temporally and thermally stable, (2) development of a method to create thick free standing polymer films, and (3) attaching the free-standing polymer film to a D-fiber. The challenge of attaching the EO polymer to the optical fiber is that the polymer bends when it is attached to fiber causing poor resonance coupling. We have developed a technique of supporting the flexible polymer with a small rigid glass or fused silica slide helping to increase the stiffness of the polymer. This paper includes detail on the fabrication and testing of the SCOS.

7982-28, Session 7

Interrogation systems for slab coupled optical fiber sensors

J. Noren, S. M. Schultz, R. H. Selfridge, Brigham Young Univ. (United States)

When introduced into the presence of an electric field the SCOS creates a shift in the spectral response of the fiber directly related to the magnitude and direction of the electric field. BYU has developed two methods to transform the output of the SCOS, a very small time-vary signal, into a usable electrical signal. The two different methods each have several pros and cons that recommend their uses for different applications. The first method, which returns the frequency domain response, uses the electrical spectrum analyzer and is excellent for the detection of slow changing single frequency fields of any frequency detectable by the ESA. The second method, gives a time domain response, is based on polarization splitting and will operate well in noisy environments over desired frequency ranges due to high error reduction rate.

To increase the error reduction rate of either method we introduced an optical power modulator into the system. By using a carrier signal at certain frequency, the interested signals can be unconverted to a frequency band that has the least amount of noise. After detection, the signal can then be recovered using a simple mixer and pass-band filter. By using modulation we have been able to increase the signal level 10db above the noise floor.

7982-29, Session 7

Experimental verification of a model describing the intensity distribution from a single mode optical fiber

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The intensity distribution of a transmission from a single mode optical fiber is often approximated using a Gaussian-shaped curve. While this approximation is useful for some applications such as fiber alignment, it does not accurately describe transmission behavior off the axis of propagation. In this paper, another model is presented which describes the intensity distribution of the transmission from a single mode optical fiber. A simple experimental setup is used to verify the model's accuracy, and agreement between model and experiment is established both on and off the axis of propagation. Displacement sensor designs based on the extrinsic optical lever architecture are presented. The behavior of the transmission off the axis of propagation dictates the performance of sensor architectures where large lateral offsets (25-1500 μm) exist between transmitting and receiving fibers. The practical implications of modeling accuracy over this lateral offset region are discussed as they relate to the development of high-performance intensity modulated optical displacement sensors. In particular, the sensitivity, linearity, resolution, and displacement range of a sensor are functions of the relative positioning of the sensor's transmitting and receiving fibers. Sensor architectures with high combinations of sensitivity and displacement range are discussed. It is concluded that the utility of the accurate model is in its predicative capability and that this research could lead to an improved methodology for high-performance sensor design.

7982-30, Session 7

Advanced image processing and artificial intelligence-based approaches to fiber optic statistical mode sensor design

H. S. Efendioglu, Fatih Univ. (Turkey); T. Yildirim, Yildiz Teknik Univ. (Turkey); O. Tokar, Fatih Univ. (Turkey)

Multi-mode fibers carry many modes because of their larger core diameter, and existence of multiple modes causes speckled appearance of the light exiting the fiber end. Deformations or other external effects to the fiber perturbs the propagation of the modes and hence the pattern of the speckles. This can be used for construction of fiber optic statistical mode sensors. The speckle pattern can be detected by projecting it from the fiber end upon a screen or directly onto a CCD camera sensor. When optical fiber is perturbed, the distribution of the speckles, more precisely their intensity, size, and/or location change with the external perturbation, with some speckles becoming brighter, some dimmer and some not changing at all. Furthermore, some of speckles become bigger, some become smaller, with possibly moving in a specific direction. Analyzing all of these complicated changes in the speckle pattern can be used to obtain information about the external perturbation, i.e. the whole system can be used as a fiber optic sensor. To the best of authors knowledge, reported results in the literature are based on basic image differencing or correlation techniques. In this study, we proposed novel advanced image processing techniques and artificial intelligence based

algorithms for analysis of these rather complicated changes in the speckle pattern. By extracting more information from the speckle pattern image, and processing these via advanced methods, a better sensor can be constructed. In summary, the proposed approach enables the construction of more sensitive fiber optic statistical mode sensors.

7982-42, Poster Session

Characterization and compaction of Lamb wave data using a combination of S and wavelet transformations

I. N. Tansel, G. Singh, G. Singh, Florida International Univ. (United States); B. L. Grisso, L. W. Salvino, Naval Surface Warfare Ctr. Carderock Div. (United States)

Lamb wave based methods have been widely used by the structural health monitoring (SHM) community. Most of the techniques used detect structural defects by creating Lamb waves with piezoelectric elements used as actuators while monitoring the propagation of the waves with similar sensors. To detect the defects and determine their locations, a very large number of data sets are generally collected and processed.

During the interpretation of the Lamb wave data, the main concern is the arrival time of the wave groups. Group arrival times determine the distance of the source or the reflector. If the waves arriving with a phase shift are ignored like many of the current methodologies, the inspection of the envelope of the wave time history is satisfactory to identify the defects. Hilbert, Hilbert-Huang, wavelet, and short time Fourier transformations are commonly used approaches to examine the changing waveform shape. In this paper, generating the signal envelope from the S-transformation and further compacting the envelope with wavelet transformations are proposed. Major structural defects could be easily identified using visual inspection of the time-frequency plots generated by the S-transformation. These plots are not convenient for detection of minor defects which generate only minimal changes in the signal characteristics. Similarly, automatic classification of 3-D plots is more difficult and computationally expensive compare to working with 2-D data. Therefore, only the single row of the 3-D plot of the S-transformation which corresponds to the excitation frequency was used to calculate the envelope of the signal. The resulting envelope was a smooth curve with good time information. The envelope was then compressed further by using the wavelet transformation. Depending on the acceptable error range, the transformation may be repeated several times until the desired compaction versus accuracy compromise is obtained.

The proposed procedure was tested on crack growth measurements from an aluminum plate. Experimental data was collected by creating Lamb waves from one side of a crack and collecting the data at the other side. The envelope of the signal was obtained by using the above procedure. The envelope was compressed to 1:5 by down sampling. Further compression was obtained by using the Daubechies 2 type wavelet transformation and representing the signal with only the approximation wavelet coefficients. The paper will present the average estimation error of the S-transformation envelope at different levels of wavelet transformations.

7982-43, Poster Session

Study on theoretic model of shape memory alloy metallic rubber based on contacted micro-beams theory and finite element simulation

S. Li, H. Li, Harbin Institute of Technology (China); C. Mao, China Earthquake Administration (China); W. Wang, Harbin Institute of Technology (China); Y. Zhao, Jilin Univ. (China)

Shape Memory Alloy Metallic Pseudo Rubber (SMAMPR) is a kind

of novel porous material with high elasticity and large restorable deformation, and it is also an ideal material for three dimensional isolators. However, the theories on the constitutive model of metallic rubber are seldom studied due to its complicated microstructure. The theoretical studies on SMAMPR are even more fewer. A theory of contacted micro-beams with equal section is presented in this study, in which the friction between the metal wires in metallic rubber is considered according to Coulomb's friction law. Firstly, the nonlinear rigidity of the micro-beams in the loading process is derived according to the simplified mathematical model. Then, the parameters in the theoretic model are also determined through establishing the relationship between the macro-structure and the micro-structure based on the law of mass conservation and the probability theory. Especially, the number of contacted points between the surfaces of the micro-beams is estimated according to a mathematical function. In order to investigate the mechanism of the sudden change of the friction at the turning point between the loading and unloading process, a birth and death like element is proposed to simulate the interaction among the metal wires. Finally, combined with the finite element method, the results of normalized stress-strain relationships under compression are obtained and compared with the experimental data.

7982-44, Poster Session

Linear phased array of piezoelectric transducers for monitoring damage in composite panel using ultrasonic Lamb waves

V. T. Rathod, N. Chakraborty, D. Roy Mahapatra, Indian Institute of Science (India)

Applications of linear phased array concept have got extended from antennas to many other areas due to their capability to direct and magnify the energy in desired direction. Apart from electromagnetic (radar), photonic and medical ultrasonic imaging, a growing area is in the non-destructive testing and SHM of structures, especially the aircrafts. The linear array has particular advantage where the wave gets attenuated due to inherent damping and loss at composite interface/joints for example. Linear phased arrays are used as actuator in ultrasonic testing to magnify the energy at a given direction or point in the structure. In the present work the property of amplifying the wave generated in a particular direction is exploited and is studied considering a composite panel. The spreading of energy in a composite laminate is studied in terms of lobe patterns obtained using amplitude of symmetric lamb wave mode (S₀) with a particular orientation of the linear array with respect to fiber direction. Lobe patterns are constructed for 0-180 degree for various inclination of the linear array with respect to the fiber direction of the composite laminate. Actuators of linear phased array and a sensor are used in pitch-catch mode so that the linear array is tilted at various angles and the sensor is swept from 0-1800. With the aid of generated lobe patterns a technique is proposed to detect and locate damage, such as delamination in the composite panel.

7982-45, Poster Session

Displacement field monitoring in real-time with the magnetic survey technique

M. Huang, Harbin Institute of Technology (China); Z. Zhou, Dalian Univ. of Technology (China) and Harbin Institute of Technology (China); J. He, Dalian Univ. of Technology (China); J. Ou, Harbin Institute of Technology (China) and Dalian Univ. of Technology (China)

The paper addresses a novel displacement field monitoring method basing on the magnetic survey technique. Magnetic matters (such as magnet or iron blocks) with separate identifying labels were previously embedded into the natural or artificial rocks to develop novel smart

sensors, name smart rocks, and their locations could be effectively measured by the magnetic surveying instruments e.g. magnetometer though detecting the magnetic strength variations with the displacement changes. In this paper, the displacement measuring principle was firstly presented in detail; and then the produced magnetic field strengths and propagating distances of several kinds of magnetic matters were tested for the embedded magnetic matter selections of the smart rock design and development. In the laboratory, smart rocks embedded magnetic matters with different sizes were fabricated and a prototype displacement field monitoring system consisting of three magnetometers was setup. The locations and displacements of the smart rocks were measured by the magnetometers. The experimental results present that the proposed system recorded the locations of the smart rocks and further measured their displacements effectively. The proposed system can be widely applied to monitor the displacement field timely in infrastructures ranging from geological slope, dam embankment and bridge foundation.

7982-46, Poster Session

An algorithm for a crack evaluation using the linearly integrated hall sensor array

S. G. Lee, Kyung Hee Univ. (Korea, Republic of)

Previous researches show that linearly integrated Hall sensor arrays (LIHaS) can detect cracks in the steel structure fast and effectively. This paper proposes an algorithm that estimates the size and shape of cracks for the developed LIHaS. In most nondestructive testing (NDT), just crack existence and location are obtained by processing 1-dimensional data from the sensor that scans the object with relative speed in single direction. The proposed method is composed with two steps. The first step is constructing 2-dimensionally mapped data space by combining the converted position data from the time-based scan data with the position information of sensor arrays those are placed in the vertical direction to the scan direction. The second step is applying designed Laplacian filter and smoothing filter to estimate the size and shape of cracks. The experimental results of express train wheels show that the proposed algorithm is not only more reliable and accurate to detecting cracks but also effective to estimate the size and shape of cracks.

7982-47, Poster Session

Design of hetero-core microbend stress sensors and comparative analysis of various hetero-core sensor architectures

A. K. Sahin, Univ. of Missouri-Columbia (Turkey); H. S. Efendioglu, K. Fidanboyulu, Fatih Univ. (Turkey)

Microbend sensors are one of the earliest developed sensors. The mechanical factors that affect the sensitivity of the microbend sensors are number of corrugations, mechanical periodicity and corrugation size. Hetero-core fibers are fabricated by inserting a small portion of fiber with a smaller core diameter into two identical fibers with larger core diameters. The core diameters of optical fibers used in hetero-core fibers and the inner section length of hetero-core fiber are the parameters affect the sensitivity of the hetero-core fiber optic sensors. Ordinary fibers (multimode at most) are used in microbend sensors. This is the first time in literature hetero-core fibers were used in the design of microbend sensors. Hetero-core fibers are built by inserting a single-mode fiber into two multimode fibers. A novel hetero-core type of multimode-multimode-multimode configuration was introduced for the first time in literature. Beside the 50-9-50 μm hetero-core fibers 62.5-50-62.5 μm hetero-core fibers were used in the analysis of hetero-core microbend sensors. It was concluded that, 62.5-50-62.5 μm hetero-core configuration is even more sensitive than ordinary fiber (50 μm) and 50-9-50 μm configuration. Several experiments were performed by using these different types of fibers for different inner section length of hetero-core fiber, mechanical periodicity and number of corrugations. The output light intensity was measured as a function of applied force. The experimental results show

that, as the number of corrugations increases, the sensitivity of the sensor increases. It has also been shown that decreasing the periodicity increases sensor sensitivity. In addition, decreasing the inner section length of the hetero-core fiber also increases the sensor sensitivity.

7982-31, Session 8

Developing damage metrics for metallic structures undergoing fatigue using real-time thermographic evaluation

E. Z. Kordatos, T. E. Matikas, Univ. of Ioannina (Greece)

The purpose of this study is to develop an innovative nondestructive methodology for analyzing the thermal effects in metallic materials caused by fatigue. Mechanical stresses induced by cyclic loading in the material cause heat release due to microstructural changes, which results in an increase of the material's temperature. The heat release was quantified as a function of fatigue cycles in aluminium alloy samples. Mechanical hysteresis phenomena were analyzed to identify the metrics of damage, which relates to thermal parameters characterizing the level of damage of the material as a function of fatigue cycles. The metrics of damage correlated with microscopic observations of microstructural changes in the material, leading to the prediction of the onset of crack and the remaining life of the material until failure.

7982-32, Session 8

Monitoring of fatigue damage in metal plates by acoustic emission and thermography

E. Z. Kordatos, D. G. Aggelis, T. E. Matikas, Univ. of Ioannina (Greece)

This work deals with the study of fracture behavior of aluminium alloys using an innovative nondestructive methodology based on lock-in thermography and acoustic emission. The heat wave, generated by the thermo-mechanical coupling and the intrinsic energy dissipated during mechanical cyclic loading of the samples (plates with a symmetric V-shape notch), was detected by an infrared camera. The coefficient of thermo-elasticity allows for the transformation of the temperature profiles into stresses. A new procedure was developed to determine the crack growth rate using thermographic mapping of the material undergoing fatigue. The stresses were evaluated in a post-processing mode along a series of equally spaced reference lines set in front of the crack-starting notch. Using this method, the exact path of the crack could be predicted by looking at the stress maxima along each of these reference lines. The thermographic results on the crack growth rate of aluminium alloys were then correlated with measurements obtained by the conventional compliance method, and found to be in agreement.

On the other hand, Acoustic Emission (AE) supplies information on the fracturing behavior of different materials. AE parameters like energy and duration exhibit a certain increase with the accumulation of damage although the hit rate was not significantly influenced. Furthermore the behavior of RA value (ratio of Rise time to Amplitude of the waveforms) which quantifies the shape of the first part of the AE signals, shows a certain shift indicating the transition from tensile mode of failure to shear which can be confirmed by the visual observation of the crack geometry after the experiment. The time history of RA is similar to the crack propagation rate (da/dN) curve but exhibits the rapid hyperbolic growth consistently about 1000 cycles earlier than final failure. Therefore, the use of acoustic emission parameters is discussed both in terms of characterization of the damage mechanisms, as well as a tool for the prediction of ultimate life of the material under fatigue. The combined study of the two methods is promising for the prediction of final failure as well the crack propagation direction.

7982-33, Session 8

Combined NDT methods for characterization of subsurface cracks in concrete

M. Strantzla, E. Z. Kordatos, D. V. Soulioti, T. E. Matikas, D. G. Aggelis, Univ. of Ioannina (Greece)

One of the most frequent problems in concrete structures is corrosion of metal reinforcement. It occurs when the steel reinforcement is exposed to environmental agents. The corrosion products occupy greater volume than the steel consumed, leading to internal expansion stresses. When the stresses exceed concrete strength, eventually lead to corrosion induced cracking beneath the surface. These cracks do not show any visual sign until they break the surface, exposing the structure to more accelerated deterioration. In order to develop a methodology for sub-surface damage characterization, a combination of non destructive testing (NDT) techniques was applied. Thermography is specialized in subsurface damage identification due to anomalies that inhomogeneities impose on the temperature field. Additionally, ultrasonic surface waves are constrained near the surface and therefore, are ideal for characterization of near-surface damage. In this study, an infrared camera scans the specimen in order to indicate the position of potential damage. For cases of small cracks, the specimens are allowed to cool and the cooling-off curve is monitored for more precise results. Consequently, ultrasonic sensors are placed on the specified part of the surface in order to make a more detailed assessment for the depth of the crack. Although there is no visual sign of damage, surface waves are influenced in terms of velocity and attenuation. Numerical simulations are also conducted, to propose suitable parameters like frequency for more accurate testing. The combination of the NDT techniques seems promising for real structures assessment.

7982-34, Session 9

Damage location using fiber optic acoustic emission sensors for structure health monitoring

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In this paper, we develop a new fiber optic acoustic sensor system, the sensor system have four channel, four FOAESs can be simultaneously connected for SHM. According to different needs, multi-sensors can be placed on the same structure monitoring the damage location or be distributed on a large structure monitoring the damage of the structure near by every sensor. The biggest advantage is that the optical fiber sensor embedded into the composite, different from the surface of paste can more directly receive AE signals. Demodulation method of the sensor system is based on optic intensity, different from other interferometric demodulation methods, such as Michelson interferometer, Mach-Zehnder interferometer, Sagnac interferometer and Fabry-Perot interferometer. It is from temperature and portable.

We have previously reported a novel Fiber Optic Acoustic Emission Sensor (FOAES) which was specially processed from fused-tapered optical fiber coupler. The production, calibration and application of the fiber optic acoustic emission sensor were also described. And the FOAES were improved so that it could be embedded in damage monitoring of composite materials. But the linear damage location of acoustic emission using double sensors had not been tried. In this article will introduce the linear damage location with two FOAES. The simulated AE source on aluminium plate, via a pencil lead-break test, was located to within ± 8 mm. Because the randomness of the monitoring waveforms, human subjective judgments of the initial wave time may increase the error of damage location. So how to reduce the error will be one of our study emphases.

7982-35, Session 9

Acoustic emission felicity ratio measurements in carbon composites laminates using fiber Bragg grating sensors

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In light of ongoing efforts to reduce weight but maintain durability, designers have examined the use of carbon composite materials for a number of aerospace and civil structures. Along with this has been the study of reliable sensing and monitoring capabilities to avoiding catastrophic failure. Fiber Bragg grating (FBG) sensors are known to carry several advantages in this area one of which is their proven ability to detect acoustic emission (AE) lamb waves of various frequencies. AE is produced in these materials by failure mechanisms such as resin cracking, fiber debonding, fiber pullout and fiber breakage. With such activity there is a noticeable change in Felicity Ratio (FR) in relation to the increase of accumulated damage. FR is obtained directly from the ratio of the stress level at the onset of significant emission and the maximum prior stress at the same AE event. The main objective of this paper is to record the FRs of a carbon/epoxy laminate and establish its trend as a method for determining accumulated damage in a carbon composite structure.

7982-36, Session 9

Structural health monitoring of shear waves in aluminum plates

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Structural Health Monitoring (SHM) as a discipline, finds applications in a variety of modern technologies where non-destructive evaluation of a structure or component's integrity is critical to providing and extending the safe operational life of a component with minimal interruption. Examples include civil infrastructure monitoring, in service testing for vehicles, and in service testing for power generating turbines (both wind and combustion). Within SHM, Acoustic Emission (AE) techniques have been shown to be effective in detecting defects.

This research details the use of AE sensors to detect crack growth in an aluminum plate subject to cyclical loading by detecting the shear waves generated at the site of incremental crack growth. Preliminary studies have shown that these shear waves to contain significant energy, and unlike pressure waves retain much of their intensity when the sensor axis is not directly inline with the AE source wavefront. We have also observed that the shear wave component in fretting related acoustic emissions signals is relatively small, making it easier to discriminate the AE of incremental crack growth from the sources of noise that have historically plagued AE with false positives. Arrays of both barrel and bonded PZT sensors are used to measure the influence of signal approach angle on the detection of the shear wave as well as the ability to use information from the array to localize the source of the acoustic emissions.

7982-37, Session 9

Damage location in composite laminates with ultrasonic sensors and artificial neural networks

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Modern aircraft, wind turbines, and space stations, along with other aerospace structures are expected to be in operation well beyond their design life. Therefore, maintenance is a major concern for these new aerospace systems and a structural health monitoring system (SHMS)

is an essential tool to provide for safe operation. The SHMS selected for this study consisted of piezoelectric actuator and sensors combined to form an ultrasonic system. A series of experiments was conducted, using a composite test specimen of eight plies and various fiber directions to evaluate the analysis capabilities of artificial neural networks (ANN) in this application. Three piezoelectric sensors and one actuator were attached to the test article. Through multiple scans of the ultrasonic system damage at various locations were simulated in the test article. An ANN was created and trained on these sets of simulated damage, followed by a testing of the system by random damage locations on the test piece. The ANN, once trained, was found to be able to locate the damaged areas, using small number of piezoelectric sensors. The research demonstrated that ANNs can be used with measured signals from an ultrasonic system to locate damage in a composite structure. The ANN was developed in such a way to allow for the adaptability onto a multitude of various composite and structural configurations, once trained by a simulated damage routine. The abilities of ANNs to provide fast, accurate analysis for ultrasonic testing data has given promise to a possible SHMS in the near future.

7982-38, Session 9

An evaluation of signal processing tools for improving phased array ultrasonic weld inspection

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Cast austenitic stainless steel (CASS) that was commonly used in U.S. nuclear power plants is a coarse-grained, elastically anisotropic material. Its engineering properties made it a material of choice for selected designs of nuclear power reactor systems. However, the fabrication processes resulted in a variety of coarse-grain microstructures that make ultrasonic inspection of in-service components difficult. This is largely due to detrimental effects of wave interactions with the microstructure and the variability that can be encountered. To address inspection needs, new approaches that are robust to these phenomena are being sought.

In recent years, low-frequency phased-array ultrasound has emerged as a leading candidate for the inspection of welds in CASS piping. The use of low frequencies decreases the ratio of mean grain size to wavelength and moves material-ultrasonic interactions toward a regime of quasi-isotropic behavior. This decreases interference in the measured signal from ultrasonic backscatter, and increases penetration of acoustic energy because the scattering portion of attenuation is reduced. However, the use of lower frequencies for inspection decreases the achievable spatial resolution for flaw localization.

Even with the use of lower inspection frequencies and phased-array systems for focusing acoustic energy, issues remain, such as scattering from the coarse-grained microstructure, and beam redirection and partitioning due to the elastically anisotropic nature of the material. The result of these adverse phenomena is measurements with a low signal-to-noise ratio (SNR), and increased difficulty in discriminating between signals from flaws and signals from benign geometric factors (such as machined counterbores). There is therefore a need for advanced signal processing tools to improve the SNR and enable rapid analysis and classification of measurements.

This paper discusses recent efforts at PNNL towards the development and evaluation of a number of signal processing algorithms for this purpose. Among the algorithms being evaluated for improving the SNR (and consequently, the ability to discriminate between flaw signals and non-flaw signals) are wavelets and other time-frequency distributions, empirical mode decompositions and split-spectrum processing techniques. A range of pattern-recognition algorithms, including neural networks, are also being evaluated for their ability to successfully classify measurements into two or more classes. Experimental data obtained from the inspection of a number of welds in CASS components are being used in this evaluation. The full paper will provide details of the different algorithms being evaluated, and present preliminary results of the analysis.

7982-39, Session 9

Simulation on photoacoustic conversion efficiency of optical fiber-based ultrasound generator using different absorbing film materials

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The low energy-conversion efficiency in photoacoustic generation is the most critical hurdle preventing its wide applications. In recent studies, it was found that the selection of the energy-absorbing layer material and design of the acoustic generator structure both determine the photoacoustic conversion efficiency. The selection of the absorbing material is based on its optical, thermal, and mechanical properties. In this research, we systematically calculated and compared the conversion efficiency using 6 different materials as the absorbing film: they are bulk aluminum, bulk gold, graphite, gold nanospheres, gold nanoshells and gold nanorods. The calculations were carried out by a 3D finite element modeling (FEM) software, COMSOL Multiphysics.

A 2D-axisymmetric model in COMSOL was built up to simulate a 3-layer structure: optical fiber tip, light absorbing film, and surrounding water. Three equations governed the thermo-elastic generation of ultrasonic waves: the heat conduction, thermal expansion and acoustic wave equations. In order to compare the conversion efficiency of these 6 materials, only the "thick-film" generation case is considered. In "thick-film" generation regime, the laser energy is entirely absorbed by the film and converted to high-frequency vibration, and the vibration excites the ultrasound wave in the adjacent water, while the water would not be heated directly by the laser. From the results of our FEM simulation, the acoustic signal generated by gold nanosphere film is over two times stronger than that generated by graphite film of the same thickness. This simulation provides guidance to the absorbing material selection for our proposed fiber ultrasound generator.

7982-41, Session 9

Vibration suppression and damage detection in smart composite laminate using high precision finite element

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Composites are fast gaining attention as structural materials due to overriding advantages over conventional metallic structures. Owing to their high specific strength and stiffness and very good corrosion and fatigue properties, they are increasingly being used in the design of light weight aerospace, automobile and civil structures. Due to greater complexity of design, high operational loads and longer lifetime, composite structures are prone to unpredicted failures. Present day non-destructive evaluation (NDE) techniques, such as ultrasonic testing, acoustic emission, eddy current method, radiography and thermography etc., primarily meant for metallic materials, are not always very effective for composites because of inherent micro-mechanical complexities. Real time damage detection and health monitoring in such cases have become one of the main areas of focus today. Efforts are being made at developing structures that can sense and control their own damage by using a network of distributed sensors and actuators. With the improvement in sensing and actuation technologies and their availability in the form of sensor patches e.g. PZT and Terfenol-D patches and flexible PVDF films and the feasibility of embedding them into or bonding those to composite structures is leading to growth of a new concept known as smart / intelligent structure.

The present work has proposed a 2-D triangular high precision finite element (HPFE) based on classical laminate theory with 38 degrees of freedom. Each triangular element has 3 nodes at the vertices and uses 12 degrees of freedom at each vertex. Two more in-plane displacements at the centroid of the element are condensed out before assembly. This high precision plate element has been used to obtain the mode

shape and fundamental frequencies for the passive composite plate. The closed form expression of stiffness and mass matrices are used to reduce the computational burden. Static condensation is used to further reduce the size of the Eigen value problem. The advantage of using 2-D high precision element is that it is simpler than 3-D element and it is computationally less intensive and highly convergent in nature. A standard FEM Package 'ABAQUS' is used to verify the FEM code and to validate the results.

The same 2-D triangular high precision finite element (HPFE) is used with piezoelectric sensory network to develop an active damping matrix that tends to suppress vibration. Control algorithm based on classical negative velocity feedback is used. Simulations are carried out in composite plate with distributed sensor and actuator and the time domain responses are obtained for different control gains. Corresponding settling times are found out to be satisfactory in comparison to undamped response. Effect of size and location of PVDF film on settling time and damping ratio is also predicted.

The high precision piezoelectric finite element is later used to identify damage signals in ribbon reinforced composites. Such composites can be nearly isotropic in the plane of a sheet exhibiting nearly equal strength in all directions and can be packed in greater volume in comparison to fiber composites. In order to identify the damage, the voltage profile and mechanical impedance responses are obtained for healthy and delaminated composites which can be used as a knowledge-base for damage detection. A change in voltage profile and impedance response is observed in simulated damage locations in comparison to the healthy laminate for different configurations used in the numerical analysis.

7982-48, Session 9

Monitoring of a wind turbine rotor blade with acousto ultrasonics and acoustic emission techniques

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To operate wind turbines safely and efficiently, condition monitoring for the main components are of increasing importance. Especially the lack of access of offshore installations increases inspection and maintenance costs.

The current work at Fraunhofer IZFP Dresden in the field of monitoring of wind turbines is focused on the development of a condition monitoring systems for rotor blades.

A special focus lies on the application of optical technologies for communication, data transfer and power supply. It is not possible to introduce metal cables in the rotor blade since it might cause tremendous damages by lightning.

The monitoring concept is based on a combination of low frequency integral vibration monitoring and acoustic monitoring techniques in the frequency range between 10 and 100 kHz using guided waves. A joint application of acousto ultrasonics and acoustic emission techniques will be presented. Challenges and solutions of such a field test like sensor application, data handling and gathering as well as temperature variation are described.

Conference 7983: Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security V

Monday-Thursday 7-10 March 2011

Part of Proceedings of SPIE Vol. 7983 Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security 2011

7983-01, Session 1A

Early state damage detection of aluminum 7075-T6 based on acoustic emission

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Aluminum alloy 7075-T6 is a commonly used material in aircraft industry. A crack usually initiates at the edge of a fastener hole and it can affect the maintenance schedule and reduce the life of an aircraft structure significantly. The fatigue property of the material has been researched widely to develop methods and models for predicting fatigue crack growth under random loading. From the point of damage tolerance design, the inspection technique of a crack for an aircraft structure is very important because it can be used to determine the inspection period of the aircraft structure. The acoustic emission (AE) technique is a nondestructive testing (NDT) method that is able to monitor damage initiation and progression in real time. Understanding the early stage of AE signature due to the damage progression using small scale laboratory samples require non-traditional data analysis approaches. In this study, 1mm thick Al-7075-T6 plates were tested under monotonic and fatigue loading. The initiation of damage progression using AE data was identified based on improved linear location algorithm and the result was verified using elasto-plastic finite element model. The improved location algorithm integrates dispersive characteristics of flexural waves and variable threshold to pick up correct arrival time. In this paper, AE results in comparison with FE model under monotonic and fatigue loading will be presented. The comparison of traditional and improved location approaches will be shown. The approach for implementing the laboratory scale results in the large scale field testing will be discussed.

7983-02, Session 1A

Environmentally stimulated acoustic emission from reinforced concrete

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A system is being developed to monitor the in-service deterioration of reinforced concrete in bridges, sponsored under NIST TIP CAN 70NANB9H9007. Environmental parameters and deterioration indicators to be monitored include temperature, humidity and acoustic emission (AE). AE can be generated by spalling of corrosion products, debonding of the rebar and cracking of the concrete. These processes are driven by mechanical and thermal stresses, including those produced by oxide buildup on the rebar. To develop a preliminary understanding of these effects, a 6ft reinforced concrete bar was monitored in the outdoors environment of a New Jersey parking lot for some months. Daily swings in the acoustic emission rate were observed, concurrent with the daily swings in temperature and relative humidity. The rate of AE activity was low, commensurate with the slow rate at which the test article was deteriorating. The main thrust of the analysis, after removal of some electrical noise, was to correlate the AE with the changing temperature and humidity around the test article. Electrode potential and pH measurements were also taken, to provide an indicator of the vulnerability of the rebar to corrosion. Understanding of the relationship between the AE and the environmental variables will help to determine the best times for AE data acquisition on concrete bridges, an important consideration for the health monitoring system being developed.

7983-04, Session 1A

Innovative sensor and nondestructive testing technologies for evaluating internal-frost damage in concrete

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Internal-frost damage is one of the major problems affecting the durability of concrete in cold regions. This paper presents innovative sensor and nondestructive acoustic emission (AE) testing technologies to evaluate the frost damage in concrete. The crystallization pressure due to ice nucleation with capillary pores is the primary cause of internal-frost damage of concrete. An innovative Time-Domain Reflectometry (TDR) sensor was developed to nondestructively monitor the freezing process within microstructure systems. The experimental data shows that the TDR sensor signals can detect the freezing degree. Controlled freezing tests are conducted with lab-prepared cylinder concrete specimens under a subcooling environmental setting with thermal couple measurements. The specimen are put inside of a specially prepared thermo insulator with the only exposure of the top surface, thus the controlled freezing follows the top-to-down direction. A liquid layer is placed on the top surface and an evaporation protection is also used to allow the specimen saturated. The AE transducer and TDR sensors are mounted on the top surface to detect the internal freeze damage and monitor the freezing status. The sensor measurements and detection can real-time unveil the internal ice nucleation and caused freezing damage processing. These sensor and nondestructive test techniques can help practitioners to evaluate the freeze-thaw resistance of mix-designed concretes.

7983-05, Session 1B

Control of robotic drilling of concrete bridge decks

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This paper presents an ongoing development of rehabilitation system of the Automated Nondestructive Evaluation and Rehabilitation System (ANDERS) for bridge decks. In ANDERS, a nondestructive rehabilitation (NDR) system is designed to use robotic repair equipment to deposit specially formulated repair materials to fill and bond hairline crevasses and repair delamination. Drilling of the concrete bridge decks is a critical process for the NDR system. In this paper, we present a modeling and control design of robotic drilling process for concrete bridge decks. A mathematical model is first proposed to capture the dynamics of the drilling process. Using the dynamic drilling model of concrete materials, we design a control system to regulate the drilling speed and monitor the drilling forces in real time. A lab testing setup is presented and preliminary experiment results show that the performance of the robotic drilling unit satisfies the requirements for the NDR system.

7983-06, Session 1B

Nanoscale materials for non-destructive repair of transportation infrastructures

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Results related to the development of an inorganic matrix that is suitable for filling very narrow cracks and thin delaminations on bridge decks are reported in this paper. Almost all the repair materials currently available for these types of repairs are organic polymer based matrices. These matrices create a discontinuity in terms of modulus of elasticity and water permeability. These discontinuities result in the failure of repairs within about five years. The matrix used in the current investigation has modulus of elasticity and permeability characteristics that are similar to the concrete used in bridge decks. The primary properties investigated were: mechanical characteristics, bonding to cracked surfaces, flow characteristics, and ease of application. Details regarding these properties and its viability for use in automated nondestructive robotic delivery system to fill delaminations and narrow cracks are presented in this paper.

7983-07, Session 1B

Multisensor data fusion for nondestructive evaluation of bridge decks

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As the bridge components directly carrying loads and moving traffic, bridge decks are prone to various deteriorations, such as corrosion of reinforcement, cracking, delaminations, and voids. Advanced nondestructive evaluation (NDE) methods, such as ground-penetrating radar (GPR), impact-echo, and ultrasonics, have been used by researchers and engineers for damage assessment of bridge decks. Each method has its own strength and limitations. For example, GPR can localize reinforcement in bridges and detect delaminations and voids, but can not penetrate through metals, and therefore is not efficient to detect defects under the metal layer. Impact echo is suitable for detection of voids and delaminations, but can not detect the rebar clearly. Ultrasonic is good at detecting cracks and voids in some materials, but is not sufficiently reliable in concrete structures if used alone. A combination of different methods can significantly improve the accuracy of deterioration identification and characterization. However, there is a lack of proper interpretation techniques that can effectively integrate data from different NDE technologies.

In this paper, we propose a multisensor data fusion approach to process, integrate and interpret the data in a way that offsets the respective limitations of each individual technology and improves the accuracy and reliability of deterioration identification and characterization for bridge decks. Two data fusion frameworks for NDE of bridge decks are presented. The success of the approach will not only facilitate the interpretation of the data, but also enhance the accessibility of advanced NDE technologies for non-specialists, which provides better decision support tools for the bridge management systems.

7983-08, Session 1B

Evaluation of corrosion effect in reinforced concrete by chloride exposure

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Durability is generally described as the ability of a material to maintain its physical and mechanical properties over time. In reinforced concrete (RC) structures, concrete is the ideal material to protect (cover) the steel

reinforcement, given its high alkalinity. In environments subjected to highly aggressive conditions, mostly due to the presence of chlorides, concrete may lose its protective characteristics causing then the corrosion of the steel reinforcement and accelerating the ageing. Concrete degradation and steel reinforcement corrosion are phenomena closely connected.

The aim of this work is the characterization of the relationship between corrosion of the steel reinforcement and concrete degradation, subjected to ageing by means of accelerated tests in a 3% Sodium chloride solution. The accelerated corrosion test is studied by the method of linear polarization, used for identification of corrosion rate of the steel rebar. In this feature the values of residual strength characteristics of the material can be obtained, in relation with both the corrosion rate and width of cracks, and the prediction of the concrete cover useful life is also estimated.

This paper shows the preliminary results of these tests.

7983-09, Session 2A

Assessment of carbon fiber-reinforced polyphenylene sulfide by means of laser ultrasound

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From the automobile industry to aerospace, the implementation of thermoformed composites grows exponentially. The application of thermoplastics offers a number of attractive ways in commercial use like short production times, tailored solutions, recyclability and lower cost. The thermoforming process allows to produce carbon fiber-reinforced parts in a huge number of different geometric shapes. On the other hand this benefit needs a demanding nondestructive testing procedure. A contactless method which can meet this requirement is the extension of the ultrasound technique with laser technology. It offers new possibilities into the production process for example the inspection on sharp bended radii and the observation under remote control. Laser ultrasonic measurement systems are particularly attractive to nondestructive structural and materials characterization of fiber reinforced thermoplastic parts because of the ability to work with hot items which allows a complete investigation directly after the thermal forming production.

We describe the successful application of laser-based ultrasound on small complex thermoformed composite parts (CETEX® PPS). It depends on semicrystalline polyphenylene sulfide thermoplastics providing outstanding toughness and excellent chemical and solvent resistance. It is qualified at Airbus for multiple structural applications. For instance, CETEX® is used in the A380 engine air intakes and the wing fixed leading edge (J-Nose).

7983-10, Session 2A

Measurement of pore size distribution in concrete by advanced ultrasonic analyses

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The structures of concrete, especially the pore sizes, are crucial for the freeze-thaw durability of concrete in cold regions. This paper presents studies on the use of advanced ultrasonic techniques to measure the capillary porosity and entrained air content in concrete. Modeling of ultrasonic attenuation are used to estimate the volume fraction and size distribution of entrained air voids. An inversion procedure based on a theoretical attenuation model was studied to predict the size distribution and volume fraction of entrained air voids. Results from the preliminary study are encouraging. The ultrasonic analyses are being extended to determine the pore characteristics of porous materials.

7983-11, Session 2A

Real-time health monitoring of metal matrix composites using nonlinear acoustics

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The objective of this work is to develop a new non-destructive technique based on nonlinear acoustics that would enable real-time monitoring the degradation of metal matrix composite structures. A reliable inspection methodology for quantifying damage in composite structures and relating the level of damage to the residual life of the material is essential for preventing catastrophic failures in such structures. During the present study Rayleigh waves were used. When a Rayleigh surface acoustic wave of given frequency and sufficient amplitude is introduced into a nonlinear or an-harmonic solid, the fundamental wave will distort as it propagates, so that the second and higher harmonics of the fundamental frequency will be generated. Measurements of the amplitude of these harmonics provide information on the coefficient of the second and higher order terms of the stress-strain relation for a nonlinear solid. A prototype system suitable for Rayleigh nonlinear measurements was constructed. The system was tested for its linearity, because has to be as linear as possible due to the fact that we are only interested in material nonlinearities. The feasibility of the method for structural health monitoring of metal matrix composites was finally demonstrated by evaluating composite samples at different levels of cyclic loading.

7983-12, Session 2A

Vibration modulated Lamb waves for structure health monitoring

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There is growing interest in the nonlinear acoustic effects in solids due to promising applications of these effects for non-destructive testing and characterization of materials and structures. An important advantage of the nonlinear acoustic methods is to discriminate between integrity reducing flaws and other inhomogeneities. Contact-type defects such as cracks, disbondings, delaminations, etc. lead to an anomalously high level of nonlinearity. One of acoustic manifestations of such nonlinearity is the modulation of a high-frequency signal by low-frequency vibration. In this paper, Lamb wave health monitoring in plate structure for detection of nonlinear contact scatter is conducted using vibration modulation technique. The low frequency vibration varies the interface area within the contact defect; therefore the amplitude and phase of high frequency Lamb waves reflected from the contact defect will be modulated. By time-frequency analysis of modulated Lamb wave series, the nonlinear responses at frequency of vibration are extracted out and used for defect imaging. It was shown that the nonlinear Lamb wave imaging method based on vibration modulation can effectively characterize and locate the nonlinear contact defects.

7983-13, Session 2A

Development of a portable ultrasonic phased array inspection imaging apparatus for NDT

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In order to improve the inspection result repetition and reliability of manual ultrasonic method in NDT field, a portable ultrasonic apparatus based on the phased array inspection technology is developed in paper. The apparatus is composed of touchpad, computer, ultrasonic circuit system, phased array transducer and inspection imaging software, the touchpad, computer and ultrasonic circuit are integrated, the transducer is external connected.

In paper, the linear phased array is fabricated according to the inspection requirement, the ultrasonic phased array circuit system is manufactured, which can support 32 or 64 elements phased array transducer. The imaging software system can implement the ultrasonic phased array detection. The apparatus is small, integrated and portable, which can perform the shear wave and longitudinal wave detection, automatically transmit and receive sound wave, accomplish data acquisition in real time, and provide many imaging modes, and give comments of the damage. As designed, the apparatus can run different algorithm of the ultrasonic phased array inspection technology.

With proposed inspection scheme, a phased array reference block was practically detected in the lab, the apparatus provides real time flaw images of the reference block. Experiment results indicate the portable ultrasonic apparatus can factually imaging the position and size of flaws, and the size and shape of flaws are nearly consistent with the practical condition. Experiment results also prove the detection capability and applicability of the apparatus, the flaw images are visible and the repeatability and reliability of the apparatus are better.

7983-14, Session 2B

Bridge scour monitoring system: a pilot field evaluation

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Scour is a major threat to the safety of bridges. Instruments for the measurement and monitoring of bridge scour are necessary to study scour processes and to support bridge management. The lack of robust and economical scour monitoring devices prevents the implementation of a bridge scour monitoring program among bridge owners. This paper explores the design and analyses of scour sensors using principles of Time Domain Reflectometry (TDR). Six TDR bridge scour sensor were installed at BUT-122-0606 bridge on SR 122 over the Great Miami River in Butler County, with assistance of project partners. Automatic monitoring units were installed to automatically taking scour sensor signals and wireless transmitting the sensor data. The sensors were installed using routine geotechnical site investigation tools and procedures. High quality signals were obtained, from which the development of scour adjacent to bridge piers were measured. The results are reasonable.

7983-15, Session 2B

Smart-label-based behavior monitoring IOT system for the infrastructures under harsh environments

Z. Zhou, Dalian Univ. of Technology (China); M. Huang, Harbin Institute of Technology (China); J. He, Dalian Univ. of Technology (China); G. Chen, Missouri Univ. of Science and Technology (United States); J. Ou, Harbin Institute of Technology (China)

Structural behavior can be characterized as deformation, large strain, crack or failure, foundation release or scour, etc. As such, displacement is the significant parameter to assess the performance of structural stability and safety using the behavior information. A real-time, durable, reliable and low-cost monitoring technique for the exterior and internal displacements is still in great need for the infrastructures under harsh environments. In this paper, a novel displacement field technique based on the smart-labels is proposed to monitor behavior of the infrastructures. The smart-labels mainly can be set up on any kind of wireless tags, such as magnetic matters, radio frequency identification (RFID) tags and even global position system (GPS) measuring sensors, etc. Each node can be used to describe and identify the local structural information at the fixed point, which can be used to configure a new network, internet of things (IOT). In practice, these smart-labels are packaged in certain highly-protected block, namely smart block or rock. The smart block can be attached or embedded directly on the structure so that the information of position and physical parameters can be

recorded and transmitted accordingly... The proposed system can be regarded as a real-time, durable, reliable and low-cost displacement field monitoring IOT. And it is feasible to be widely applied in infrastructures ranging from high geological slope, dam embankment and bridge foundation.

7983-16, Session 2B

Model updating for a continuous rigid frame bridge based on long-term structural health monitoring

L. Wang, Harbin Institute of Technology (China); B. Li, J. Ou, Dalian Univ. of Technology (China)

Bridge serviceability and safety is a concerned problem in recent years due to fatigue loads such as traffic, wind, temperature and so on. Cracks, corrosion, creep develop along with bridge the operational process since the construction period. Thus structural health monitoring (SHM) system is prominent in observing the state of bridges. Fiber Bragg grating (FBG) sensors are advanced materials for SHM; vibration method is adopted to evaluate bridge performance; finite element model (FEM) is a necessary mean for comparing and estimating the bridge static and dynamic properties in SHM process. The vibration properties are influenced by traffic load, also, temperature differential in rigid frame bridge induces concrete cracks, causes additional stress, and affects dynamic characteristics. So, finite element model considering environmental effects is necessary to predict bridge safety based on FBG sensor technology from long-term bridge monitoring.

Dongying Yellow River Bridge is a twin-deck continuous rigid frame concrete bridge with spans of 116+200+220+200+116 meters, which is implemented with about 200 FBG sensors for temperature, more than 1600 for strain and 32 for acceleration. In this paper, Eigen Realization Algorithm (ERA) method is applied for identifying the dynamic characteristic parameters. A three dimensional finite element model with solid elements is built and updated based on the tested modal parameters considered environmental effects. The model considered thermal gradient and uniform temperature, which affected the dynamic properties together with the fixed bearing. The results showed that considered the temperature and traffic loads effect, the updated model reflect more accurate dynamic properties, and obtain better connection with environmental conditions.

7983-17, Session 2B

Bridge reliability assessment based on PDF of long-term monitored static strain

M. J. Jiao, L. Sun, Tongji Univ. (China)

Structural health monitoring (SHM) systems can provide valuable information for evaluation of bridge performance. As the development and implementation of SHM technology in recent years, the data mining and use has received increasingly attention and interests in civil engineering. Based on the principle of probabilistic and statistics, a reliability approach provides a rational basis for analysis of the randomness in loads and their effects on structures. A novel approach combined SHM systems with reliability method to evaluate the reliability of a cable-stayed bridge instrumented with SHM systems was presented in this paper. In this study, the reliability of the steel girder of the cable-stayed bridge was denoted by failure probability directly instead of reliability index as commonly used. Under the assumption that the probability distributions of the resistance are independent of the response of structures, a formulation of failure probability was deduced. Then, as a main factor in the formulation, the probability density function (PDF) of the strain at sensor locations based on the monitoring data was evaluated and verified. And by means of theoretical analysis, the static strain response served as dominating components in the failure probability was decomposed from the time history of strain. Finally, Donghai bridge was taken as an example for the application of the

proposed approach. In the case study, 4 years' monitoring data since the operation of the SHM systems was processed, and the reliability assessment results were discussed.

7983-18, Session 2B

Advanced bridge asset management and the role of structural health monitoring: a New Zealand perspective

P. Omenzetter, The Univ. of Auckland (New Zealand); S. Bush, Opus (New Zealand); T. Henning, The Univ. of Auckland (New Zealand); P. McCarten, Opus (New Zealand)

This paper proposes and discusses a strategy for planned integration of structural health monitoring (SHM) into bridge asset management.

Bridges are critical to the operation and functionality of the whole road networks. It is therefore essential that specific data is collected regarding bridge asset condition and performance, as this allows proactive management of the assets and more accurate long-term financial planning. This paper focuses on road bridges and the type of data that needs to be collected, the variability in the data that is collected, and the development of a strategy for implementation of enhanced data collection and monitoring regime.

Structural health monitoring (SHM) can be used to enhance the range and quality of the data collected on asset condition and performance. However, the success of SHM technologies can arguably be measured by the degree of its up-take by the practitioners and industry. In order to realize its potential, SHM needs to be applied strategically, purposefully and in a cost effective manner, so that it is well integrated into the wider asset management and decision making process.

This paper reports the results of a survey conducted in order to understand bridge asset management practices in New Zealand and the role of SHM in advanced practice. However, general findings and discussion will be of interest to the international bridge engineering and SHM community. The central message is a proposed framework for data collection that closely aligns the extent and detail of the data gathered with criticality and risk of bridges within their networks. The strategic role of SHM is envisaged for enhanced data collection for critical and high risk structures.

7983-19, Session 3A

Health monitoring of cracked rotor systems using external excitation techniques

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Cracked rotors present a significant safety and loss hazard in nearly every application of modern turbomachinery. This paper focuses on the health monitoring, modeling, and analysis of machines with transverse breathing cracks, which open and close due to the self-weight of the rotor. After considering the modeling of cracked rotors, the paper investigates an active structural health monitoring approach, focusing on the application of an active magnetic actuator to apply a specially designed external force excitation to the rotating shaft. Extensive experimental data has been collected and analyzed utilizing advanced diagnostic techniques. The presented results demonstrate that the use of a magnetic force actuator to apply external excitation has potential in the diagnostics of cracked rotors. The observed unique crack signatures demonstrate the ability of the method for early diagnosis of transverse rotor cracks.

7983-20, Session 3A

Improved software algorithm development of self diagnostic accelerometer system

R. P. Tokars, Jr., J. D. Lekki, NASA Glenn Research Ctr. (United States)

The self diagnostic accelerometer (SDA) is a sensor system designed to actively monitor the health of an accelerometer. An accelerometer is considered healthy if it can be determined that it is responsive and its measurements may be relied upon. The SDA system accomplishes this by actively monitoring the accelerometer for a variety of failure conditions including accelerometer structural damage and accelerometer detachment. In recent testing of the SDA system in emulated engine operating conditions, the SDA system demonstrated a variety of autonomous software algorithms to effectively and quickly compensate for a variety of issues including temperature changes, mechanical noise, and accelerometer structural changes and attachment. The improved SDA system utilizes updated electronics and software to do so and the results of such work are presented in this paper.

7983-21, Session 3A

Detecting damage in ceramic matrix composites by electrical resistance

C. Smith, Ohio Aerospace Institute (United States)

Ceramic matrix composites are under development for high temperature structural aerospace applications because of the potential savings in weight and increased power and efficiency. Since ceramics are brittle by nature, implementation will require health monitoring techniques that are capable of detecting life-limiting damage. Many traditional techniques are insensitive to the transverse, in-plane matrix cracks that grow through-thickness and ultimately lead to failure. Self-sensing of such damage is possible in these composites by monitoring electrical resistance. Results will be presented regarding the sensitivity of electrical resistance to damage in ceramic matrix composites.

7983-22, Session 3A

Nondestructive evaluation techniques for the assessment of braided polymer composite materials subjected to accelerated aging conditions

R. E. Martin, Cleveland State Univ. (United States)

Carbon fiber composite materials are a popular choice for many aerospace components due to their high strength and low weight. However, due to cyclic temperature and moisture exposure during operation, long term material performance must be understood and accounted for. Mechanical testing alone can measure performance changes, but techniques are needed to identify changes in material structure over time as an aid in material selection. This paper examines various nondestructive evaluation techniques used to assess a series of braided carbon fiber epoxy matrix composites subjected to cyclic exposure to temperature and humidity. Ultrasonic and X-ray CT methods are used to assess the composite over time as well as identify damage evolution under mechanical loading.

7983-23, Session 3B

Carbon nanotube yarns sensors for structural health monitoring of composites

H. Zhao, F. Yuan, North Carolina State Univ. (United States)

With increasing application of composite materials, real time monitoring of composite structures becomes vital for maintenance purpose as well as prevention of catastrophic failure. It has been reported that carbon nanotubes (CNTs) have excellent piezoresistive properties, which may enable a new generation of sensors in nano or micro scales. Many study have been done on dispersing CNTs into polymer matrix to enable the composites with the capability of self-sensing. The results shown by the past research are very promising in utilizing CNT composites for structural health monitoring. However, the past research also show several issues in attempting to develop the new type of CNT strain sensors, such as stability and repeatability issues. We report here, for the first time, a novel prototype of carbon nanotube yarn sensors with excellent repeatability and stability for in-situ structural health monitoring. The CNT yarn is spun directly from CNT arrays, and its electrical resistance increases linearly with tensile strain, which makes it an ideal strain sensor. Importantly, it shows repeatable piezoresistive behavior under repetitive straining and unloading. Yarn sensors show stable resistances at temperatures ranging from -196 to 110 . Neat yarn sensors are also embedded into resin to monitor the loading conditions of the composites. With multiple yarn sensor elements aligned in the composite, the crack initiation and propagation could be monitored. Yarn sensors could be easily incorporated into composite structures with minimal invasiveness and weight penalty to enable the structure has self-sensing capabilities.

7983-24, Session 3B

Interaction of surface waves induced by IDT sensors with flaws in fiberglass composite panels

J. Na, Edison Welding Institute (United States)

Polyester resin based glass fiber reinforced composite panels obtained from a local windmill turbine blade manufacturing company are used to evaluate the performance of inter-digital transducer (IDT) based surface wave transducers. Interaction of surface waves with glass fibers is addressed in this work. Additionally, artificially created flaws such as cracks, delamination and impact damage are also studied in terms of amplitude changes in order to attempt to quantify the size, location and severity of damage in the test panels. As a potential application to the structural health monitoring of windmill turbine blades, the coverage distance within the width of the wave field is estimated to be over 80 cm when a set of IDT sensors consisted of one transmitter and two receivers is used in a pitch-catch mode.

7983-25, Session 3B

Non-invasive damage detection in composite beams using marker extraction and wavelets

Y. Song, C. R. Bowen, A. H. Kim, A. Nassehi, J. Padgett, Univ. of Bath (United Kingdom)

Simple and contactless methods of determining the health of metallic and composite structures are necessary to allow non-invasive Non-Destructive Evaluation (NDE) of damaged structures. Many recognized damage detection techniques, such as frequency shift (FS), generalized fractal dimension (GFD) and wavelet transform (WT), have been described that aim to identify, locate damage and even determine severity of damage. These techniques are often tailored for factors such as (i) type of material (isotropic and composites), (ii) damage patterns (crack, impact, delamination etc.), and (iii) nature of input signals (space and time). In this paper, we describe a wavelet-based damage detection framework that locates damage on cantilevered composite beams via NDE using Computer Vision technologies. Two types of damage are investigated: (i) cracks induced by reduced stiffness and (ii) manufactured delaminations in a composite laminate. The novelty in our approach is the use of bespoke Computer Vision algorithms for the contactless acquisition of modal shapes, a task that is commonly

regarded as a barrier to practical damage detection. We demonstrate that modal shapes of cantilever beams can be readily reconstructed by extracting markers using Hough Transform from images captured using conventional slow motion cameras. This avoids the need to use expensive equipments such as laser doppler vibrometers. The extracted modal shapes are then input to our wavelet transform damage detection technique, exploiting both discrete and continuous variants. The experimental results are verified using finite element models (FEM).

7983-26, Session 3B

Structural health monitoring of woven composites under biaxial loading

M. Yekani Fard, Y. Liu, A. Chattopadhyay, Arizona State Univ. (United States)

Composite structures often develop complex biaxial or multiaxial stress states during service life. A damage event will further compromise the integrity of such composite structures and can lead to reduced strength and load carrying capacity ultimately causing failure. Structural health monitoring (SHM) approaches rely heavily on the accurate in-situ assessment of damage states. Woven polymer composite material exhibits significant nonlinear structural behavior under different kinds of loadings. In many cases, the nonlinearity may even be detected upon initial loading of the material and continues until catastrophic failure. In order to effectively detect and quantify damage, the structure should be modeled correctly and the stress state should be determined with high accuracy. In this paper, the structural behavior of plain woven polymer composites under different biaxial loading conditions will be studied. A cruciform type specimen will be subject to inplane biaxial loading using a MTS biaxial/torsion test frame. The optimum geometry of the cruciform specimen will be designed using finite element (FE) simulations. Successful FE simulation depends largely on employing accurate fiber and matrix material models. The proper stress-strain relationship for epoxy resin will be based on the results of our current studies. In order to experimentally validate the simulation results, passive and active sensing will be used to monitor real time changes in the structural response. Local regions of high strain concentration will be examined to identify where failure initiates and to determine the local strain at failure initiation using the ARAMIS, which is a digital image correlation system. The integration of multiscale modeling and passive/active sensing approaches will result in a real-time monitoring system for plain woven polymer composite structures.

7983-27, Session 3B

Coupled attenuation and multiscale damage model for composite structures

A. M. Moncada, A. Chattopadhyay, Arizona State Univ. (United States); B. Bednarzyk, S. M. Arnold, NASA Glenn Research Ctr. (United States)

It is well known that incident wave energy is scattered between the fiber and matrix interface during elastic wave propagation in composite structures. This type of scattering occurs because the wave is subjected to a sudden change in stiffness between the fiber and the matrix and also the curvature of the fiber. Consequently, the amplitude attenuation of incident waves occurs as the waves propagate through the composite specimen. This attenuation happens in healthy structures and its characteristics will change again when additional scattering surfaces, which are attributed to damage, are introduced. The types of damage that cause these changes are fiber-matrix debonding, matrix cracking, and interlaminar delamination. In structural health monitoring (SHM) applications, this change in attenuation can be used to indicate the presence of damage. Thus it is important to develop an accurate model to characterize attenuation in composites.

For this work, the wave attenuation in composites will be investigated through a multiscale analysis. The damage at the micro level will be

simulated using MACGMC, a micromechanics analysis code developed by NASA Glenn Research Center. This will be coupled with a single fiber scattering code that calculates the attenuation of a fiber within a matrix with debonding between the fiber and the surrounding matrix.

Piezoelectric transducers will be used as the sensors and actuators for this work. Experiments will be carried out to quantify the attenuation of a 4.5 cycle burst wave at frequencies ranging from 5 kHz to 25 kHz on a composite beam. The final manuscript will present simulation results from the multiscale analysis and will be validated with experiments conducted using active sensing.

7983-28, Session 3B

Effect of fiber surface conditioning on the acoustic emission behaviour of steel fiber reinforced concrete

D. V. Soulioti, E. Gatselou, N. Barkoula, A. Paipetis, T. E. Matikas, D. G. Aggelis, Univ. of Ioannina (Greece)

The role of coating in preserving the bonding between steel fibers and concrete is investigated in this paper. Different types of fibers with and without chemical coating are used in steel fiber reinforced concrete mixes. The specimens are tested in bending and the mechanical parameters are examined, such as bending strength and toughness. Simultaneously, acoustic emission was monitored throughout the failure process using two broadband sensors. The different stages of fracture (before, during and after main crack formation) exhibit different acoustic fingerprints, depending on the mechanisms that are active during failure (concrete matrix micro-cracking, macro-cracking and fiber pull out). Additionally, it was seen that the acoustic emission behaviour exhibits distinct characteristics between coated and uncoated fiber specimens. Specifically, the frequency of the emitted waves is much lower for uncoated fiber specimens, especially after the main fracture incident, during the fiber pull out stage of failure. Additionally, the duration and the rise time of the acquired waveforms are much higher for uncoated specimens. These indices are used to distinguish between tensile and shear fracture in concrete and suggest that friction is much stronger for the uncoated fibers. On the other hand, specimens with coated fibers exhibit more tensile characteristics, more likely due to the fact that the bond between fibers and concrete matrix is stronger. The fibers therefore, are not simply pulled out but also detach a small volume of the brittle concrete matrix surrounding them. It seems that the effect of chemical coating can be assessed by acoustic emission parameters additionally to the macroscopic measurements of ultimate toughness.

7983-29, Session 3B

Inspection for kissing bonds in composite materials using vibration reciprocity measurements

N. D. Sharp, N. Myrent, D. E. Adams, Purdue Univ. (United States)

Improper bonding of composite structures can result in close contact cracks under compressive stresses, called kissing bonds. These bond defects are very difficult to detect using conventional inspection techniques such as tap testing or local ultrasonic scanning and these defects can lead to failure if they are subject to crack opening stresses. A vibration based inspection technique increases the ability to detect kissing bonds in composite materials while decreasing inspection time.

A method is investigated for identifying kissing bonds in composite materials based on vibration reciprocity measurements. A damage feature of the kissing bond is extracted from the response of two input-output structural paths due to the load path dependence associated with the cracks. Experimental reciprocity measurements from composite materials are presented along with the results of the damage detection algorithm for the healthy sections of the material and the kissing bond sections.

The benefits of implementing this method of identification rather than conventional techniques include its robustness, its objective methodology and procedure, and its rapidity when compared with tap testing and ultrasonic scanning.

7983-30, Session 4

X-ray scan detection for cargo integrity

J. D. Valencia, Pacific Northwest National Lab. (United States)

The increase of terrorism and its global impact has made the determination of the contents of cargo containers a necessity. Existing technology allows non-intrusive inspections to determine the contents of a container rapidly and accurately. However, cargo shipped to an embassy is exempt from such inspections. Hence, there is a need for a technology that enables rapid and accurate means of detecting whether such containers were non-intrusively inspected. Non-intrusive inspections are most commonly performed utilizing high powered X-ray equipment. The challenge is creating a device that can detect short duration X-ray scans while maintaining a portable, battery powered, low cost, and easy to use platform. The Pacific Northwest National Laboratory (PNNL) has developed a methodology and prototype device focused on this challenge.

The prototype, developed by PNNL, is a battery powered electronic device that continuously measures its X-ray and Gamma exposure, calculates the dose equivalent rate, and makes a determination of whether the device has been exposed to the amount of radiation experienced during an X-ray inspection. Once an inspection is detected, the device will record a timestamp of the event and relay the information to authorized personnel via a visual alert, USB connection, and/or wireless communication.

The results of this research demonstrate that PNNL's prototype device can be effective at determining whether a container was scanned by X-ray equipment typically used for cargo container inspections. This paper focuses on laboratory measurements and test results acquired with the PNNL prototype device using several types of X-ray radiation levels.

7983-31, Session 4

A wireless sensor tag platform for container security and integrity

I. Amaya, Pacific Northwest National Lab. (United States)

Cargo containers onboard ships are widely used in the global supply chain. The need for smarter and more secure containers is evidenced by the Container Security Initiative launched by the U.S. Bureau of Customs and Border Protection (CBP). One method of monitoring cargo containers is using low power wireless sensor tags. The wireless sensor tags are used to set up a network that is comprised of tags internal to the container and a central device. The sensor network reports alarms and other anomalies to a central device, which then relays the message to an outside network upon arrival at the destination port. This allows the port authorities to have knowledge of potential security or integrity issues before physically examining the container. Some of the challenges of using wireless sensor tag networks for container security include battery life, size, environmental conditions, information security, and cost among others. PNNL developed an active wireless sensor tag platform capable of reporting data wirelessly to a central node as well as logging data to nonvolatile memory. The tags, operating at 2.4 GHz over an IEEE 802.15.4 protocol, were designed to be distributed throughout the inside of a shipping container in the upper support frame. The tags are mounted in a housing that allows for simple and efficient installation or removal prior to, during, or after shipment. The distributed tags monitor the entire container volume. The sensor tag platform utilizes low power electronics and provides an extensible sensor interface for incorporating a wide range of sensors including chemical and environmental sensors.

7983-32, Session 4

Application and assessment of ultrasonic inspection methods for flaw detection and characterization of manganese steel frogs

A. D. Cinson, A. A. Diaz, Pacific Northwest National Lab. (United States)

Ultrasonic nondestructive examination (NDE) has a long and successful history of application across a wide array of industries, including nuclear, aerospace, and transportation sectors. In coarse-grained, cast Manganese (Mn) steel frog components, NDE/inspection challenges are encountered both in-field (after the frogs have been installed on a rail line) or at the manufacturing facilities during post-fabrication QA/QC activities. Periodically frogs are inherently flawed from a manufacturer, and put into service, as most railroad operators do not have a means to conduct pre-service examinations once these components are received. The problem generates a more significant impact when the cost of labor for repair and/or replacement is then added to the equation. In some cases, warranty claims cannot be made due to the lack of part identification and uncertainty in the root cause of the failure. Accordingly, there is a need for a pre-service inspection system that can provide a rapid, cost-effective and non-intrusive inspection capability for detection of defects, flaws, and other anomalies in frog components that eventually lead to premature initiation of cracks or failures of these components during service.

This study focused on evaluating an ultrasonic phased array volumetric inspection approach to monitor fabrication quality assurance. Phased array data were acquired using a variety of frequencies on several flawed Mn steel frog components directly from manufacturing facility. The components contained flaws commonly found in the manufacture of these cast specimens. The data were analyzed and anomalies found were localized and sized; and a detection metric was reported in the form of signal-to-noise values.

7983-33, Session 5A

Advanced sensing technologies and advanced repair materials for the infrastructure: research funding

T. Wiggins, H. F. Wu, National Institute of Standards and Technology (United States)

This talk will present the results of recent funding by the NIST Technology Innovation Program (TIP) in advanced sensing technologies and advanced repair materials for the nation's critical physical infrastructure, and the research projects that are underway. TIP is a cost-shared, federal program that funds high-risk, high-reward translational research that is expected to transform the Nation's capacity to address areas of critical national need. The program funds proposals for innovative R&D that are high-risk, high-reward in nature, and have high potential to be transformational in outcome and impact! U.S. businesses, institutions of higher education, and other organizations such as national laboratories and nonprofit research institutions are eligible participants in TIP funded projects. The talk will conclude with a preview of TIP's 2011 activities and anticipated call for proposals.

7983-34, Session 5A

Intelligent renewal of aging civil infrastructure

M. Q. Feng, Univ. of California, Irvine (United States)

America's and the world's quality of life and prosperity rely on elaborate civil infrastructure systems. Unfortunately, many of these systems are aging, rapidly deteriorating, and becoming increasingly vulnerable to catastrophic failure during natural or man-made events. Despite the urgent need for restoration, these massive systems must be renewed

in a cost-effective and resource-sustainable manner. This talk explores an intelligent renewal methodology that consists of: (1) timely detection of problems using innovative sensors, (2) reliable assessment of triage opportunities through the development of effective diagnostic and prognostic techniques, and (3) economical solutions for such problems through the use of advanced materials and technologies. This talk focuses on the speaker's work on novel fiber optic sensors, vision-based sensors, microwave imaging technology, and vibration-based damage assessment algorithms. They have been validated by means of large-scale experiments and field implementation in bridges and buildings. In addition, this talk previews a new research project on trenchless rehabilitation of underground water pipes using robotic application of carbon fiber composites. These studies will form the foundation for a fundamental change in infrastructure maintenance and design. Such a paradigm shift is essential if we are to address our aging and deteriorating civil infrastructure effectively.

7983-35, Session 5A

Long-term assessment of autonomous wireless structural health monitoring system at the new Carquinez Suspension Bridge

M. Kurata, J. P. Lynch, Univ. of Michigan (United States); G. W. van der Linden, V. Jacob, SC Solutions, Inc. (United States); Y. Zhang, Univ. of Michigan (United States); E. J. Thometz, P. K. Hipley, L. Sheng, California Dept. of Transportation (United States)

A dense network of sensors installed in a bridge can continuously generate response data from which the health and condition of the bridge can be assessed. This approach to structural health monitoring lessens the efforts associated with periodic bridge inspections and can provide timely insight to regions of the bridge suspected of degradation or damage. Nevertheless, the deployment of fine sensor grids on large-scale structures is not feasible using wired monitoring systems because of the rapidly increasing installation labor and costs required. Moreover, the enormous size of raw sensor data, if not translated into meaningful forms of information, can paralyze the bridge manager's decision making. This paper reports the development of an autonomous wireless structural health monitoring system for long-span bridges; the system is entirely wireless which renders it low-cost and easier to install. Unlike central tethered data acquisition systems where data processing occurs in the central server, the distributed network of wireless sensors making up the wireless monitoring system support data processing capabilities. Embedded computing is a powerful tool for reducing raw data streams into useful and actionable information of immediate value to the bridge manager. The proposed wireless bridge monitoring system is currently under development and recently deployed on the New Carquinez Suspension Bridge in California. Current efforts on the bridge site include: 1) long-term assessment of a dense wireless sensor network with solar power harvesters, 2) the deployment of a Linux-based wireless data receiver station, and 3) embedded data processing. The data acquisition program at the receiver station is linked to cyber-infrastructure using a client interface which enables autonomous data communication with a remote database server. At the remote server, a model calibration and damage detection module uses a high-fidelity finite element bridge model to continuously update the bridge model and warn bridge owners when damage occurs.

7983-36, Session 5A

Networked computing in wireless sensor networks for structural health monitoring

A. Jindal, M. Liu, Univ. of Michigan (United States)

This paper studies the problem of distributed computation over a network of wireless sensors. While this problem applies to many emerging applications, to keep our discussion concrete we will focus on sensor

networks used for structural health monitoring. Within this context, the heaviest computation is to determine the singular value decomposition (SVD) to extract mode shapes (eigenvectors) of a structure. Compared to collecting raw vibration data and performing SVD at a central location, computing SVD within the network can result in significantly lower energy consumption and delay. Using recent results on decomposing SVD, a well-known centralized operation, we seek to determine a near-optimal communication structure that enables the distribution of this computation and the reassembly of the final results, with the objective of minimizing energy consumption subject to a computational delay constraint. We show that this reduces to a generalized clustering problem, and establish that it is NP-hard. By relaxing the delay constraint, we derive a lower bound. We then propose an integer linear program (ILP) to solve the constrained problem exactly as well as an approximate algorithm with a proven approximation ratio. We further present a distributed version of the approximate algorithm. We present both simulation and experimentation results to demonstrate the effectiveness of these algorithms.

7983-37, Session 5A

Energy harvesting of radio frequency and vibration energy to enable wireless sensor monitoring of civil infrastructure

T. Galchev, J. McCullagh, R. L. Peterson, K. Najafi, A. Mortazawi, Univ. of Michigan (United States)

To power a distributed network of wireless sensors across large infrastructure such as bridges, traditional wired power is not feasible and battery replacement is expensive and places limits on sensor locations. This study thus seeks to develop two power harvesting technologies: radio frequency (RF) and vibration energy scavengers. An RF scavenger operating at medium and shortwave frequencies has been designed and tested. Power scavenging at MHz frequencies allows for lower antenna directivities, reducing sensitivity to antenna positioning. Furthermore ambient RF signals at these frequencies have higher power levels away from cities and residential areas compared to the UHF and SHF bands utilized for cellular communication systems. An RF power scavenger operating at 1 MHz along with power management and storage circuitry has been demonstrated. It is capable of powering a LED at a distance of 15 km from AM radio stations. Detailed circuit design along with test results will be presented. Mechanical vibrations offer another energy source but are characterized by non-periodicity, low frequency and low acceleration. A novel parametric frequency-increased generator (PFIG) harvester has been designed in which a mass, moving with bridge vibrations, latches sequentially onto two electro-magnetic transducers which, when released, oscillate at a higher frequency, increasing the harvester bandwidth and mechanical-to-electrical conversion efficiency. Requiring no tuning, the fabricated PFIG harvester operates over unprecedentedly large frequency (2 to 30 Hz) and acceleration ranges ($0.55\text{-}9.8\text{m/s}^2$), and generates average power greater than 2 microWatts when operated at 2Hz and 0.55m/s^2 . Successful operation has been demonstrated using bridge-recorded non-periodic vibration traces.

7983-38, Session 5A

Nondestructive corrosion monitoring using miniaturized, planar carbon nanotube-based thin films

Y. Liu, Univ. of Michigan (United States)

Corrosion adversely impacts almost all civil infrastructure systems that are constructed from metallic materials (e.g., steel). It is therefore desirable to detect corrosion at an early stage so that remedial action can be taken in a cost-effective manner. Traditional corrosion detection is often done in a destructive manner; such methods are also labor-intensive and time-consuming. Nondestructive monitoring techniques, however, can offer the potential for early detection of corrosion without

requiring interruption of the structure's service. In this paper, we present a nondestructive corrosion sensor using miniaturized, planar carbon nanotube thin films. The key component of the corrosion sensor is a planar working electrode made from single-walled carbon nanotube (SWNT)-polyelectrolyte (PE) thin films that are fabricated by the layer-by-layer (LbL) assembly method. The high surface areas of SWNTs are leveraged to chemically bond polymeric species (e.g., poly(vinyl alcohol) or PVA) that, when blended into the composite, exhibit high sensitivity to corrosion process. Combined with a reference and counter electrode, the miniaturized corrosion sensor can monitor several key factors in the corrosion of steel-reinforced concrete structures including open circuit potential, linear polarization resistance, and corrosion current. The paper presents results aimed to characterize the behavior of a SWNT-based working electrode in the corrosive environment. Moreover, cyclic voltammetry shows that SWNT-based working electrodes offer both good electron transport capability and long-term stability as a sensing element in the field. Due to its flexibility, it can be attached to any surface subjected to corrosive environments. The proposed carbon nanotube-based corrosion sensor could be an ideal candidate for long-term continuous monitoring of corrosion in civil infrastructure systems.

7983-39, Session 5A

Development of self-sensing carbon black ECC

V. C. Li, J. P. Lynch, M. Li, M. Mockaitis, Univ. of Michigan (United States)

The realization of next generation intelligent infrastructure requires multi-functional materials with intrinsic damage tolerance as well as smart functionalities such as damage self-sensing; both characteristics are essential for enhancing infrastructure resilience and reducing maintenance needs and/or improve user experience. In this presentation, we discuss the development of a new type of Engineered Cementitious Composite (ECC) that aims to combine high damage tolerance (tensile ductility) with damage self-sensing ability. This is achieved through incorporating a small dosage of carbon black (CB) into the ECC system to enhance the piezo-resistive response of ECC without impairing its fiber, matrix, and fiber/matrix interfacial characteristics necessary for resisting fracture localization. The effects of CB on ECC rheology during the processing stage, and on its fiber dispersion at the hardened stage are reported. CB-ECC composite properties, including mechanical properties (compressive and tensile strength, tensile strain capacity and crack width) and electrical properties (resistivity change with CB dosage), are also presented. These preliminary results show the promise of CB-ECC as a new damage-tolerant construction material with the ability to continuously report its own damage state, which can support decision making pertaining to infrastructure safety and serviceability.

7983-40, Session 5B

A quasi-distributed optical fiber sensor network for large strain and high-temperature measurements of structures

Y. Huang, Missouri Univ. of Science and Technology (United States); Z. Zhou, Missouri Univ. of Science and Technology (United States); Y. Zhang, H. Xiao, G. Chen, Missouri Univ. of Science and Technology (United States)

Critical buildings such as hospitals and police stations must remain functional immediately following a major earthquake event. Due to earthquake effects, they often experience large strains, leading to progressive collapses. Therefore, monitoring and assessing the large strain condition of critical buildings is of paramount importance to post-earthquake responses and evacuations. However, few monitoring system can work under such harsh environments. Optical fiber sensors, due to their unique attributes such as compactness, immunity to electromagnetic interference and high temperature durability, they are especially attractive for quasi-distributed strain sensing purposes

in harsh environments. In this paper, a quasi-distributed optical fiber sensor network based on extrinsic Fabry-Perot interferometer (EFPI) and long-period fiber grating (LPFG) sensors for both large strain and high temperature measurements has been developed. EFPI sensors function as strain measurement components and each EFPI sensor in the sensor network system could measure large strain up to 12%. LPFG sensors, on the other hand, function as temperature measurement components and each LPFG sensor in this paper has a temperature measurement range of up to 700°C. To obtain strain and temperature information for multiple locations more efficiently, the best optical fiber sensor network system has been investigated and studied in this paper. Experimental results demonstrate that the quasi-distributed optical fiber sensor network system based on EFPIs and LPFGs is capable for both large strain and high temperature measurements. The proposed optical fiber sensor network system can be applied to monitor the quasi-distributed strain for collapse of civil infrastructure in harsh environments.

7983-41, Session 5B

Highly dense strain measurement of concrete retrofitted with smart fabric

M. Imai, H. Suzuki, Kajima Technical Research Institute (Japan)

A significant technical advancement in distributed fiber optic strain sensors has been accomplished: Brillouin optical correlation domain analysis (BOCDA) provides a high spatial resolution and the smallest measurement interval owing to Brillouin scattering stimulated by the correlation of two counter-propagating light waves. In a BOCDA-based system, the measurement position can be varied continuously by changing the correlated frequency, whereas other systems require a sophisticated A/D board for localizing the measurement position. In fact, 50 mm is the current limit of the measurement interval in conventional time-domain-based systems because higher sampling rates are required to process information travelling at the speed of light waves. This paper presents an experimental study on cracked concrete retrofitted with a ply of smart fabric; a fiber optic sensor is woven into the fabric. The strain distribution along the sensing fiber is measured under loading. Once debonding of the smart fabric from the concrete specimen occurs at the tip of a crack, it propagates towards the edge of the specimen. The measured highly dense strain information reveals a mechanism of debonding adjacent to the crack. The strain distribution obtained using BOCDA can potentially facilitate a better understanding of structural behavior, rather than the strain distribution obtained using conventional devices such as a discrete strain gauge.

7983-42, Session 5B

Stability and reliability of fiber optic measurement systems: basic conditions for successful long term structural health monitoring

Y. Yang, P. S. Muley, W. L. Sham, Nanyang Technological Univ. (Singapore)

Recent developments in fiber optic sensors for monitoring civil structures have been of great help for engineers dealing with these structures. After literature survey it was observed that while using fiber optic sensor system for health monitoring of civil structures not much attention is given to the core quality of the fiber, types of coating on fiber, implementing methodologies, handling of fiber optic sensors and their long term effect on reliability of the performance of the monitoring system. These issues are important because the structural conditions, stress level and environment in which fiber optic sensors are placed are different from telecommunication industry. In this paper issues related to long term structural health monitoring of civil structures are considered. Reversal bending of the fiber may cause some effect on the light carrying capacity of the fiber so issue of the fatigue property of fiber addressed in this paper. Other Long term SHM issues such as life of fiber, strain

transfer process from fiber core to coating, calibration of fiber and selection of fiber are also discussed based on the experiments carried out for successful implementation of long term health monitoring of civil structures.

7983-43, Session 5B

Nanofilm-coated long-period grating refractive index sensors for corrosion detection in structural health monitoring

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Long-period gratings (LPGs) have shown their significant promising applications in sensors owing to the attractive features that they possess such as small size, immunity for electromagnetic interference, geometric versatility, multiplexing capability, and resistance to corrosive and hazardous environments. Recent researches have revealed that LPGs written on the standard optical fibers could be used as a powerful sensing platform for health structural monitoring. In this work, we inscribe LPGs into SMF-28 optical fiber by focused-beam CO₂ laser, demonstrating the sensitivity to the refractive index value of the surrounding material of the LPG, and exploring as a refractive index sensor for nondestructive chemical detections in the civil infrastructures. Although evanescent field-based LPG sensors have been applied in quantitatively monitoring chemical analytes including moisture, chloride, and corrosion by-product, etc, the sensitivity, selectivity, and response time of such sensors are still issues for some special purposes. In order to improve those characteristics of the sensors, we propose two types of nanostructured coatings that are coated in grating region by electrostatic self-assembly (EAS). The first coating is insensitive to LPG parameters such as resonance wavelength to be sensed, and is used to increase the sensitivity to refractive index change of surrounding material. The refractive index (1.550) of this coating is higher than that of pure silica, and the coating thickness is around 250 nm. The coating is able to favor the transition between cladding guided modes to coating guided modes, causing a strong redistribution of the cladding modes. The second coating is for selectively absorption of analyte molecule. The refractive index of this coating is 1.455 that is lower than that of pure silica, and the coating thickness is around 50 nm. Response time of nanofilm-coated LPG sensor is dependent on the analyte absorption and de-absorption rates as well as the thicknesses of the coating materials, and is also investigated. Multi-channel sensor system has been designed to monitor different analytes simultaneously in this work that is continuing to further explore the monitoring of structural health conditions through in situ measurements of corrosive analytes in the concrete structures.

7983-44, Session 5B

Condition monitoring and life-cycle cost analysis of stay cable by embedded OFBG sensors

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Stay cables are some of the most critical structural components of a bridge. However, stay cables readily suffer from fatigue damage, corrosion damage and their coupled effects. Thus, health monitoring of stay cables is important for ensuring the integrity and safety of a bridge. Glass Fibre Reinforced Polymer Optical Fibre Bragg Grating (GFRP-OFBG) cable, a kind of fibre Bragg grating optical sensing technology-based smart stay cables, is proposed in this study. For the smart stay cables, three Glass Fibre Reinforced Polymer (GFRP) bars embedded with Optical Fibre Bragg Grating optical (OFBG) strain and temperature sensors were inserted into the hollows of steel wires and fixed with the steel wires at the anchorages of the cable. Therefore, the GFRP-OFBG bars can consistently deform with the steel wires in a cable and that the smart stay cable can sense its own strain the temperature. The fabrication procedure of the smart stay cable was developed and the self-sensing property of the smart stay cable was

calibrated. The application of the smart stay cables on the Tianjin Yonghe Bridge was demonstrated and the vehicle live load effects smart stay cables were evaluated based on field monitoring data. Furthermore, the probability distribution and extreme value distribution of live load effects of the stay cables were established. Finally, the fatigue load effects of smart cables and fatigue accumulative damage of the smart stay cables was evaluated based on field monitoring strain.

7983-45, Session 5B

Stress monitoring in FRP externally wrapped wood cylinders subjected to freeze-thaw cycles with FBG sensors

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Wood structures such as bridge piles have been widely used in the world. Due to the harsh environments, such as water immersion, bacteria attack, static and dynamic loadings and freeze thaw cycles, etc., such wood structures are needed to be strengthened. Among possible strengthening methods, using externally bonded FRP (fiber reinforced polymer) has already been considered as one potential technology. However, the concerns of the durability of the FRP as well as the strengthened wood structures have been drawn, especially for the environments of freeze thaw cycles. In the present study, experiments were conducted to measure the stress developed for the FRP wrapped wood cylinders. Glass and carbon fiber reinforced FRPs were wrapped to wood cylinders with wet layup process. During the sample preparation, FBG (fiber Bragg grating) sensors were embedded along the hoop and perpendicular directions. After the resin hardened, the FRP wrapped wood cylinders were immersed into water and subjected to freeze thaw cycles. The variation of the strain monitored with the FBG sensors were recorded and used to calculate the stress developed in the interfaces. The possible degradation mechanisms of the FRP-wood structure are proposed based on both experimental and theoretical studies.

7983-46, Session 5B

Integrating single-point vibrometer and full-field electronic speckle pattern interferometer to evaluate micro-speaker performance

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A testing system contains an advanced vibrometer/interferometer device (AVID) and a high-speed electronic speckle pattern interferometer (ESPI) was developed. AVID is a laser Doppler vibrometer that can be used to detect single-point linear and angular velocity with DC to 20 MHz bandwidth and with nanometer resolution. In swept frequency mode, frequency response from mHz to MHz of the structure of interest can be measured. The ESPI experimental setup can be used to measure full-field out-of-plane displacement. A five-one phase shifting method and a correlation algorithm were used to analyze the phase difference between the reference signal and the speckle signal scattered from the sample surface. In order to show the efficiency and effectiveness of AVID and ESPI, we designed a micro-speaker composed of a plate with fixed boundaries and two piezo-actuators attached to the sides of the plate. The AVID was used to measure the vibration of one of the piezo-actuators and the ESPI was adopted to measure the two-dimensional out-of-plane displacement of the plate. A microphone was used to measure the acoustic response created by the micro-speaker. Driving signal includes random signal, sinusoidal signal, amplitude modulated high-frequency carrier signal, etc. Angular response induced by amplitude modulated high-frequency carrier signal was found to be significantly narrower than the frequency responses created by other types of driving signals. The validity of our newly developed NDE system will be detailed by comparing the relationship between the vibration signal of the micro-speaker and the acoustic field generated.

7983-47, Session 6A

A new fast inversion analysis algorithm for the spectral analysis of surface wave (SASW) method

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Among the NDT techniques for highway roads and bridges, the Spectral Analysis for Surface Wave (SASW) is widely practiced for its ability to identify the shear velocity profile of subsurface layers. However, the SASW method is limited to one-time inspection because all data enters an inversion process that is iterative and manual. Some automated iteration techniques were developed to improve the efficiency of inversion analysis. These attempts did not change the situation much because they are still based on the guess-and-check procedure required by a forward analysis. In this paper, a new inversion analysis algorithm is proposed to estimate the shear velocity profile rapidly without performing conventional forward analysis. Unlike conventionally determining the dispersion curve with stiffness matrix or similar, the dispersion curve of a layered structure is assumed to be a weighted combination of the shear velocity profile. The weighting factors are determined according to the variation of particle velocity with depth for a specified wavelength of surface wave. Based on this assumption, a fast inversion algorithm is established to estimate the shear velocity profile from a given dispersion curve. No prior knowledge of the test site or personal expertise is needed because this method does not require the initial values of the layer depths and shear velocities. This new method allows the SASW method been to be a fully automatic or even real-time reporting method for highway pavement detection. The accuracy of this fast inversion algorithm is verified by comparing with the results of a conventional algorithm.

7983-48, Session 6A

Wave number estimation based method on in situ subsurface ground truth profiling with near source-receiver sensing

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SASW (Spectral Analysis of Surface Waves) is practical and relatively simple in characterizing subsurface ground truth. According to the surface wave in the interesting range of frequency, some criteria for source-receiver configuration is employed. Challenges emerge when SASW is applied to study the surface wave in the low frequency range and when the source is near the receiver. In such cases, the wavelengths are long compared to sensor array spacing and evanescent fields are present in the array measurements. In this work, this issue is analytically investigated and an existing method based on wave number estimation is proposed to increase the accuracy of the subsurface ground truth profiling as well as to estimate the ground damping factor. Finally, simulated experimental data from analytical and FEA models are used to demonstrate the algorithm and the effects are discussed.

7983-49, Session 6A

Compact, programmable, ground-penetrating radar system for roadway and bridge deck characterization

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A compact, high-performance, programmable Ground Penetrating Radar (GPR) system is described based on an impulse generator transmitter, a direct sampling single shot receiver, and high directivity antennas.

The digital programmable pulse generator is developed for the transmitter circuit and both the pulse width and pulse shape are tunable to adjust for different modes of operation. It utilizes a step-recovery diode (SRD) and short-circuited microstrip lines to produce sub-nanosecond wide ultra-wideband (UWB) pulses. Sharp step signals are generated by periodic clock signals that are connected to the SRD's input node. Up to four variable width pulses (0.8, 1.0, 1.5, and 2.1 ns) are generated through a number of PIN switches controlling the selection of different microstrip lengths. A schottky diode is used as a rectifier at the output of the SRD in order to pass only the positive part of the Gaussian pulses while another group of short-circuit microstrips are used to generate amplitude-reversed Gaussian pulses. The addition of the two pulses results in a Gaussian monocycle pulse which is more energy efficient for emission.

The pulse generator is connected to a number of UWB antennas. Primarily, a UWB Vivaldi antenna (500 MHz to 5 GHz) is used, but a number of other high-performance GPR-oriented antennas are investigated as well. All have linear phase characteristic, constant phase center, constant polarization and flat gain. A number of methods including resistive loading are used to decrease any resonances due to the antenna structure and unwanted reflections from the ground. The antennas exhibit good gain characteristics in the design bandwidth.

7983-50, Session 6A

Novel, low-cost, millimeter-wave system for road surface characterization

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A novel low-cost low-complexity design based on Radar technology operating at millimeter wave is presented for the characterization of road surface conditions in real-time. At frequencies of 24-77 GHz the wavelength is long enough to obtain slight penetration in the top 1-2" of asphalt or concrete surface, but is also short enough to resolve details such as crack or pothole depth/etc. The Radar system operates by continuously outputting radiation and sampling the roadway-reflected radiation through a receiver-downconverter-sampler system.

In initial laboratory testing, the received signal strength was observed to obey the inverse distance $1/R^2$ relationship. The received signal is further dependent on the incidence angle between the plane of the sensor and the plane of the roadway. One observation from this is the need of auxiliary sensors for determining the distance above the road surface as well as providing incident angle data.

The sensor was further mounted on a movable cart used to measure the reflected signal on a variety of road surfaces (smooth, rough, surface defects, and environment factors such as various levels of moisture). By comparing measurements of the material after soaking to measurements in the dry state, there is substantial differentiation in measurements, which indicates the ability to measure the porosity of various materials.

Lastly the sensor bandwidth provides the capability to measure surface roughness illustrated in the standard deviation of measurement data. On a macroscopic level, the aggregate in a roadway acts as a series of

random scatterers and rough roadways or roadways with surface voids show a large variance between measurements of nearby points.

7983-51, Session 6A

Dielectric measurement and modeling of cementitious composite panels using a coaxial probe

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Dielectric properties of construction materials have become a valuable information in the condition assessment of civil infrastructure using microwave and radar nondestructive evaluation (NDE) techniques and sensors. Multiphase dielectrics are usually encountered when structures are made of cementitious composites (e.g., Portland cement). In this paper, the dielectric dispersion of cement paste panels in the frequency range of 0.5 GHz and 4.5 GHz is studied. Cement paste panels of various water-to-cement (w/c) ratios (0.35, 0.40, 0.45, 0.50) were manufactured and their relative complex permittivity (dielectric constant and loss factor) was measured by a coaxial probe in room temperature (77F). Contact dielectric measurements were collected at different locations on each panel to study the dielectric heterogeneity of the cement paste panels. The relaxation time in Debye's model was calculated for each panel. It is found that the measured relative complex permittivity varies even within one cement paste panel. The measured relative complex permittivity decreases with the increasing w/c ratio, both the real (dielectric constant) and imaginary (loss factor) parts.

7983-52, Session 6B

Geometric analysis for the size estimation of subsurface delamination in transient electromagnetic response

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Detection of subsurface defects (e.g., delamination, cracking) using microwave/radar sensors (e.g., ground penetrating radar or GPR) is an important and promising technique for the effective and efficient maintenance of civil infrastructure. In this technique, reflected and scattered electromagnetic signals are typically collected and used for interpreting the size and property of subsurface damages. The objective of this paper is to investigate the feasibility of using finite measurements in the reflected signal for size estimation, through the geometric analysis of waveform. Simulated transient electromagnetic response was generated by finite difference time domain (FDTD) methods in two dimensional domain. A modulated Gaussian impulse at a center frequency of 3.5 GHzs was used

as the source. Rectangular delaminations with a width ranging from 3.048 cm to 16.256 cm and a thickness of 0.762 cm were considered. The depth of subsurface delamination was also studied. The curvature of reflected waveforms, obtained by three measurements, was used to correlate with the width of subsurface delamination. A relative width parameter was defined and used in the proposed equations for estimating the delamination width with less than 10% error. It is found that the relative width parameter is linearly proportional to the difference in waveform curvature. The proposed approach is potentially applicable to other subsurface defects with different shapes.

7983-53, Session 6B

Development of a baseline model for a steel girder bridge using remote sensing and load tests

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A new skewed two span continuous steel girder bridge was constructed and just opened to traffic. This bridge uses high performance steel (HPS 100W) in the flanges of the negative moment region over the intermediate pier. It is one among few this type of HPS bridges in U.S. and its structural performances is critical to the highway transportation safety. For construction verification and long-term structural health monitoring purposes, a 3D finite element (FE) model was developed for the bridge superstructure. Various field tests were performed to verify the FE model including: 1) 3D terrestrial LiDAR scan, 2) static truck load tests, and 3) laser Doppler vibrometer scan testing. The LiDAR scanner was introduced to gain geometrical information of the as-built bridge, which was used to update the original FE model developed based on design drawings. The LiDAR scanner was also used to measure girder deflections during static load tests. The fundamental frequency of the bridge vibration was obtained by using a laser Doppler vibrometer under ambient traffic. The dead-load static analysis results using this FE model were compared with field testing results as well as design calculations in this paper. Modal analysis was performed and the results were compared with dynamic measurements. Through these comparisons, the bridge FE model was verified and it was provided to local DOT bridge engineers for future structural performance evaluation and monitoring applications. This study shows that remote sensing techniques are helpful in bridge structural assessment field testing as well as FE model verification.

7983-54, Session 6B

Bridge deck joints evaluation using lidar and aerial photography

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Bridge deck joint is an important component of a bridge, which can affect the overall performance of the bridge structure. According to national bridge inspection program, deck joints and other bridge components are required to be inspected at a two-year cycle. However, bridge deck joint movement is difficult to establish within the two year cycle. Any cost-effective evaluation methods that can help trace bridge joint movements for frequent evaluations can provide valuable data to bridge engineers.

In this paper, two remote sensing technologies, 3D Terrestrial LiDAR and Aerial photography are being investigated as potential low-cost joint evaluation tools to capture joint movements. The laser scanner can record the position of the surface points of surrounding objects and generate point clouds that contain XYZ coordinates and reflectivity values. Aerial images are taken by commercial DSLR cameras in a small plane flying at 1000 feet and have a higher resolution than satellite or large-format aerial pictures. Both techniques have sub-inch pixel resolutions. Several bridges in Florida and Alabama have been scanned using both techniques and comparisons are made on the scanned images using both techniques.

The laser scanner data could be used to quantify some of the problems in the bridge deck joints, such as joint opening, loss of materials, cracks, and so on. Most of the problems can also be recognized in the aerial images and they could be processed and quantified using computer image processing technology. The results from the bridges in Florida and Alabama so far have shown that LiDAR and aerial imaging technology are compatible and can be applied in bridge deck joint performance evaluation. Moreover, they have the potential to reduce the cost in bridge inspection and management nationwide.

7983-55, Session 6B

3D terrestrial lidar for bridge operation condition monitoring

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Bridge movements under daily traffic operations can be detrimental to the durability and long term performance of the structure. Issues such as heavy traffic flow and excessive vehicle overloads can induce early-age cracking and fatigue failure of bridges. This is especially critical for bridges with high flexibilities. However, currently, there is no cost-effective approach to quantify bridge movements. This study explores applications of short range 3D terrestrial LiDAR scanners as a method of bridge assessment for bridge movements from bridge vertical under-clearance measurements. 3D terrestrial LiDAR scanners, as a range finder, can generate massive point clouds underneath a bridge allowing establishments of static clearance measurements at several points underneath a bridge. The point cloud, a collection of hundreds of thousands of data points with position information, allows applications to be developed to analyze the properties of the bridge structure under varying loading conditions. This study compares several scans conducted on bridge 590512 on route 24 in Charlotte, NC under live loading conditions. The scans were repeated both during winter and summer time allowing the bridge loading and environmental condition changes be integrated into the scan measurements of the characteristics of the bridge structure and the traffic operations associated with the bridge. Performance and resolution issues of terrestrial LiDAR are critically evaluated to determine if LiDAR can be used to reliably determine clearance measurements during normal traffic conditions.

7983-56, Session 6B

Reliability analysis of 3D lidar bridge evaluation

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Bridge health monitoring as a method of protecting aging infrastructure potentially can produce significant highway safety and economic benefits. Current challenges to improve and augment existing health monitoring methods include decreasing the cost and operational logistics involved in these techniques. Non-Destructive Inspection (NDI) technologies for structural health monitoring have achieved significant degrees of maturity. Due to the sheer size of many bridge structures, the number of sensors required and the level of details, monitoring techniques become expensive, and the long-term search for meaningful applications may not be cost effective. Terrestrial 3D LiDAR scanner has been suggested as a remote sensing technique for existing and newly constructed bridges. Using high resolution laser, 3D LiDAR can populate a surficial area with millions of position data points. Bridge problems can benefit from LiDAR scan and current studies have found potential application including: bridge clearance, static deflection measurement and damage detection. The technique is especially useful when accurate measurement of bridge geometry cannot be achieved by traditional survey technique, especially when site topography is prohibitive. However, resolution is still one of the main reasons that limit the application of LiDAR technology for advance bridge monitoring. The accuracy of the bridge evaluation results is depend on the resolution of the raw LiDAR data as well as the efficiency of the developed bridge evaluation algorithm. This paper discusses the reliability issues of such technique as well as the LiDAR based bridge monitoring methodologies. Several experimental results are presented to establish the sensitivities for different assessments.

7983-57, Session 7A

Development of high-toughness, low-viscosity, nano-molecular resins for reinforcing pothole patching materials

J. Yang, Univ. of California, Los Angeles (United States)

Development of High Toughness, Low Viscosity Nano-molecular Resins for Reinforcing Pothole Patching Materials

W. Yuan¹, M. Yuan², J.-M. Yang¹, J. W. Ju², W. H. Kao³, L. Carlson³

As the nation's asphalt pavements age and deteriorate, the need for corrective measures to restore safety and rideability increases. All previous approaches, including different ways of putting down asphalt-aggregate mixtures and manipulation of asphalt properties, could only provide incremental improvement to potholes repair. To solve the issue of potholes, a revolutionary solution must be developed to prolong the service life of pothole repairs. A strong bonding material to reinforce the asphalt-aggregate mixtures is needed to improve the resistance of pothole repair material to endure the repeated traffic loads under various weather conditions. The material desired needs to have extremely high impact toughness, low viscosity for infiltration into aggregates, controlled curing behavior, high strength, compatible with deployment methods, environmental friendly, recyclable and other properties that are critical to the pothole repair.

Under a NIST TIP, we are investigating an innovative and integrated approach to develop potholes repair technology for both warm and cold weathers and for both cold-mix and hot-mix repairs. We have identified a polymeric material, a dicyclopentadiene (DCPD) nano molecular resin, which can be cured by Grubb's catalyst and other commercially available catalysts to become an ultratough material with all the desired properties for pothole repair. Our innovative concept is to use DCPD nano-molecular resin as a reinforcement or binder for the asphalt-aggregate pothole repair materials. The resin will be infiltrated into the mixture of aggregate-asphalt, or neat aggregate through the interconnected voids in the compacted asphalt-aggregate mixture. After the DCPD is infiltrated, cured and hardened under controlled conditions, it will form a continuous network of mechanical cages.

In this presentation, the progress on material development, compatibility studies, interfacial chemistry and adhesion, performance evaluation, durability modeling and life prediction, and nondestructive monitoring of the resulting pothole patching materials will be discussed.

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7983-58, Session 7A

Development of a wireless monitoring system for fracture-critical bridges

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Highway bridges are vital links in the transportation network in the United States, providing the public with routes for daily commutes and businesses with the infrastructure needed to supply goods and services. Identifying possible safety problems in the approximately 600,000 bridges across the country is generally accomplished through labor-intensive, visual inspections. This paper outlines ongoing research sponsored by NIST to improve inspection practices by providing the technology and methodology for real-time monitoring of bridges.

Past monitoring systems for bridges have been time-consuming to install and unreliable in operation. However, with improving technology, the ability to develop resilient systems that are simple to install and maintain are possible. A likely candidate for long-term monitoring are fatigue

sensitive areas in fracture-critical steel bridges. The concentration of the study is on developing a long-term monitoring system that is economical and rugged-able to accommodate the severe temperature ranges, humidity fluctuations, and natural weathering processes that bridges experience. To make installation easier, the focus is on wireless sensors designed to continuously monitor fracture-critical bridges with a targeted 10-year battery life. The sensor nodes will be capable of supporting multiple sensors with sufficient computing power to process raw sensor data and send notifications off-site when a threshold level of damage occurs.

The use of an advanced monitoring system will enhance detection of distress without the need to mobilize an inspection crew or disturb traffic, while giving transportation officials the tools to better allocate inspection resources. This paper will present the current status of the project.

7983-59, Session 7A

Low-cost passive sensors for monitoring corrosion in concrete structures

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The goal of this research is to develop a class of low-cost, wireless sensors to monitor corrosion of embedded reinforcement in reinforced concrete structures. The sensors are powered and interrogated using magnetic coupling between a reader coil and the embedded sensor (Figure 1). The sensors are designed to be placed during construction and interrogated periodically over the service life of the structure.

Previous sensor designs employed a sacrificial steel wire that protrudes beyond the hermetically sealed sensor components. Corrosion of the exposed wire causes the wire to fracture, which causes a discrete change in the resonant response of the sensor. However, the physical connection between the wire and the circuit components is also susceptible to corrosion, which could limit the service life of the sensor.

In this paper, a new sensor generation that addresses the durability concern of the previous design is presented. The sensor incorporates a sacrificial corroding element that is placed entirely outside the sensor components and interacts with the resonant circuit by inductive coupling and shielding of the magnetic fields. The presence of the corroding element increases the frequency of the resonant circuit while reducing the amplitude of its phase dip. As corrosion develops, the resistance of the corroding element increases, which reduces the resonant frequency (Figure 2). Therefore, this design could be used to provide analog output describing the corrosion level within concrete.

The results of preliminary experimental work demonstrating the sensor behavior will be presented. Furthermore, the results of an ongoing, accelerated corrosion test of sensor response within reinforced concrete beams will be discussed (Figure 3).

7983-60, Session 7A

Corrosion detection in concrete member through integrated heat induction and IR thermography

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Steel corrosion in concrete is a main cause of deterioration and early failure of concrete structures. A novel integration of inductive heating and infrared (IR) thermography is proposed for nondestructive detection of steel corrosion in concrete, by taking advantage of the difference in thermal characteristics of corroded and non-corroded steel. This paper focuses on experimental investigation of the concept. An inductive heater is developed to remotely heat the steel rebar from concrete surface, which is integrated with an IR camera. Concrete specimens with different cover depths (1.0, 1.5, 2.0in) are prepared. Each sample has single steel

with a diameter of 0.5in and an identical cover depth from the front and the back sides, which enable heat induction from the one side and IR imaging from the other side simultaneously. For accelerated corrosion, the impressed current method is adopted and three different corrosion conditions respectively representing 10, 20, and 30% of weight loss are prepared. Through the pilot tests, the appropriate heating and cooling periods are determined. During the tests, the IR images in the entire heating and cooling period are recorded. The test results demonstrate a clear difference in thermal characteristics between corroded and non-corroded specimens. The corroded specimens show a higher rate for both the heating and cooling stages than the non-corroded specimens. Based on the test, a quantitative correlation between the corrosion amount and the heating/cooling rates is obtained considering the cover depth effect. This study demonstrates a potential for nondestructive early detection of rebar corrosion in concrete.

7983-61, Session 7A

Scalable cognitive autonomous nondestructive sensing network (SCANSn) for infrastructure health management in the United States

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Efficiently and effectively maintenance of civil infrastructures such as bridges are extremely difficult. The most "desired" technology must be able to a) automatically detect and quantify local damages, b) monitor the integrity of the entire structure, c) provide a management capability in a global scale to account for disaster in a region or as a nation. It is apparent that the current state of the inspection technology and decision-making health management strategies are not quite well developed and requires complete solution to address the current societal challenges which is also mentioned by NIST in CNN column, 2008. SCANSn is designed to overcome these challenges. SCANSn are targeted with the following novelty functionalities to address the local damage and global integrity monitoring capabilities of bridge structures. 1) Built-in innovative sensor-based NDE technique for local damage detection 2) Automatic generation of digital images of damages for remote inspection 3) Self-powered and self-networking capabilities for life-long operation 4) Self-expandable local-global monitoring capability 5) Robust network to monitor multiple structures. In this paper brief subjective description of the proposed ongoing efforts are presented. Once all the tasks are accomplished SCANSn can revolutionize the concept of SHM of bridges in United States.

7983-62, Session 7A

On energy harvesting modules in scalable cognitive autonomous nondestructive sensing network (SCANSn) system for bridge health monitoring

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SCANSn system requires quite significantly high energy for its daily operations. The output voltage requirement is around 18V for active scanning. The power consumption is around 8W. Thus we have proposed energy harvesting from both solar and thermal sources to recharge the system's lithium ion battery. A solar panel and a Thermal Electric Generator (TEG) will be used to drive a battery charger. To maximize the temperature gradient of the TEG, the thermoelectric device will be placed in a Fresnel dome. During shading of the solar panel, the TEG will continue to supply small amounts of power to the battery charger.

Maximum Power Point Tracking (MPPT) is to be integrated into the battery charging circuit so that optimal power conversion is obtained from either source. In order to reduce the peak current that flow through the battery, the converters will operate in continuous conduction mode. Since the output voltages and currents of the solar and thermal harvesters vary significantly, the battery charger will be constructed by two buck-boost converters operating in parallel. Due to the consistent low voltage of the TEG, a simple boost converter may be used. The system design will be benchmarked against the LT3652, a solar battery charger provided by Linear Technology. The preliminary circuit design has been simulated using PSIM, a power electronics program with the ability to model a micro-controller using an embedded C-compiler.

7983-63, Session 7B

In service damage assessment of bonded composite repairs with full field thermographic techniques

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Thermographic techniques offer distinct advantages over other techniques usually employed to assess damage accumulation and propagation. Among the advantages of these techniques are the fully remote-non contact monitoring and their ability for full field imaging. Due to the transient nature of the heat transfer phenomenon, phase and lock-in techniques are of particular interest in order to increase the resolution of the signal. Last but not least, the techniques can be used in order to monitor the irreversible damage phenomena, as manifested by the local heat accumulation in the vicinity of the defect. This eliminates the need for external heat source, as any cyclic loading can induce the heat gradient necessary to pinpoint the defect accumulation and propagation.

In aforementioned context, lock-in thermography has been employed to monitor the delamination propagation in composites and the critical failure of bonded repairs when the materials are subjected to fatigue loading. Lock-in thermography proved successful in identifying debonding initiation and propagation. Finally, the results obtained using thermographic imaging were compared against other techniques, such electrical tomography and ultrasonic monitoring.

7983-64, Session 7B

Detection of surface breaking cracks using thermographic and non-contact ultrasonic methods

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A combined ultrasound and thermography defect detection system using a raster scanned Q-switched laser as a source of heat and ultrasound has been developed for identifying surface breaking defects. Heat is generated on a sample surface by a laser source and the resultant thermal image is examined by a thermal imaging camera. This can be done using a cw or a pulsed laser, but for ultrasonic generation a pulsed laser beam is required. When a defect is present, the flow of heat in the sample is disturbed and a change in shape of the thermal spot on the sample's surface can be detected. The pulsed laser beam generates simultaneously an ultrasonic wave that can be detected by a suitable transducer, which in this case is an electromagnetic acoustic transducer (EMAT). The presence of a defect changes both the amplitude and frequency content of the received wave. Three dimensional finite element modelling of the interaction between Lamb waves and defects have been studied and compared with experimental data, in order to optimise source and detector positions around a defect. The approach can detect surface crack defects via the ultrasonic and thermography method in one measurement.

7983-65, Session 7B

Feasibility of using line scanning thermography in NDE of wind turbine blades

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Today, the increasing energy demand and the need for clean power generation has lead to the improvement of wind turbines and the development non invasive inspection techniques for the assessment of wind turbine blades in manufacturing and in service to maintain long term reliability as well as to avoid catastrophic failures.

Given the complexity of the geometry, the material composition and material thicknesses finding a NDT technique to effectively and rapidly inspect the blades is a challenging task. Wind turbine blades are fabricated using different materials like fiber glass, carbon composites, PVC foam and/ or balsa wood. Layers of these materials are bonded together using an epoxy type resin. Inspection of the bond quality between external layers and structural elements of the blade is of fundamental importance.

Conference 7984: Health Monitoring of Structural and Biological Systems V

Monday-Thursday 7-10 March 2011

Part of Proceedings of SPIE Vol. 7984 Health Monitoring of Structural and Biological Systems 2011

7984-01, Session 1

Wave propagation in isogrid structures

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This work focuses on an analysis of wave propagation in rib-stiffened structures as it relates to Structural Health Monitoring (SHM) methods. Current satellite validation tests involve numerous procedures to qualify the vehicle for the vibrations expected during launch and for exposure to the space environment. SHM methods are being considered in an effort to truncate the number of validation tests required for satellite checkout. The most promising of these SHM methods uses an active wave-based method in which an actuator propagates a Lamb wave through the structure, where it is then received by a sensor and evaluated over time to detect structural changes. Thus far, this method has proven effective in locating structural defects in a complex satellite panel; however, the attributes associated with the first wave arrival change significantly as the wave travels through ribs and joining features. Previous studies have been conducted in simplified ribbed structures, giving initial insight into the complex wave propagation phenomena. In this work, the study will be extended both numerically and experimentally in an isogrid plate. Wave propagation will be modeled using finite element software, and experiments will be carried out using piezoelectric transducers for both actuator and sensor. These results will be analyzed for an understanding of dispersion and mode conversion within the structure.

7984-02, Session 1

Monitoring of hidden damage in multi-layered aerospace structures using high-frequency guided waves

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Aerospace structures contain multi-layered components connected by fasteners, where fatigue cracks and disbonds or localized lack of sealant can develop due to cyclic loading conditions and stress concentration. High frequency guided waves propagating along such a structure allow for the efficient non-destructive testing of large components, such as aircraft wings. The type of multi-layered model structure investigated in this contribution consists of two adhesively bonded aluminium plates with an epoxy based sealant layer. Using commercially available transducer equipment, specific high frequency guided ultrasonic wave modes that penetrate through the complete thickness of the structure were excited. The wave propagation along the structure was measured experimentally using a laser interferometer and shows good agreement with predictions from numerical simulations. Two types of hidden damage were considered: a localized lack of sealant and small surface defects in the metallic layer facing the sealant. The interaction of the high frequency guided wave with the hidden defects was studied from laser measurements at the specimen surface and verified employing numerical simulations. The detection sensitivity using standard pulse-echo measurement equipment has been quantified and the detection of small hidden defects from significant stand-off distances has been proven. Fatigue experiments were carried out and the potential of high frequency guided waves for the monitoring of fatigue crack growth at a fastener hole during cyclic loading was investigated. The sensitivity and repeatability of the measurements were ascertained, showing the potential for fatigue crack growth monitoring at critical and difficult to access fastener locations from a stand-off distance.

7984-03, Session 1

Acoustic emission-based structural health monitoring of stiffened panels

T. Whitlow, M. J. Sundaresan, North Carolina A&T State Univ. (United States)

Using Lamb waves to study acoustic emissions has proven to be a useful asset when examining acoustic emissions (AE) in structures. AE based structural health monitoring (SHM) allows for real time monitoring of crack growth and damage. This technique has proven to be useful when studying basic structural elements, such as flat plates and bars. However, the majority of aircraft structures are more complicated geometries. Sudden changes in thickness or additional geometrical features, such as stiffeners, can cause abundant complexity: mode conversion, attenuation, frequency loss, etc.. Traditional AE parameters no longer suffice in helping to understand the source type of the AE signal. The objective is to explore the acoustic emission technique in determining damage as well as source location. An aluminum stiffened panel (300 mm x 300 mm x 2mm) is examined and incremental crack growth is simulated by applying triangular impulses of 1, 2, and 5 microseconds at several locations on the panel. The simulated waveforms are seen to be very similar to the experimentally obtained data. A standard finite element package was used to model the stress wave propagation via an explicit finite element technique. A comparison of the waveforms in the stiffened panel and those in the flat plate shows the complexity induced by the stiffener, which hinders interpretation. In order to overcome this complexity, the waveforms generated in the stiffened panel will be compared to base signatures in both the flat plate and a single stiffener. The correlation results will be used for training automatic classification algorithms that can potentially identify the source type and source location.

7984-04, Session 1

Holographic imaging of acoustic waves in piezo-electric ceramics by Coulomb coupling

A. Habib, Univ. Siegen (Germany); A. Shelke, The Univ. of Arizona (United States); U. Amjad, M. Pluta, Univ. Leipzig (Germany); T. Kundu, The Univ. of Arizona (United States); U. Pietsch, Univ. Siegen (Germany); W. Grill, Univ. Leipzig (Germany)

Scanned imaging with excitation and detection by the electric field of a sphere has been applied to 1 mm, thick Lead Zirconate Titanate (PZT) piezo-sinter material in transmission. A short pulse has been used for broad band excitation. This scheme has also been applied to holographic imaging of the transport properties of acoustic waves in piezo-crystals. The study includes three dimensional, (spatial and temporal) high resolutions holographic imaging of acoustic wave's propagation in a sintered piezo-ceramic plate. The gradient of the electric field normal and parallel to the surface of the piezo-material are evident in the holographic images. The Coulomb field is modeled by Christoffel's solution to determine the effective elastic tensor and the piezoelectric properties. The excitation and detection methods as well as a theoretical approach are demonstrated and applications are briefly illustrated and discussed.

7984-05, Session 2

Delamination detection in a composite plate using a dual piezoelectric transducer network

C. Yeum, H. Sohn, KAIST (Korea, Republic of); J. Ihn, The Boeing Co. (United States)

In this study, a new damage detection technique is developed so that delamination in a multilayer composite plate can be detected by comparing multi-path pitch-catch Lamb wave signals in a piezoelectric transducer network rather than by comparing each signal with its corresponding baseline signal obtained from the pristine condition. The development of the proposed technique is based on the premise that the fundamental anti-symmetric mode (A0) slows down when it passes through a delamination area while the speed of the fundamental symmetric mode (S0) is invariant of delamination. First, the delay of the A0 mode in each path is used as a damage sensitive feature and extracted using the mode extraction technique previously developed by the authors. This mode extraction technique uses dual piezoelectric transducers composed of concentric ring and circular piezoelectric transducers, and it is capable of decomposing the A0 mode in any desired frequency without frequency or transducer size tuning. Once the time delays of the A0 mode are computed for all pitch-catch paths in the transducer network, an instantaneous outlier analysis is performed on these features to identify wave propagation paths affected by the delaminated region(s). Because the time delays of the A0 mode are instantaneously computed from multiple paths, it has been demonstrated that robust delamination detection can be achieved even under varying temperature conditions.

7984-06, Session 2

Structural health monitoring strategy for detection of interlaminar delamination in composite plates

N. Quaegebeur, P. Micheau, P. Masson, A. Maslouhi, Univ. de Sherbrooke (Canada)

In this paper, a Structural Health Monitoring (SHM) strategy is proposed in order to detect interlaminar delamination in a Carbon Fiber Reinforced Polymer (CFRP) structure using Lamb waves. The delamination is simulated by inserting a Teflon tape between two transverse plies of a 32 - plies quasi isotropic plate and the Lamb wave generation and measurement is ensured by piezoceramic (PZT) elements. Lamb wave theoretical propagation and through-the-thickness strain distribution are studied, in order to determine the optimal configuration of the final system in terms of mode and frequency selection, piezoceramic sizing and spacing for detection of cross-sectional delamination. Experimental assessments are first conducted using variable angle wedges in order to guarantee the detectability of the damage. Then, pitch and catch measurements are performed by comparing wave propagation for different frequencies and along damaged and undamaged paths of the structure and the analysis of results is performed using Reassigned Short-Time Fourier Transform (ReSTFT). It appears that in the low frequency range (below 300 kHz), A0 mode is sensitive to the damage while in the high frequency range, S1 and A1 modes are both very sensitive to the damage while the propagation of the S0 mode is not much affected. Thus, frequency and mode ranges must be chosen with care for practical implementation of guided waves methods for SHM of composite structures.

7984-07, Session 2

Composite piezoelectric strip transducer development for structural health monitoring

S. Li, C. J. Lissenden, The Pennsylvania State Univ. (United States)

Structural health monitoring of plate and shell structures with ultrasonic guided waves is investigated. Damage modes of interest include fatigue cracks and corrosion. Fiber composite piezoelectric elements for use in a comb-like strip transducer are designed for specific poling directions and electrode orientations. Size and number of elements are considered as well. The goal of the transducer design is to generate a strong and uniform plane wave. The analysis includes finite element analysis and wave propagation experiments. The finite element analysis employs cosimulation using ABAQUS Standard and ABAQUS Explicit to model transient wave propagation from a piezoelectric composite transducer. Experiments include wave propagation visualization using a Doppler laser vibrometer.

7984-08, Session 2

Design of mode selective actuators for Lamb wave excitation in composite plates

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In this study mode selective actuators are developed to excite a particular Lamb wave mode in quasi-isotropic CFRP (Carbon fiber reinforced polymer) plates. The actuators are based on interdigital transducer design in order to control the frequency as well as the wavelength of the desired mode within the excitation. The actuators are made of monolithic piezoceramic plates with an interdigitated electrode structure which was realized by laser ablation process.

To determine the wavelength of the desired Lamb wave mode experimental dispersion diagrams of the CFRP plates were measured by using air-coupled ultrasonic scanning technique. The dispersion diagrams show the A0 and S0 mode in a frequency range of 10 to 400 kHz and different fiber directions of the CFRP plates. A set of mode selective actuators for different wavelengths and frequencies were designed to operate in the A0 or S0 mode. Within experimental tests the actuators and circular piezoceramic sensors are applied on the CFRP plates in order to determine the mode selectivity. These tests are accompanied by 2D finite element simulations. On the basis of simulations and experimental test the influence of different parameters such as number and width of electrode segments, excitation signals and apodization is investigated.

The results show that a mode selectivity of the A0 or the S0 mode in CFRP plates can be achieved by the designed actuators.

7984-09, Session 2

Modeling of three-dimensional guided wave propagation in composite plate and extreme temperature environment

G. Huang, F. Song, Univ. of Arkansas at Little Rock (United States)

Surface-bonded piezoelectric wafers have been widely utilized in integrated structural health monitoring systems to generate ultrasonic guided waves. In this work, a three-dimensional piezoelectric actuator and sensor models are developed to simulate guided wave propagation in composite plate structure. Based on the proposed model and relevant temperature-dependant parameters, temperature effects upon the guided waves in composite plate are discussed. Specially, phased array beamsteering is investigated under different temperatures. It is found that the temperature effects should be compensated such that desirable directional characteristics can be achieved.

7984-10, Session 3

Time reversal data communications on pipes using guided elastic waves Part I: basic principles

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Guided ultrasonic waves that can propagate long distances along civil structures have been widely studied for detection and localization of structure damage. Although it is common to use propagating waves such as electromagnetic radio waves and ultrasonic underwater acoustical waves for data communications, the studies of data communication using elastic waves are very limited. Data communication using guided elastic waves on structures such as pipes potentially provides an alternative to many conventional communication schemes which may not be possible in practical operational conditions.

In this paper, we develop a framework for time reversal signal processing and data communication using guided elastic waves on pipes. In general, the guided waves travelling along a pipe consist of many orthogonal wave modes that result from the pipe structure. Each of the wave modes is dispersive and propagates in the elastic medium at different velocities. Therefore, conventional communication schemes would result in severe performance degradation in terms of data throughput and communication accuracy. Time reversal is an adaptive transmission technique that can compensate for the propagation delay due to its unique focusing properties. We will show in this paper that time reversal communication over pipes is a feasible approach and achieves high data rate. Our algorithm will be verified by experimentally measured guided pipe wave signals in a laboratory.

7984-11, Session 3

Time reversal data communications on pipes using guided elastic waves Part II: experimental studies

Y. Jin, Univ. of Maryland Eastern Shore (United States); Y. Ying, Carnegie Mellon Univ. (United States); D. Zhao, Univ. of Electronic Science and Technology of China (China)

Data communication technology has been extensively implemented using electromagnetic radio waves. However, ultrasonic guided waves through solid structures such as pipes have been rarely studied for data communication purposes. The multi-modal and dispersive characteristics of guided waves make it difficult to interpret the channel responses and to transfer useful information in pipes. Time reversal is an adaptive transmission technology that can improve the spatial and temporal wave focusing. Based on the focusing effect of time reversal, we have developed a data communication technique using guided waves in a highly dispersive pipe environment.

In this paper, we experimentally investigate the feasibility of time reversal communication on pipes. Three-step laboratory tests have been performed using piezoelectric transducers in pitch-catch mode. We first measure the channel responses between the transmitter and the receiver on a pipe. We then carry out the time reversal transmission by reversing the sounding signal and feeding it back. At last, we perform the time reversal communication experiment by sending the modulated time reversal signals as a stream of binary data at a certain data rate. These signals are generated by modulating the message data onto the time reversal signal obtained from the second step with a pulse position modulation scheme. To generalize the application, a series of experiments have also been demonstrated on a pipe with a welded butt joint and a pipe with internal pressure. The results show that time reversal data communications can be achieved on pipes using guided elastic waves and provide a potential alternative to conventional structural health monitoring techniques.

7984-12, Session 3

Simulation and control system of a power harvesting device for railroad track health monitoring

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With the sheer size of existing railroad infrastructure, there exist numerous road crossings which are lacking warning light systems and/or crossing gates due to their remoteness from existing electrical infrastructure. Along with lacking warning light systems, these areas also tend to lack distributed sensor networks used for railroad track health monitoring applications. With the power consumption required by these systems being minimal, extending electrical infrastructure into these areas would not be an economical use of resources. This motivated the development of an energy harvesting solution for remote railroad deployment. This paper describes a computer simulation created to validate experimental on-track results for different mechanical prototypes designed for harvesting mechanical power from passing railcar traffic. Using the Winkler model for beam deflection as its basis, the simulation determines the maximum power potential for each type of prototype for various railcar loads and speeds. Along with calculating the maximum power potential of a single device, the simulation also calculates the optimal number and position of the devices needed to power a standard railroad crossing light signal. A control system was also designed to regulate power to a battery, monitor and record power production, and make adjustments to the duty cycle of the crossing lights accordingly. On-track test results are compared and contrasted with results from the simulation, discrepancies between the two are examined and explained, and conclusions are drawn regarding suitability of the device for powering high-efficiency LED lights at railroad crossings and powering track-health sensor networks.

7984-13, Session 3

Guided ultrasonic waves for the health monitoring of existing sign support structures

X. Zhu, P. Rizzo, Univ. of Pittsburgh (United States)

This paper describes a method based on Guided Ultrasonic Waves (UGWs) for the structural health monitoring of sign support structures. The method combines the advantages of UGWs with an unsupervised learning algorithm (outlier analysis). The general framework presented in this paper is applied to ultrasonic data collected from an overhead sign structure removed from service and tested at the University of Pittsburgh and subjected to varying environmental condition. The probing hardware consists of a National Instruments-PXI platform that controls the generation and detection of the ultrasonic signals by means of piezoelectric transducers made of Lead Zirconate Titanate. The effectiveness of the proposed approach to detect damage under large temperature variations and dry/wet/snowy conditions is demonstrated. Finally, the same hardware / algorithm are applied for the health monitoring of two structures deployed in the Pittsburgh (Pennsylvania) area.

7984-14, Session 3

A comparison of impedance and Lamb wave SHM techniques for monitoring structural integrity of and through welded joints

B. L. Grisso, Naval Surface Warfare Ctr. Carderock Div. (United States); I. N. Tansel, G. Singh, G. Singh, Florida International Univ. (United States); L. W. Salvino, Naval Surface Warfare Ctr. Carderock Div. (United States)

In the near future, welded aluminum structures are expected to be widely used in the fabrication of high performance ships. Structural health monitoring (SHM) systems will aid in the safety and low cost operation of these ships. To work efficiently at detecting flaws in ships, these SHM systems will need to be inexpensive, capable of operating on thick plates, and able to detect defects at and beyond welded interfaces.

In this study, the feasibility of monitoring the structural integrity of welded thick aluminum plates was experimentally tested using two widely used SHM methods: impedance and Lamb wave analyses. Two ¼ inch thick aluminum plates were welded together. On one side of the weld, two piezoelectric elements were bonded to the structure, while one piezoelectric patch was attached to the other plate. Damage was initially introduced to the structure by simulating degradation of the weld. A narrow, 1/8 inch long cut was made at the edge of the weld to represent cracking. The cut was then extended to 1/4 of an inch. Finally, a 1/16 inch diameter hole was drilled at the center of the weld. To provide an indication of detection capability through the weld, one 1/16 inch diameter hole was placed in the plate on either side of the weld. At each of these damage steps, data were collected for both the impedance and Lamb wave techniques.

Collected impedance signatures were analyzed using several methods, including the statistical correlation coefficient, over a number of different frequency ranges. Results consistently revealed the impedance method to be sensitive to damage in and through the weld. The envelopes of the Lamb wave signals were calculated using the S-transformation of the time histories. There was significant change to the curves when different defects were added to the plate.

Both of the SHM methods briefly studied detected each of the cuts and holes acting to reduce the overall strength of the structure. Each technique also detected the hole damage on the opposite side of the weld as the sensor(s) used for damage detection. The study further verified that surface waves move across welds allowing SHM methods to detect the defects even if the sensors are located on neighboring plates or geometries.

7984-15, Session 3

Torsional guided waves for monitoring cylindrical structures using piezoelectric macro-fiber composite

L. Cui, Y. Liu, C. K. Soh, Nanyang Technological Univ. (Singapore)

In cylindrical structures such as pipelines, cracks are most likely to occur along the longitudinal (axial) direction and they are usually fatal to the serviceability of the structures. Unfortunately, the conventional ultrasonic crack detection methods are not very sensitive to this type of cracks. This paper focuses on using piezoelectric macro-fiber composite (MFC) to generate torsional wave for the health monitoring of cylindrical structures. Theoretical works have shown that torsional wave is a kind of non-dispersive pure shear wave which propagates at a fixed wave speed. Intuitively, the propagation of shear wave will be affected by the longitudinal cracks while the influence on the axial Lamb wave is rather small. Numerical simulations are performed using ANSYS. Nodal release method is used to model the crack. The time of flight (TOF) of waves and the difference between the crack induced disturbances on axial Lamb wave and that on torsional wave are used to determine the crack position and orientation. Experimental verifications are also presented. Four pieces of MFC oriented at 45° against the axis of the specimen are used to generate both axial Lamb wave and torsional wave. Mode separation techniques are used to separate the two wave modes from the acquired signals. The conformity among the experimental results, the numerical results as well as the theoretical results shows that the existence, the location and the orientation of the cracks in cylindrical structures can be identified using the presented wave propagation approach.

7984-16, Session 3

Pipeline health monitoring using a multi-scale actuated sensing system

C. Lee, S. Park, Sungkyunkwan Univ. (Korea, Republic of)

In a structure, damage can occur at several scales from micro-cracking to corrosion or loose bolts. This makes the identification of damage difficult with one scale of sensing. Hence, a multi-scale actuated sensing system is proposed based on a self-sensing circuit using a piezoelectric active sensor. In the self sensing-based multi-scale actuated sensing, one scale provides a wide frequency-band structural response from the self-sensed impedance measurement and the other scale provides a specific frequency-induced structural wavelet response from the self-sensed guided wave measurement. In this study, an experimental study using the pipeline system under a water flow-operation is carried out to verify the effectiveness and the robustness of the proposed structural health monitoring (SHM) approach. Different types of structural damage, which are bolt loosening, corrosion and notches, are artificially inflicted on the pipeline system. To classify the multiple types of structural damage, supervised learning-based statistical pattern recognition is implemented by composing a two-dimensional (2D) plane using the damage indices extracted from the impedance and guided wave features. For more systematic damage classification, several control parameters to determine an optimal decision boundary for the supervised learning-based pattern recognition are optimized. Finally, further research issues will be discussed for real-world implementation of the proposed approach.

7984-17, Session 4

Multi-mode and multi-frequency guided wave imaging via chirp excitations

J. E. Michaels, S. J. Lee, J. S. Hall, T. E. Michaels, Georgia Institute of Technology (United States)

Guided wave imaging has shown great potential for structural health monitoring applications by providing a way to visualize and characterize structural damage. For successful implementation of delay-and-sum and other elliptical imaging algorithms employing guided ultrasonic waves, some degree of mode purity is required because echoes from undesired modes cause imaging artifacts that obscure damage. But it is also desirable to utilize multiple modes because different modes exhibit increased sensitivity to different types and orientations of defects. The well-known mode-tuning effect can be employed to use the same PZT transducers for generating and receiving multiple modes by exciting the transducers with narrowband tonebursts at different frequencies. However, this process may be inconvenient and time-consuming, particularly if extensive signal averaging is required to achieve a satisfactory signal-to-noise ratio. In addition, data storage requirements may be prohibitive if signals from many narrowband toneburst excitations are measured.

In this paper, we utilize a chirp excitation to excite PZT transducers over a broad frequency range to acquire multi-modal data with a single transmission, which can significantly reduce both the measurement time and data storage requirements. Each received signal from a chirp excitation is post-processed to obtain multiple signals corresponding to different narrowband frequency ranges. Narrowband signals with the best mode purity are selected and then used to generate multiple images of damage in a target structure. The efficacy of the proposed technique is evaluated experimentally using an aluminum plate instrumented with a spatially distributed array of piezoelectric sensors and with artificially generated damage. Results from the chirp excitation are compared with those obtained from toneburst excitations at multiple frequencies.

7984-18, Session 4

Chirp generated acoustic wavefield images

T. E. Michaels, J. E. Michaels, S. J. Lee, X. Chen, Georgia
Institute of Technology (United States)

Guided waves are being considered for structural health monitoring (SHM) applications, and they can also be used to reduce subsequent inspection times once defects are detected. One proposed SHM method is to use an array of permanently attached piezoelectric transducers to generate and receive guided waves between the various transducer pairs. The interrogation can be done on a continuous or periodic basis to determine the health of the structure. Once defects are suspected in the structure, the traditional approach is to disassemble components for conventional nondestructive evaluation (NDE); however, this is an expensive and time consuming process. A less expensive alternative to conventional NDE is to record acoustic wavefield images of guided waves generated from the attached transducers. These images contain a wealth of information and clearly show details of guided waves as they propagate outward from an acoustic source, reflect from structural discontinuities and specimen boundaries, and scatter from any damage sites within the structure. However, the recorded waves are typically narrowband to enable effective visualization of echoes that are relatively compact in time.

In this paper, we consider wavefield images that are recorded from a chirp excitation, which offers the advantage of high quality broadband data from a single excitation. However, responses are not directly useful because the direct, reflected and scattered echoes are too extended in time. Signals are post-processed to obtain multiple narrowband and broadband responses containing echoes that are more compact in time to enable direct visualization of guided waves interacting with structural features. This technique is demonstrated on an aluminum plate specimen that contains an attached stiffener and various types of induced damage. Wavefield data are recorded using an air-coupled PZT transducer scanned over the plate surface while permanently attached PZT transducers act as guided wave sources. Waves scattered from induced defects are compared after broadband and narrowband processing at multiple frequencies.

7984-19, Session 4

Defect detection using time reversal imaging technique

S. Liu, F. Yuan, North Carolina State Univ. (United States)

A damage detection technique based on time reversal concept is proposed to detect and locate the defects in a plate structure. Time reversal imaging method is widely used as an advanced, robust data processing and imaging technique in structure health monitoring to detect the defects. Physically, it says that the time reversed signal will retrace its original path precisely, which means that the signals will be refocused back on the source and defects after we record, time reverse and back propagate the wave signal experimentally or numerically. In this paper, a distributed actuator/sensor network is placed on a square homogeneous plate and utilizes piezoelectric as both actuators and sensors to generate and collect the guided wave signals in the plate. The time reversal technique is then used to interpret the physical meaning of the recorded data and image the defects in the plate. Both computer simulations and experiments are presented to illustrate the feasibility of the technique in this paper.

7984-20, Session 5

Monitoring initial material damage of nuclear reactor steel using second harmonic generation

K. H. Matlack, J. Kim, L. J. Jacobs, Georgia Institute of Technology (United States); J. Qu, Northwestern Univ. (United States)

This research investigates the relationship between the acoustic nonlinearity and material damage that is typical of nuclear reactor steels, such as irradiation damage, thermal embrittlement, and corrosion. The acoustic nonlinearity parameter is manifested by the generation of a second harmonic component in an originally monochromatic ultrasonic wave signal. It has been shown that the acoustic nonlinearity parameter correlates to an intrinsic material property, the material nonlinearity. Previous literature has experimentally and theoretically reported a direct correlation of the acoustic nonlinearity parameter and accumulated material damage prior to crack initiation. Multiple types of ultrasonic waves are suitable for detection of this nonlinearity parameter - longitudinal, Rayleigh, and Lamb waves. The selection of the wave type used in this research is based on an analysis of efficient second harmonic generation and experimental feasibility of different ultrasonic wave modes. Rayleigh waves are chosen since they effectively generate the second harmonic, can interrogate far propagation distances, and are non-dispersive and thus easier to experimentally excite and detect.

To monitor the material state of damage, the acoustic nonlinearity parameter is measured at increasing states of material damage. Recent work has shown that an increase in number of fatigue cycles produces an increase in the acoustic nonlinearity parameter, though this resulting increase is dependent on the type of fatigue (e.g. low- or high-cycle fatigue). An increase in the acoustic nonlinearity parameter is greater with low-cycle fatigue, since material damage is more uniformly distributed, than with high-cycle fatigue, where the material damage is more localized. The acoustic nonlinearity parameter is sensitive to changes in microstructure, and different types of material damage will produce different changes in the material's microstructure - for example, accumulation of irradiation damage can produce dislocation loops that obstruct motion of dislocations, segregation of solutes at grain boundaries, and other changes in microstructure. It is expected that the acoustic nonlinearity parameter will increase due to increasing material damage such as irradiation, but with a different trend than reported for fatigue damage. Experimental results for samples from nuclear reactor shell material subjected to irradiation damage are presented.

7984-21, Session 5

Integrated material state awareness system with self-learning symbiotic diagnostic algorithms and models

X. P. Qing, Acellent Technologies, Inc. (United States); F. Yuan, North Carolina State Univ. (United States); S. Banerjee, S. J. Beard, Acellent Technologies, Inc. (United States)

Materials State Awareness (MSA) goes beyond traditional Non-destructive Evaluation (NDE) and Structural Health Monitoring (SHM) in its challenge to characterize the current state of material damage before the onset of macro-damage such as cracks. For many structural components, when the macrocrack is detected from the current SHM techniques, it could already reach an unacceptable length. It is important to develop an integrated diagnostic system that not only detects macro-scale damages in the structures but also provides an early indication of flaw precursors and microdamages. An integrated MSA system with self-learning symbiotic diagnostic algorithms and models to identify precursors, detect microdamages and flaws near a high stress area or in a distributed region is presented in the paper. The SMART Layer concept is used as a basis for the development of hybrid distributed sensor network with special emphasis on minimizing the total volume of wiring material. The nonlinear behavior of microstructure defects (called micro-defects hereafter), which is intentionally eliminated or simply disregarded in the current conventional ultrasonic diagnosis, is served as the basis for the development of nonlinear diagnostics for MSA. The Self-learning Symbiotic Diagnostic Algorithms employs nonlinear acoustic interpretation and statistical data driven analysis. The approach is based on the principal physics of nonlinearity of materials and its effect on macro scale sensor signals together with an intelligent self instructing data driven algorithm as a wrapper program.

7984-22, Session 5

Diagnosis of space structures using embedded sensors and elastic waves

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Pre-launch testing of space vehicles is a complex process taking weeks if not months to accomplish. An on board structural health monitoring system is considered for reduction of testing time and component validation. Active elements of the system, embedded sensors, are utilized to transmit and receive elastic waves carrying information on component characteristics and structural integrity. Parameters of the elastic wave measured with embedded sensors are investigated using several measurements methods coupled with temporal analysis of elastic wave signatures. In particular, attention is given to temporal distribution of signal phase and nonlinear effects. Specimens of simple and complex geometry incorporating defects typical to space structures were considered in experimental studies. Local measurements with a single sensor as well as global assessment of structural component with a sensor network were explored for damage detection, characterization, and location. Proposed diagnostic approaches were validated on a realistic satellite panel with isogrid. Conclusions are presented on sensing capabilities of active sensors and effectiveness of the associated signal analysis.

7984-23, Session 5

Effects of experimental variation on nonlinear measurements

A. J. Croxford, S. Neild, Univ. of Bristol (United Kingdom)

Nonlinear ultrasonic measurements offer great potential for the detection of damage at an early stage. However measurements are subject to a high degree of variability. This variability limits both the resolution of such measurements and also the confidence of end users in nonlinear techniques. This paper studies the effects of various parameters on the resulting measured nonlinearity. This allows models of the performance of measurements for different experimental conditions to be developed and gives an insight into how nonlinearity may be measured. Variables studied are coupling, angular misalignment, variation in transducer location and effects of propagation distance. Together these cover most of what is experienced practically. The paper shows experimental and modelling results and gives a methodology whereby the confidence in nonlinear measurements can be greatly increased.

7984-24, Session 6a

Autofocus for guided wave SHM in the presence of dispersion

A. J. Croxford, A. J. Hunter, Univ. of Bristol (United Kingdom)

Guided wave SHM shows great potential for the long term inspection of large structures. It has been shown that the effects of environmental conditions can be managed to ensure good sensitivity. However inaccuracies and uncertainties in the placement of transducers cannot be managed in the same way. This paper addresses this by describing a technique whereby the properties of a structure and the network used to inspect it can be automatically calculated. This ensures maximum accuracy in terms of network properties but also allows the material properties to be estimated. This allows the effects of dispersion in a guided wave system to be compensated for allowing maximum imaging accuracy. The paper first outlines the algorithm that is applied then demonstrates its efficacy on simulation data before finally showing how it can be employed on a practical structure.

7984-25, Session 6a

Structural health monitoring as a real-time thermal verification tool

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Research at the space vehicles directorate is invested into reducing schedule times for assembly, integration, and testing and making the satellite more responsive to problems that may occur during pre-launch activities. Structural Health Monitoring has been pursued as a means for validating workmanship. Embedded ultrasonic piezoelectric wafer active sensors have been utilized with local and global inspection capabilities and have shown promise in detecting structural changes that may occur during a build and test cycle, specifically focused on interface qualification. It is now reasonable to believe that evaluations of interfaces through the use of these sensors can also be used to indirectly qualify the structure thermally, and that tedious thermal-vacuum test may be eliminated altogether. This paper will focus on the theoretical development of extracting thermal properties from ultrasonic transmission records. Methods are verified on simple bolted lap-joint cantilever beams. Experiments also involve vacuum chamber tests to see if the presence of atmosphere significantly impacts ultrasonic impedance of guided waves through a solid-solid interface in the same way it impacts thermal measurements due to radiation. If results show that guided wave measurements in atmosphere and in vacuum are relative, then it may be possible to infer the thermal characteristics of that joint.

7984-26, Session 6a

Phased annular array transducers for ultrasonic guided wave applications

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Mode and frequency control always plays an important role in ultrasonic guided wave applications. In this paper, theoretical understanding on guided wave excitation of axisymmetric sources on plate structures is established. It is shown that a wave number spectrum can be used to investigate the guided wave excitations of an axisymmetric source. The wave number spectrum is calculated from a Hankel transform of the axial source loading profile. On the basis of the theoretical understanding, phased annular array transducers are developed as a powerful tool for guided wave mode and frequency control. By applying appropriate time delays to phase the multiple elements of an annular array transducer, guided wave mode and frequency tuning can be achieved fully electronically. The phased annular array transducers have been successfully used for various applications. Example applications presented in this paper include guided wave tomography under water loading conditions, guided wave multi-mode interrogation for defect differentiation, and a novel ultrasonic vibration modal analysis technique for damage detection.

7984-27, Session 6a

Hybrid model prediction of guided wave array system detection sensitivity for the SHM of fatigue cracks in large structures

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Localized and distributed guided ultrasonic wave array systems allow for the efficient structural health monitoring of large structures, such as aircraft, ship hulls, or oil storage tanks. Permanently attached sensor arrays have been applied for the detection of corrosion and fatigue damage. A hybrid model has been developed for the efficient prediction

of the sensitivity of guided waves array systems to detect through thickness and part-through fatigue cracks at different locations in plate structures. Using a point transmitter and receiver model for the wave propagation along the structure, the distances between sensor elements and potential defect locations are taken into account. The influence of the orientation of the crack relative to the transducer elements has been predicted from localized 3D Finite Element simulations. The directivity pattern of the scattered guided wave field has been shown to depend on the defect orientation and on the ratio of the characteristic defect size and depth to wavelength, and has been verified from experimental measurements. Good agreement was found and the localized amplitude and directivity patterns provide the basis for the quantification of the detection sensitivity for fatigue cracks. Using the hybrid model, the relative amplitudes of received pulses for different sensor array layouts can be calculated. From a comparison with the signal to noise ratio of the array system, detection capabilities can be predicted for various defect sizes and orientation. This provides a rapid tool for the development and optimization of guided wave array SHM systems.

7984-28, Session 6a

A novel imaging technique for structural health monitoring using sparse and compact arrays

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In the present paper, a technique called "excitelet" is presented for the imaging of damages in thin-walled structures using the correlation of the measured signals with dispersed versions of the excitation signal (atoms). Piezoceramic (PZT) actuators are used to generate burst Lamb waves which interact with defects in metallic structures and the measurement is taken using sparse and compact array configurations of PZT sensors. The sparse sensing configuration consists of individual circular PZT elements distributed over the plate while the compact array configuration consists of a linear arrangement of sensors micro-machined on a single piece of bulk PZT wafer. This approach is presented as an extension of the classical imaging techniques and takes advantage of the chirplet-based matching pursuit algorithm. The approach is investigated experimentally on a 1.54 mm thick aluminum plate and comparison with existing Embedded Ultrasonic Structural Radar (EUSR) algorithm is performed for A0 and S0 modes for three frequency ranges of interest (centered at 150 kHz, 350 kHz and 550 kHz). Damages are simulated using stacked magnets at different locations on the plate. Significant improvement of imaging quality is demonstrated with respect to existing imaging techniques based on group velocity and Time-of-Flight (ToF), for both sparse and compact PZT array configurations. Moreover, it is shown that the imaging results remain accurate in the case of dispersive propagation, while existing imaging techniques are no longer applicable.

7984-29, Session 6b

a novel hyper-elastic thin film nitinol covered stent significantly decreases intra-aneurysmal flow in vitro

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A novel hyper-elastic thin film nitinol (HE-TFN) covered stent has been developed to promote aneurysm quiescence by diminishing flow across the aneurysm's neck. Laboratory aneurysm models were used to assess the flow changes produced by stents covered with different patterns of HE-TFN. Flow diversion stents were constructed by covering Wingspan stents (Boston Scientific, DxL:4x20mm) with HE-TFNs (i.e., 77 and 82% porosity). Stents were deployed in both in vitro wide-neck (i.e., sac:8.0/neck:5.5mm) and fusiform (i.e., sac:4.0mm) glass aneurysm models with a diameter of 4.0mm parent vessels. Fluid containing 11 μ m polystyrene

particles suspended in a glycerol and water (58.5:42.5) mixture was circulated through the models at a velocity of 0.5m/sec. Three particles were analyzed for each location in each model by high-speed microscope. In wide-neck aneurysms, the 82% porous HE-TFN stent reduced the mean flow velocity in the middle of the sac by 86.42 \pm 0.5%, while a 77% porous stent reduced the velocity by 93.44 \pm 4.99% (n=3). Other sac regions showed more than 97 \pm 4.81% reduction with both of the devices. Local wall shear rates were also significantly reduced by about 98% in this model after device placement. Tests conducted on the fusiform aneurysm revealed smaller intra-aneurysmal flow velocity reduction to 48.96 \pm 2.9% for 82% porous and to 59.2 \pm 6.9% for 77% porous stent, respectively. The wall shear was reduced by only a factor of two by HE-TFN stents in fusiform models. The results showed that HE-TFN covered stents significantly reduced intra-aneurysmal flow velocity magnitudes and local wall shear rates. This suggests that HE-TFN covered stents with both 77% and 82% porosity have great potential to promote thrombosis in both wide-necked and fusiform aneurysm sacs.

7984-30, Session 6b

Phononic crystal sensor and actuator for biomedical applications

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We propose a new phononic crystal sensor/actuator suite based on the recent discovery of highly nonlinear solitary waves, to offer a compact, inexpensive, and reliable diagnostic tool for biomedical applications. Phononic crystals composed of tightly packed elastic particles are assembled to form the proposed sensor/actuator device to generate and retain self-reinforcing and non-dispersive diagnostic solitary waves. Via contact with biological systems this device is capable of nondestructively quantifying the mechanical properties of biological systems based on the responsiveness of the diagnostic solitary waves. The pilot study using osteoporotic cadaver bone samples showed that a site-specific nondestructive evaluation (NDE) of mechanical properties of anisotropic and inhomogeneous bone are achievable, exploiting unique properties of highly nonlinear solitary waves propagating in the nonlinear phononic crystals. This is remarkable considering that none of the conventional techniques, such as radiography, computerized tomography, and ultrasonic scanning, offer comprehensive, directional evaluation of bone mechanical properties in a noninvasive and time-efficient manner. Extending the application to macroscopic biomedical structures, we also assessed the mechanical integrity of the biomechanical interfaces of an artificially implanted femoral stem. Preliminary studies are very promising, demonstrating that the proposed phononic crystal sensor/actuator successfully detected the development of fracture in the stem-cement interface of a composite cemented femoral stem model. This study suggests that the phononic crystal sensor/actuator might be utilized as a novel biomedical instrument for a nondestructive evaluation and a visualization of biological systems through enhanced resolution.

7984-31, Session 6b

Online monitoring of cartilage tissue in a novel bioreactor

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Standard techniques for the analysis of biological tissues like immunohistochemical staining are typically invasive and lead to mortification of cells. Non-invasive monitoring is an important element of regenerative medicine because implants and components of implants should be 100% quality-checked with non-invasive and therefore

also marker-free methods. We report about our new bioreactor for the production of collagen scaffolds seeded with Mesenchymal Stem Cells (MSCs). It implies computer controlled mechanical activation and ultrasonic online monitoring and has been constructed for the in situ determination of ultrasonic and rheological parameters.

During the cultivation period of about two weeks the scaffold is periodically compressed by two movable pistons for improved differentiation of the MSCs. Furthermore the periodic compression beneficially ensures the supply with nutrition even inside the sample. During the physiological stimuli, rheological properties are measured by means of highly sensitive load cells. In addition measurements of the speed of sound in the sample with frequencies up to 16 MHz and in the culture media are performed continuously. Therefore piezoceramic transducers are attached to the pistons and emit and detect ultrasonic waves, travelling through the pistons, the sample and the culture medium. The time-of-flight (TOF) of the ultrasonic signals is determined in real time with the aid of chirped excitation and correlation procedures with a resolution of at least 10 ps. The implemented ultrasonic measurement scheme allows beside the speed of sound measurements the detection of the distance between the pistons with a resolution better than 100 nm.

The monitoring delivers information on rigidity, fluid dynamics and velocity of sound in the sample and in the culture media. The hermetically sealed Bioreactor with its life support system provides a biocompatible environment for MSCs for long time cultivation.

7984-32, Session 6b

Elastic characterization of swine aorta by scanning acoustic microscopy at 30 MHz

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The mechanical properties of blood vessels walls are important determinants of physiology and pathology of the cardiovascular system. Acoustic imaging (B mode) is routinely used in a clinical setting to determine blood flow and wall distensibility. In this study scanning acoustic microscopy is used to determine spatially resolved tissue elastic properties. Broadband excitation of 30 MHz has been applied through scanning acoustic microscopy (SAM) for topographical imaging of swine aorta in reflection mode. Amplitude of the plane wave reflection coefficient by the multi-layered structure was modulated to take into account the effect of the change in defocusing distance. Topographical images are modeled by considering the multilayered reflector structure for soft tissue resting on impedance matching substrate. Through the Simplex inversion algorithm, optimized tissue properties such as longitudinal wave velocity, attenuation, density and thickness are predicted. Time resolved acoustic microscopy and Confocal Laser Scanning Microscopy are performed for accurate determination of thickness and first arrival time of flight to incorporate as feedback information in inversion optimization algorithm. The experimental and numerical algorithm provided a confident measure of elastic parameters of soft tissue.

7984-33, Session 6b

A footsize fiber optic plantar pressure/shear sensor

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Diabetes mellitus is a disease that impacts the lives of millions of Americans. Lower limb complications associated with diabetes, such as the development of plantar ulcers, can lead to infection and subsequent amputation. A full-scale foot pressure/shear sensor that has been developed to help diagnose the cause of ulcer formation in diabetic patients is presented. The design involves a tactile sensor array

using intersecting optical fibers embedded in soft elastomer. The basic configuration of the optical sensor systems incorporates a mesh that is comprised of two sets of parallel optical waveguide planes; the planes are configured so the parallel rows of waveguides of the top and bottom planes are perpendicular to each other. The planes are sandwiched together creating one sensing sheet. Two-dimensional information is determined by measuring the loss of light from each of the waveguide to map the overall pressure distribution. The shifting of the layers relative to each other allows determination of the shear stress in the plane of the sensor. The goal of the project is to demonstrate distributive pressure and shear measurement on a human foot. This paper presents latest development and improvement in the sensors design. In this report, fabrication and results from the tests will be described in detailed. Algorithm of two-layer neural network will be used to train the full-scale foot sensor to recognize three different heel shapes and five applied load magnitudes.

7984-34, Session 7a

Determination of the stress dependence of the velocity of Lamb waves in aluminum plates

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Mode selective excitation and detection together with chirped excitation and digital pulse compression is employed to study the variation of the time-of-flight (TOF) of Lamb waves. The stress coefficients for the variation of TOF depend not only on the actual modes but also on the actual frequency or center frequency of the observed propagating wave. The modes are selected from dispersion relations obtained by appropriate modeling. To allow for a continuous variation of the load a specially designed apparatus based on hydraulic principles has been designed, minimizing the disturbing influence of static and dynamic friction. The experimental results are demonstrated and discussed. The results concerning the observation of positive and negative coefficients and dependencies of the coefficient on load are discussed with expectations derived from modeling.

7984-35, Session 7a

Multi-component mode coefficients for damage estimation using Lamb wave polarization from 1D laser vibrometry

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Polarization defines the phase and amplitude relationships between the various components of wave motion, and is significant in many technological applications based on wave propagation, such as optics, seismology, telecommunications and radar science. As opposed to other fields, wave polarization in mechanics has received relatively little attention, due to the general difficulty in evaluating the phenomena experimentally. However, the ability to measure and characterize the polarization of ultrasonic waves could lead to the development of novel diagnostic tools, which could rely on the sensitivity of polarization to surface roughness, cracks, temperature or residual stresses, among others.

This paper initially presents the elliptical estimation of the Lamb wave particle motion using a 1D Laser Vibrometer. The approach is validated by comparing experimental results with analytically derived 3D-elasticity Lamb wave solutions. Specifically, an analytical formulation of Lamb waves generated by a circular piezoelectric disc is used, along with descriptions of bi-modal and single mode polarization characteristics. Implementing a frequency-wavenumber filtering technique, the proposed method is demonstrated for a single point location and then shown for

multiple points along a radial distance from the source. Subsequently, this multi-component extraction technique enables the evaluation of multi-component mode coefficients in damage estimation. Spatially integrated multiple component mode coefficients are formulated with the intent to better characterize wave reflections and conversions and to increase the signal to noise ratios. Numerical and experimental parametric studies are conducted, and the current strengths and weaknesses of the proposed approaches are discussed.

7984-36, Session 7a

High-resolution damage imaging in flat and bent plate-like structures through warped-basis pursuit

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Critical challenges related to Guided Wave inspection for Structural Health Monitoring include the size and proximity of damages that can be individually resolved as well as accessibility of the areas to be monitored. Effective damage imaging has been recently demonstrated through a Warped-Basis Pursuit (W-BP) approach that provides dispersion removal and high localization accuracy. Theoretical limits to the pixel size of images provided by this technique have been derived, highlighting the potentials for super-resolution. In this work, resolution capabilities of the W-BP are assessed in challenging situations. This is done by processing the wavefield recorded by a Scanning Laser Doppler Vibrometer outside of the damaged area of an aluminum plate. The considered damage consists in a series of holes of various dimensions and spacing. Potentials and limitations of W-BP are analyzed, along with its application for the inspection of remote/inaccessible areas in complex waveguides. Specifically, the case of an L-bent plate is considered. The ability of W-BP to handle multimodal propagation and to isolate individual modes is exploited to separate relevant damage-induced scattering from reflections due to the bend and to study mode conversion associated to the structural feature.

7984-37, Session 7a

High-resolution imaging of acoustic waves in piezoelectric materials

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In acoustics, visualization of individual acoustic wave fronts on the surface of piezoelectric material is one of the challenges of current scientific era; the propagation velocity of surface acoustic waves is five orders of magnitude smaller than those of radio waves of the same frequency. At the same time, the amplitude of these waves decays more slowly with distance than the acoustic bulk waves. Due to these characteristics, generation and detection of surface acoustic waves in piezoelectric materials has attracted widespread scientific interest from the late 1960's for high-frequency signal processing and filtering applications. For this purpose a 3 staged amplification circuitry which is suitable to detect and amplify signals with low noise response is developed with a fixed gain. At the first stage an IC (INAA16) is used with a gain of 9, 9. This IC has the advantages of having high input impedance up to 1012 Ω and low noise response level of about 50 $\mu\text{V Hz}^{-1}$ at 10 KHz and 15 μVHz^{-1} at 100Kz. Second and third stages amplifiers each with a gain of ten are used and in result the 3 stage amplifier gives an amplification factor of 990 times. Samples with thicknesses of 0.5 mm to 5mm are scanned in the x and y axis with scanning steps of 50 μm , 100 μm , and 200 μm . The principles of the developed method together with instrumental details are discussed.

7984-38, Session 7a

Investigating mode-converted Lamb wave signals induced by a notch on a beam in the frequency domain

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A pair of identical piezoelectric (PZT) wafers collocated on a beam enable extraction of individual Lamb wave mode signals due to their polarization characteristics. Among these extracted Lamb wave mode signals, mode-converted ones proved to be promising for reference-free crack detection in a beam. This paper investigates the mode-converted Lamb wave signals induced by a notch on the beam in the frequency domain. First, time-domain FE analysis for a notched beam with a pair of collocated PZT wafers is conducted to obtain the mode-converted Lamb wave signals. The time period for the numerical analysis is set to be sufficiently long so that the beam can be excited steady-state. Then, a series of temporal windows are used to truncate the mode-converted Lamb wave signals with different time periods. Through the FFT of the truncated mode-converted Lamb wave signals, the convergence of the FFT data is demonstrated. At first, the FFT data is governed by the dominant frequency components of input excitation signal and arrival time lags due to initial wave reflections. As the size of temporal window increases, the FFT data converge to the frequency response function of the beam at the locations of the PZT wafers. The amount of mode conversion energy is computed with respect to the size of temporal window for different depths and locations of a notch. Finally, the optimal size of temporal window for reference-free crack detection is discussed in the context of the modal characteristics of the beam.

7984-39, Session 7a

Metamorphosis of bulk waves to Lamb waves in anisotropic piezoelectric crystals

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Acoustic bulk waves were excited by Coulomb coupling in an anisotropic piezo-electric crystal Lithium Niobate. A narrow pulse with a width of 25 ns was used for excitation to obtain a wide frequency content in the Fourier domain. A wide spectrum ensures metamorphosis of bulk waves into Lamb waves for scan lengths comparable to the involved wavelengths. The low frequency content experiences multiple reflections from the thickness and disperses along propagation. Acoustic bulk wave's evolution and transformation to Lamb waves are illustrated and explained with the aid of the universal Lamb wave dispersion phenomenon. The holographic images in the Fourier domain exemplify the metamorphosis of waves during propagation following the excitation at an approximate point source.

7984-40, Session 7a

Acoustic emission source localization in anisotropic structures with diffuse field conditions using a time reversal approach

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Localization of acoustic emission sources is traditionally based on triangulation techniques associated to a network of passive transducers. Usually, these methods employ the time of arrival (TOA) estimation of the ballistic wave measured by multiple receiving points, i.e. the coherent part of the transmitted field that arrives first to the sensors. Although most of these systems have proved to be effective for both isotropic and anisotropic materials [1-6], the dispersive nature of Lamb waves

and the presence of scatterers (rivets, holes, voids and stiffeners etc...) alter the resulting waveform, causing poor localization. In other words, the wavefield of complex structures due to a mix of multiple scattering, reflections and mode conversion is incoherent diffuse [7-9].

This research work presents an in-situ imaging method for the localization of the impact point in complex anisotropic structures with diffuse field conditions, using only one passive transducer. The proposed technique is based on the time reversal approach applied to a number of waveforms containing the experimental Green's function of the medium [10-12]. The present method exploits the benefits of multiple scattering, mode conversion and boundaries reflections to achieve the focusing of the source with high resolution. The optimal re-focusing of the back propagated wave field at the impact point is accomplished through a "virtual" imaging process, which does not require any iterative algorithms and a priori knowledge of the mechanical properties of the structure.

The robustness of the time reversal method is experimentally demonstrated on a stiffened composite panel (Fig.1) and the source position can be retrieved with a high level of accuracy in any position of the structure (Fig. 2). Its very simple configuration and minimal processing requirements and computational time (less than 1 sec) make this method a valid alternative to the conventional imaging Structural Health Monitoring systems for the acoustic emission source localization.

7984-41, Session 7b

Study of thinly sectioned melanoma skin tissues with mechanical scanning acoustic reflection microscopy

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The contents of the present report are focused on characterizing a thinly sectioned skin tissue with a mechanical scanning acoustic reflection microscope (tone-burst-wave mode). The report is organized into two parts: the first is an analysis of optical and acoustical images, the second describes the quantitative data acquisition technique with $V(z)$ analysis. For the section on image analyses, we optically and acoustically visualized the same portion of the tissue with operating frequencies ranging from 200MHz to 1GHz for image comparison. The image analyses were complemented by transmission electron microscopy. The results are promising for potential in-situ observation (surface and/or subsurface) of fresh thick-sections of tissue for quick medical diagnosis. For the section on quantitative data acquisition, the tissue was first imaged with an acoustic lens attached to a shear polarized transducer to confirm that the tissue was elastically isotropic. Second, a reflectance function for the tissue located on a substrate was theoretically determined, and fitted into the mathematical model of the $V(z)$ curve. The $V(z)$ curves with frequency at 200 MHz for thinly sectioned normal and abnormal tissues located on soda-lime glasses were theoretically and experimentally formed. Finally, a computer simulation with a parameter-fitting technique (i.e., matching the distances of the periods of the theoretical and experimental $V(z)$ curves by inputting different longitudinal wave velocities and densities of the tissue) was implemented to obtain the longitudinal wave velocities and densities of the tissues. The obtained longitudinal wave velocity may be used to simulate contrast analysis.

7984-42, Session 7b

K edge x-ray imaging

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It is known that high X-ray dose irradiation increases the probability of cancer development in humans. Therefore, to decrease the dose at every X-ray imaging instance is a major goal, especially at CT tests, where the applied dose is generally multiplies of a single radiographic imaging dose.

Using narrow energy X-ray beams instead of wide energy X-rays has several advantages. First, it reduces the beam hardening effect, when the output beam (after the patient) is harder, i.e. it consists of a higher ratio of high energy X-ray photons than did the input beam. Imaging with narrow energy X-rays also provides lower scatter noise than using wide energy X-rays. As a result we can obtain high signal to noise (S/N) ratio X-ray images while using much lower dose than with a regular x-ray beam.

The paper points out how we can generate narrow energy X-ray beams by using special materials for which the K edge absorption peak falls into the diagnostic X-ray energy range. Furthermore, it will be shown that contrast agent materials such as Iodine are more effective when combined with the right K edge filter material.

7984-43, Session 7b

Synchronous monitoring of muscle dynamics and electromyogram

M. Zakir Hossain, W. Grill, Univ. Leipzig (Germany)

Non-intrusive novel detection scheme has been implemented to detect the lateral muscle extension of skeletal muscle and the motor action potential (EMG) synchronously. This allows comparative study between muscle dynamics and EMG signal as a basis for modeling and further study to determine which architectural parameters are most sensitive to changes in muscle activity. Transmission time for ultrasonic chirp signal from 100 kHz to 2.5 MHz through muscle and motor action potentials are recorded synchronously to monitor and quantify biomechanical parameters related to muscle performance. Ultrasonic transducers are placed on opposite position of the monitored gastrocnemius muscle. Surface electrodes are used to pick up the potential difference from the site of the monitored muscle. Maximum voluntary isometric contraction (MVC) of the monitored muscle is ensured by restricting the flexion of the knee joint. Synchronous monitoring was initiated by the audio beep triggered by the implemented software at zero time of the data acquisition. Computer controlled electronics are used to generate and detect the ultrasonic and EMG signals. Custom developed software and data analysis is employed to analyze and quantify the monitored data. Reaction time, nerve conduction speed, latent period between on-set of EMG and muscle movement, degree of muscle activation and muscle fatigue development, rate of energy expenditure and motor neuron recruitment rate in isometric contraction, and other relevant parameters relating to muscle performance have been quantified with high spatial and temporal resolution.

7984-44, Session 7b

Adaptive sensor fusion algorithm for helmet structural health monitoring

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The adaptive neural network is a standard technique used in nonlinear system estimation and learning applications for dynamic models. In this paper, we introduced an adaptive sensor fusion algorithm for a helmet structure health monitoring system. The helmet structure health monitoring system is used to study the effects of ballistic/blast events on the helmet and human skull. Installed inside the helmet system, there is an optical fiber sensor array which consists with strain and pressure sensors. After implementing the adaptive data fusion algorithm into helmet system, a dynamic model for the sensor array has been developed. The dynamic response characteristics of the sensor network are estimated from the pressure and strain data by applying an adaptive control algorithm using artificial neural network. With the estimated parameters and position data from the dynamic model, the strain & pressure distribution of the whole helmet can be calculated. The distribution pattern inside the helmet will be very helpful for improving helmet design to provide better protection to soldiers from head injuries. Simulation results are provided in the end of the paper.

7984-45, Session 7b

Determination of the mechanical properties of fixed red blood cells by phase-sensitive-acoustic microscopy

A. M. T. Esam, A. Kamanyi, W. Grill, Univ. Leipzig (Germany)

Based on the magnitude and phase obtained by scanning acoustic microscopy the attenuation, the density and the velocity of ultrasonic waves can be determined. The evaluation is based on a polar plot representation. The results of modeling are fitted to these data. This method has earlier been used for wax and chitosan samples. A resolution for the mechanical properties down to below 1 % can be achieved. The developed method is applied here to characterize red blood cells (RBCs) smeared and fixated on glass substrates. The velocity and the attenuation of longitudinal acoustic waves in the cells as well as the density of individual cells were determined with high resolution. These parameters were then used to derive the elastic modulus and viscosity of the individual cells. The method is presented and the results for the biomedical application are discussed.

7984-46, Session 7b

A reliable wireless monitoring network for healthcare applications

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In the last decade, the performance of healthcare monitoring networks is enhanced by improving their abilities to accurately measure, record, and analyze data. On the other hand, healthcare monitoring network problems became more complicated due to the increasing number of people who need the network services. This makes the development of a reliable and low cost healthcare monitoring network a must. The fast progress in wireless communication makes the implementation of efficient remote healthcare monitoring network easier. The aim of the present work is to design and implement a reliable wireless healthcare monitoring network to meet all capital projects needs.

The main features of our suggested wireless monitoring network are, the ability to monitor any environmental physical quantity, the usage efficient programming environment to allow all features of monitoring, controlling, and data processing to be implemented, the ability to extend the number of monitored patients, the ability to transfer data from sensor circuits to local monitoring unit over wireless channels, and in addition to all of the above features the system components are designed to achieve the minimum costs without sacrificing accuracy operation. It has to be mentioned that the zero cost infra structure of the wireless network allows the use of our suggested monitoring network for all capital projects with minimum costs and the flexibility of the system ensures the upgrading of the system to adapt any additional users' requirements.

7984-47, Session 7b

Point measurement of water concentration using millimeter wave illumination

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No abstract available

7984-106, Poster Session

A no-calorimetric method for measuring SAR in MRI

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During an MRI procedure, the patient absorbs a portion of the transmitted RF energy, which may result in tissue heating and other adverse effects, such as alterations in visual, auditory and neural functions.

The Specific Absorption Rate (SAR), in W/kg, is the RF power absorbed per unit mass of tissue and is one of the most important parameters related with thermal effects and acts as a guideline for MRI safety. In fact, strict limits to the SAR levels are imposed by patient safety international regulations (CEI - EN60601 - 2 - 33) and SAR measurements are required in order to verify its respect. SAR value depends on different factors, such as the induced electric field, the pulse duty cycle, the tissue density, permittivity and conductivity. SAR estimation in Magnetic Resonance scanners can be conducted both numerically and experimentally. In the former case, SAR is estimated theoretically by numerical solution of the Maxwell equations and the induced field determination based on field source and human body models. In the last case, the induced field by real source is estimated directly in experimental phantoms having dielectric properties similar to the human body. In the experimental approach, the used sensors can be either electric field sensors or temperature sensors. Present used approaches and methods have some important limits: the numerical approach is not easy to use in modeling field sources, above all with the most recent used pulse sequences. The possibility of measuring the absorbed power, as a difference between the pulse power produced by the scanner and the reflected power, requires the use of electronic instruments that should be connected to the scanner coils. That operation would require the presence and collaboration of the scanner producer technicians and in this manner the method is not so easily feasible as well as not much sensitive. In the experimental approach, the most promising techniques are those relative to temperature sensors, because they refer directly to dielectric, conductivity and thermal properties of the human body. Simpler are the calorimetric methods, also if in this case long acquisition times are required in order to have significant temperature variations and accurate heat capacity knowledge. In this method, it is necessary to reduce thermal losses by a totally adiabatic phantom. Furthermore, long measurement times (1 hour and a 1W/kg SAR is required to have a temperature increase of 0.86°C) and compatible magnetic field thermometer are required. In this approach, however, a perfect adiabatic phantom and accurate heat capacity knowledge are required. The phase transition method, here proposed, is a new method to measure mean SAR in MRI which has the advantages to be very simple and to overcome all the typical calorimetric method problems. In fact, it does not require any in gantry temperature measurement and any specific heat or heat capacity knowledge, but only simple mass and time measurements. For its simplicity, it can be used in order to verify the respect of SAR limits without the presence and collaboration of any scanner producer technicians and without long operational stops.

7984-107, Poster Session

MATCAKE: a flexible toolbox for 2D NMR spectra integration by CAKE algorithm

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MatCAKE (cake.unisa.it) is a toolbox for integrating 2D NMR spectra by the CAKE (Monte Carlo peak volume Estimation) [1] algorithm within the Matlab environment (www.mathworks.com). Quantitative information from multidimensional NMR experiments can be obtained by peak volume integration. The standard procedure (selection of a region around the chosen peak and addition of all values) is often biased by poor peak definition because of peak overlap. CAKE is a simple algorithm designed for volume integration of overlapping peaks. Methods Assuming the axial

symmetry of two-dimensional NMR peaks, as it occurs in NOESY and TOCSY when Lorentz-Gauss transformation of the signals is carried out, CAKE estimates the peak volume by multiplying a fractional peak volume by an R factor, which is a proportionality ratio between the total and the fractional peak volume, both evaluated with Monte Carlo techniques. Results and Conclusions Integration of simulated and experimental 2D in-phase peaks with different degree of overlap shows that CAKE works well even for strongly overlapping peaks. The main advantage of CAKE is its simplicity as difficulties in its use are comparable to those presented by methods that sum all data points in a defined area. In fact, the user only has to select a peak slice not overlapping with other peaks therefore avoiding the guess of the total contour shape of the peak. Furthermore, CAKE does not require any time-consuming fitting of the peaks to functional forms, and therefore it can be easily incorporated as a subroutine in any NMR processing software. Tests on tripeptides have shown that CAKE is a powerful method for volume integration. The substantial independence of CAKE on digital resolution and SNR warrants that it can be safely used for peak integration in three-dimensional spectra. Because of its inherent simplicity the software can be extended to automated integration of three- and possibly higher-dimensionality NMR spectra.

7984-108, Poster Session

Intelligent monitoring of seismic damage identification using wireless smart sensors: design and validation

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Structural health monitoring (SHM) has been adopted as a technique to monitor the structure performance to detect damage in aging infrastructure. The ultimate goals of implementing an SHM system are to improve infrastructure maintenance, increase public safety, and minimize the economic impact of an extreme loading event by streamlining repair and retrofit measures.

With the recent advances in wireless communication technology, wireless SHM systems have emerged as a promising alternative solution for rapid, accurate and low-cost structural monitoring.

Networks of wireless smart sensors are being used to measure static and dynamic strain in structures and structural models to monitor structural health and predict damage incurred from a seismic event. These sensors are being used to experimentally verify analytical models of post-earthquake evaluation based on system identification analysis. Deformation measurement system could play a significant role in monitoring/recording with a higher level of completeness the actual seismic response of structures and in non-destructive seismic damage assessment techniques based on dynamic signature analysis.

This article presents an enabling, developing algorithms to advance the detection and diagnosis of damage to structures and open-source framework for SHM using networks of wireless smart sensors. The framework is based on a service-oriented architecture that is modular, reusable, and extensible, thus allowing engineers to more readily realize the potential of smart sensing technology. To demonstrate the efficacy of the proposed framework, an example SHM application is provided

7984-109, Poster Session

Reflective measurement of water concentration using millimeter wave illumination

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THz and millimeter wave technology have shown the potential to become a valuable medical imaging tool because of its sensitivity to water and safe, non-ionizing photon energy. Using the high dielectric

constant of water in these frequency bands, reflection-mode THz sensing systems can be employed to measure water content in a target with high sensitivity. This phenomenology may lead to the development of clinical systems to measure the hydration state of biological targets. Such measurements may be useful in fast and convenient diagnosis of conditions whose symptoms can be characterized by changes in water concentration such as skin burns, dehydration, or chemical exposure. To explore millimeter wave sensitivity to hydration, a reflectometry system is constructed to make water concentration measurements at 100 GHz, and the minimum detectable water concentration difference is measured. This system employs a 100 GHz Gunn diode source and Golay cell detector to perform point reflectivity measurements of a wetted polypropylene towel as it dries on a mass balance. A noise limited, minimum detectable concentration difference of less than 0.5% by mass can be detected in water concentrations ranging from 70% to 80%. This sensitivity is sufficient to detect hydration changes caused by many diseases and pathologies and may be useful in the future as a diagnostic tool for the assessment of burns and other surface pathologies.

7984-111, Poster Session

Nonstationary thermal wave imaging techniques for nondestructive testing

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Thermal wave imaging is one of the widely used nondestructive testing and evaluation (NDT&E) method for detecting subsurface defects in most of the solids. Presently, three different active thermographic techniques are widely in use: Pulsed Thermography (PT), Lock in Thermography (LT) and Pulse Phased Thermography (PPT). In PT, the test material is warmed (or cooled) by a short duration high peak power heat source and measurement of the temporal evolution of the surface temperature is recorded with an infrared (IR) camera. The surface temperature gradients over the sample help to identify and localized sub surface defects in the test specimen. However the surface temperature gradients are not only because of subsurface features but also affected by local surface emissivity variations over the material. LT uses periodic sinusoidal thermal excitation in order to derive information of reflected thermal wave phase at considerably low peak powers. The phase angle has the advantage of being less sensitive to local variations of surface emissivity. Because of its single frequency excitation for a given experiment, the depth resolution of the experiment in a run gets fixed (i.e. fixed 'thermal wavelength'). To detect defects located at various depths in the test sample, repetition of the test at various frequencies becomes a time consuming process. The experimental arrangement for PPT is similar to that of pulse thermography, but the fundamental idea of post processing is different. To overcome some of these limitations of conventional thermographic techniques (resolution and peak power), present work focuses on modeling and simulations of recently proposed non-stationary thermal excitation technique named as frequency modulated thermal wave imaging for non destructive testing. This present paper highlights advantages and limitations of the proposed method by comparing with the conventional widely used thermographic methods.

7984-112, Poster Session

Research progress of microbial corrosion of reinforced concrete structure

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Microbial corrosion of reinforced concrete structure is a new branch of learning. This branch deals with civil engineering, environment engineering, biology, chemistry, materials science and so on and is a interdisciplinary area. Research progress of the causes, research methods and contents of microbial corrosion of reinforced concrete

structure is described. The research in the field is just beginning and concerted effort is needed to go further into the mechanism of reinforce concrete structure and assess the security and natural life of reinforce concrete structure under the special condition and put forward the protective methods.

7984-113, Poster Session

Microorganism index, physical, and chemical property of silt around pier in the typical area of yellow river

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The microorganism index, physical and chemical property such as the pH value, water content, conductivity and main ion content of silt around pier in the typical area of yellow river are determined. These get ready to research the microorganism corrosion of pier in the silt of the typical area of yellow river and have very important theoretical significance and realistic meaning for researching systematically the microorganism corrosion of pier in the silt of the typical area of yellow river.

7984-48, Session 8

Validation of the piezoelectric rosette technique for locating impacts in complex aerospace panels

S. Salamone, Univ. at Buffalo (United States); I. Bartoli, Drexel Univ. (United States); J. Rhymer, F. Lanza di Scalea, H. Kim, Univ. of California, San Diego (United States)

The authors have previously proposed the technique of Piezoelectric Rosettes for locating impacts in complex aerospace structures where conventional Acoustic Emission source location (Time-Of-Flight triangulation) is challenging. The Piezoelectric Rosette technique does not require knowledge of the material's properties (i.e. the wave velocities), and it is hence attractive for anisotropic, multilayered, or tapered structures where the wave velocity can change with both wave propagation direction and wave propagation distance. Each rosette is comprised of three unidirectional Macro-Fiber Composite (MFC) sensors.

This paper extends the study in two fronts. On the modeling front, the rosette reduction algorithm takes now into account the more realistic circularly-crested (flexural) guided waves generated by the point impact. On the experimental front, an extensive testing program was conducted to validate the technique in close-to-realistic structures. The experimental testing involved the following six specimens: an aluminum panel, a quasi-isotropic CFRP composite panel, a highly anisotropic CFRP composite panel, a stiffened aluminum panel, a stiffened quasi-isotropic CFRP composite panel, and a stiffened anisotropic CFRP composite panel. These panels were subjected to low-velocity hammer impacts and to high-velocity gas-gun impacts by ice projectiles at speeds up to 170 m/sec using UCSD's gas-gun test facility. In all these cases, the Piezoelectric Rosette technique showed good performance in locating the impacts despite the structural complexities of the panels and with no failure of the MFC sensors.

7984-49, Session 8

Impact force identification in aerospace panels by an inverse ultrasonic guided wave problem

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This paper deals with monitoring impacts on aluminum and composite aerospace panels. The specific problems addressed are (1) the

identification of the impact forces (force magnitude time history) and (2) the discrimination of "damaging impacts" from "non-damaging impacts." Ultrasonic guided waves generated by the impacts are used as the sensing mechanism. Flexible Macro-Fiber Composite (MFC) patches are used as the ultrasonic receivers.

The impact force identification method is based on an optimization routine which minimizes the difference between the experimental impact waves and the numerical impact waves calculated by a Semi-Analytical Finite Element (SAFE) forced analysis. The differentiation of "damaging impacts" vs. "non-damaging impacts" is based on a frequency analysis of the impact waves.

These techniques are demonstrated through an extensive experimental testing program involving the following six specimens: an aluminum panel, a quasi-isotropic CFRP composite panel, a highly anisotropic CFRP composite panel, a stiffened aluminum panel, a stiffened quasi-isotropic CFRP composite panel, and a stiffened anisotropic CFRP composite panel. These panels were subjected to low-velocity hammer impacts and to high-velocity gas-gun impacts by ice projectiles at speeds up to 170 m/sec using UCSD's gas-gun test facility. In all of these experiments, the techniques summarized above gave excellent results for both impact force identification and impact force discrimination.

7984-50, Session 8

Impact localization in an aircraft fuselage using laser based time reversal

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This study presents a new impact localization technique that can pinpoint the location of an impact event within a complex aircraft fuselage using a time reversal concept and a Laser Doppler Vibrometer (LDV). First, an impulse response function between an impact location and a sensing piezoelectric transducer is approximated by exciting the sensing piezoelectric transducer instead and measuring the response at the impact location using a LDV. Then, training impulse response functions are assembled by repeating this process for various potential impact locations and sensing piezoelectric transducers. Once an actual impact event occurs, the impact response is recorded and compared with the training impulse functions. The correlations between the impact response and the impulse response functions in the training data are computed using a unique concept of time reversal

7984-51, Session 9

Turbine engine disk health monitoring assessment using spin test data

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Detecting rotating engine components malfunctions and structural anomalies is increasingly becoming a crucial key feature that will help boost safety and lower maintenance cost. However, achievement of such technology which can be referred to as a health monitoring attribute remains somewhat challenging to implement. This is mostly due to the fact that presence of scattered loading conditions, crack sizes, component geometry and material property hinders the simplicity of imposing such application. Though, currently other approaches are being considered through usage of other means of health monitoring or nondestructive techniques to pre-detect hidden flaws and mini cracks before any catastrophic event occurs. These methods extend more to assess materials' discontinuities and other defects that have matured to the level where a failure is very likely.

This paper is geared towards presenting experimental data obtained from spin tests experiments of a turbine engine like rotor disk and their correlation to the development of a structural health monitoring and fault

detection system. The data collected include blade tip clearance, tip timing measurements and shaft displacements. The experimental results are collected at a range of rotational speeds and the tests are conducted at the NASA Glenn Research Center's Rotordynamics Laboratory, a high precision spin rig. Measurements and data observations obtained from the experimental tests are evaluated and examined to explore their relevance towards the development of a crack detection system and a supplemental physics based fault prediction analytical model.

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7984-52, Session 9

Vibration characteristics of shear loaded postbuckled aluminum panels

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Structural Health Monitoring (SHM) can be used to detect a variety of failure modes in both homogeneous and composite materials used for critical components in civil infrastructure, aerospace assemblies, and turbines for power generation. Buckling is one of the key failure modes, by which in plane loads produce out of plane displacements. The onset of buckling however does not necessarily imply failure of the structure. Further understanding of the behavior of postbuckled structures will reveal indicators of impending failures as well as allow designers to reclaim the region where a structure has buckled, but retains the ability to elastically recover.

In this research, an aluminum plate was subject to shear loading that resulted in buckling. The out of plane static displacements caused by this buckling were measured for a variety of loads within the elastic region of the postbuckled state. At each of these load levels vibration characteristics were measured using a laser vibrometer. These experimental results were correlated with numerical results. Interesting features in the postbuckled states such as snap through points and the corresponding indicators in terms of mode shapes and frequencies are examined in detail.

7984-53, Session 9

Vibration-based detection of fatigue cracks in structures

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This paper presents the application of a novel vibration based technique for detecting fatigue cracks in structures. The method utilizes the empirical mode decomposition method (EMD) to establish an effective energy-based damage index. To investigate the feasibility of the method, fatigue cracks of different sizes were introduced in an aluminum beam subjected to a cyclic load under three point bending configuration. The vibration signals corresponding to the healthy and the damaged states of the beam were acquired via piezoceramic sensors. The signals were then processed by the proposed methodology to obtain the damage indices. In addition, for the sake of comparison, the natural frequencies of the healthy and damaged states of the beam were obtained through

the Fast Fourier Transform (FFT). The results of this study concluded in two major observations. Firstly, the method was highly successful in not only predicting the presence of the fatigue crack, but also in quantifying its progression. Secondly, the proposed energy-based damage index was proved to be superior to the frequency-based method in terms of sensitivity to the damage detection and quantification. Moreover, this technique could be regarded as an efficient non-destructive tool, since it is simple, cost effective, and does not rely on analytical modelling of the structure.

7984-54, Session 9

Structural health monitoring by high-frequency vibration measurement with non-contact laser excitation

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In traditional vibration testing methods, the excitation force is generally applied using an impulse hammer or a vibration exciter; in particular, the impact testing using an impulse hammer is used widely for vibration testing due to the simplicity of the apparatus. However, the impact testing relies significantly on the skill and experience of the experimenter; additionally, it does not allow application of an ideal impulse excitation, limiting its use to measurements of low- and mid-frequency regions of under several kilohertz.

In this paper, a vibration testing method based on non-contact impulse excitation using laser ablation is developed in order to apply excitation force in the high frequency region to structures. This method realizes the ideal impulse excitation force by instantly causing laser ablation by pulse-irradiating a metal surface with a high power YAG laser with its pulse duration of 5 ns. A health monitoring system is constructed by this vibration testing system and damage detecting algorithm. A microscopic damage of structures can be extracted by detecting fluctuations of high frequency vibration response with this health monitoring system. In this study, loosening of bolt tightening torques is defined as the damage of the system and the vibration responses in some damage conditions are measured by the laser excitation system. These responses have some dispersion due to the error of the tightening torque in each condition, and so these data are statistically analyzed for detecting the damage condition with Recognition-Taguchi method. It is verified by experiment that the damage conditions are exactly identified by the proposed approach.

7984-55, Session 10a

Energy harvesting in electroactive materials: a comparison between ferroelectrics and electrostrictive polymers

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Extending the number of functions and to improving their reliability of portable equipments is a current issue. Considering the recent progresses in ultralow-power electronics, powering complex systems on ambient energy is not chimerical anymore

This paper addresses the problem of the mechanical to electrical energy conversion in the electroactive materials (ferroelectrics and electrostrictive polymers) and underlines the similarities and differences between these two classes of materials in terms of energy conversion. These materials exhibit different conversion abilities and mechanical properties. The lightweight, flexible, conformable polymer properties are definitively a strong advantage for practical application like energy harvesters.

The proposed energy conversion improvement is an extension, to polymer materials, of the so-called "SSHI" technique previously

developed for ferroelectric materials. This non-linear voltage processing basically consists in switching the voltage, for a short period, when the voltage reaches a maximum or a minimum, resulting in a large enhancement of the conversion as much as 1000% increase of the harvesting capability.

Unlike ferroelectrics based energy harvesters, polymer harvesters require a bias electrical field to convert mechanical to electrical energy that forbids a direct extension of the SSHI technique. The needed adaptations will be discussed as well as the different trade-offs between the mechanical and electrical characteristics that the system must meet to maximize the converted energy.

Increasing the polymer capacitance to enhance the conversion has been done by introducing nano-conductive particles in the polymer matrix. The paper will present and discuss experimental and theoretical data.

7984-56, Session 10a

Thickness effects in electroactive polymers actuators: a simple explanation and modeling

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For practical use, the electrical field requirements of Electro Active Polymer (EAP) actuators have to be lowered down significantly. Recently, we developed nano carbon filled polymeric material which can generate a large strain (30-50%) at moderate electrical field (less than 20 MV/m). We found that the electrostrictive strain saturates versus electrical field and that the maximum strain value depends strongly on the sample thickness. Between 20 to 200 μm , the thinner specimen generates strain level four times higher than the thicker one. Combining polarization saturation effect and heterogeneities in the polymer thickness lead to a model that describes correctly the strain behavior versus electrical field, polymer thickness and frequency. A three-layer model was established which assumes that the polymer is not homogeneous along the thickness but presents some skin effect. It consists, so, two outer layers and one inner layer, which must be formed during the polymer curing. It is considered that the skin layers have "slightly" different characteristics, such as permittivity and Young's modulus, compared to the "bulk" layer. When the electrical field is input parallel to the polymer thickness, a different strain would take place in each layer according to the field distribution in each layer. Since the layers are "attached" together and considering only an in-plane motion, the strain must be the same in each layer. Consequently stresses appear in the different layers. Introducing in this model a saturation of the polarization for high field value leads to simulation results that fit well the experimental data.

7984-57, Session 10a

An improved control algorithm for an optical feedback reference tracking diamagnetically levitating motor system

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The presented paper describes a low friction, low maintenance power delivering motor using a diamagnetically stabilized levitating rotor. This application can be scaled to micro scale for MEMS applications for delivering mechanical power to micro actuators and sensors. The planar rotor described in this paper uses a triangular configuration of magnets that rotates due to nine electric coils evenly spaced around the rotor. The principle behind levitation of the rotor and the dynamic forces on it are described in detail. An optical encoder feedback system is designed and fabricated that controls the frequency of the levitating rotor. An improved control algorithm and a faster actuator system result in faster time response and stable control of the motion of the rotor at desired reference frequencies. Experimental data suggests that the optical encoder feedback control system can do reference tracking on the levitating rotor. The designed control algorithm can drive the rotor to specified reference frequencies up to 1.3 Hz using the optical encoder

measurements.

7984-58, Session 10a

Focused GHz ultrasound as a tool for micro-displacement and cell manipulation

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Ultrasound causes acoustic streaming in fluids and radiation forces which act on insonified matter. These effects can aggregate particles, remotely move atomic force microscope (AFM) cantilevers, and deform biological cells. A recently developed combined optical and acoustic microscope was modified and used in experiments demonstrating these phenomena on a small scale. The combined microscope includes a confocal laser scanning microscope (CLSM) and a phase-sensitive scanning acoustic microscope positioned on opposite sides of the sample with the acoustic lens coaxially aligned with the optical objective. The acoustic lens is used to emit the focused ultrasound beam with frequencies up to 1.2 GHz and the movement of fluorescent particles with 0.175 μm diameter due to streaming is monitored optically with the CLSM. This set-up is also used to monitor the deformation of red blood cells. In a new operation mode the acoustic microscope combines actor and sensor functions. The average acoustic intensity is modulated by ultrasound pulses which are additionally introduced in the pulse-echo sequence. We demonstrate that AFM cantilevers can be displaced by the modulation of the average acoustic intensity and we use the acoustic phase contrast to track this displacement with high resolution.

7984-59, Session 10a

Development of a prototype self-configuring building block

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In the nineteen-sixties the architectural collective Archigram began to explore the design of dynamic structures, buildings that moved around and reconfigured themselves to suit the needs and whims of their inhabitants. But without a system to actually construct dynamic structures research into their architectural applications has been limited. Robotics researchers have recently developed several modular robotics systems with groups of identical tiny robotic modules that reconfigure themselves to take on a variety of forms. This document follows the attempts to create a prototype system of self assembling robots. The self assemble blocks is an attempt to adapt the design of modular robotics systems to the scale of a brick or concrete block to create a platform for the exploration of the design possibilities of dynamic structures. Beginning with an initial design concept, various techniques were used to try to bridge the gap from theoretical to an actual physical model. The current self assembling cube operates by having each of its' six faces able to extend outwards or retract inwards. Three of the faces are equipped with a metal plate, and the other three contain a magnetic latching mechanism. The magnetic latching mechanism uses a strand of shape memory alloy to reposition a series of Halbach magnetic arrays such that the outwards facing magnetic field is turned off or on simulating a "latching" effect. Systems of such cubes can then push or pull their neighboring cubes to reconfigure the overall structure into new shapes. In this paper, we will present our latest design and results from the tests and suggest some potential applications for the self assembly blocks design.

7984-60, Session 10b

Breathing crack detection using bio-inspired combination tone

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A new nonlinear system identification technique is presented to detect the damage of breathing cracks in a metallic structure. Biologically inspired by the combination tone phenomenon occurred in the human auditory system, the difference of two harmonic excitation frequencies (ω_1) is utilized to detect the breathing crack. The method of multiple scales is utilized to analyze a representative bilinear single degree of freedom system and gain insight of the proposed concept. Experimental investigation is performed to verify the proposed approach. Compared to previously introduced techniques for nonlinear system identification of breathing cracks using super-harmonic or sub-harmonic signals, the proposed approach is much more robust and easier to implement.

7984-61, Session 10b

Electrode mass influence on the broadening of the angular spectrum of waves generated by Coulomb coupling in piezoelectric crystals

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Coulomb excitation and detection in piezoelectric materials is caused by the electric field distribution in the vicinity of the point-like electrodes. That field creates a local stress on the base of the inverse piezoelectric effect. The stress is released and turned into the mechanical movement at the material's surface that is a location of a step jump of the acoustic impedance. In our earlier papers that model of wave generation and detection was verified experimentally and numerically, exhibiting high accuracy for bulk waves propagating in lithium niobate. One of the conclusions was that by piezoelectric coupling the angular spectrum and the wave's representation in $k||$ space are narrower than in the case of acoustic coupling with acoustic lenses of 60 deg full aperture angle. Such narrow coupling in $k||$ space would limit or even exclude the possibility of Coulomb generation and detection of the surface acoustic waves (SAW). Our new results, demonstrating SAW generated by Coulomb coupling on piezoelectric material, create the demand for an extension of the earlier model. An effect enhancing the excitation of SAW by Coulomb type coupling is the inertial behavior of the mass of the electrode touching the material surface. Our work is dedicated to the theoretical description of that effect and its influence to the modification of the angular spectrum of generated wave.

7984-62, Session 10b

Wave propagation and vibration analysis in two-dimensional elastic chiral metamaterial

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In this work, a new chiral metamaterial is proposed by integrating two-dimensional periodic chiral lattice with elastic metamaterial inclusions for low-frequency wave applications. The plane harmonic wave propagation in the proposed metamaterial is investigated through the finite element technique and Bloch's theorem. From that, band diagrams, dispersion surfaces as well as phase and group velocities are obtained to illustrate wave properties of the chiral metamaterial. Effective dynamic properties of the chiral metamaterial are numerically calculated to explain low-frequency bandgap behavior in the chiral metamaterial. Specifically, design of a metamaterial beam structure for the broadband low-frequency vibration suppression is demonstrated.

7984-63, Session 10b

Introducing a user-friendly MATLAB-based interface for ultrasonic field modeling by DPSM

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Distributed Point Source Method or DPSM is being developed for last ten years. It is a semi-analytical technique based on analytical Green's functions or point source solutions and is being used for ultrasonic and electromagnetic field modeling. DPSM is more efficient than conventional finite element methods. In spite of its many advantages the use of DPSM has been primarily confined to two research groups at ENS Cachan in France and the University of Arizona in USA who have developed this technique. Only recently others have started using it. Objective of this paper is to increase the awareness of DPSM among various research groups by giving them an opportunity to have a hand-on experience with this technique. With this goal in mind a stand-alone MATLAB based interface code has been developed. The aim of this interface is to provide the users an executable computer program that they can run to model the ultrasonic field generated by various transducer geometries at signal frequencies specified by them. It should be noted that although simple rectangular transducer geometries can be easily modeled by DPSM they require three-dimensional (3D) finite elements that make finite element analysis prohibitively time consuming and expensive at high ultrasonic frequencies.

7984-64, Session 11a

Scattering of guided waves from straight features

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A frequency-domain finite element (FE) method is presented for modeling the scattering (i.e. reflection and transmission) of plane guided waves obliquely incident on an infinitely-long, straight feature with uniform cross-section in a planar host waveguide. The method utilizes a mesh of 2-dimensional finite elements with harmonic shape functions in the perpendicular direction, commonly referred to as semi-analytical finite elements (SAFE). The model domain comprises a cross-section through the feature and short lengths of the adjoining host waveguide. An integral representation of the incident mode at the desired angle is used to determine a suitable system of harmonic forces to uniquely excite that mode on one side of the feature. The displacement field is measured on either side of the feature and decomposed into reflected and transmitted modes. The cases of guided wave transmission in a featureless waveguide and the reflection of guided waves from a free-edge are examined as validation cases for the FE model. Then the case of an hollow, square-section, adhesively-bonded stiffener is modeled. The transmission coefficient results for the S0 guided wave mode using this model are compared with experimental measurements made using a pair of electromagnetic acoustic transducers (EMATs) to transmit waves across a stiffener with the same geometry. Excellent agreement is obtained.

7984-65, Session 11a

Scattering of the lowest Lamb wave modes by a corrosion pit

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Lamb waves have been used with considerable success to detect and quantify damage in aerospace, mechanical and civil structures. The mathematical representation of these particular waves is well known and understood, and we build upon these results in an attempt to detect and quantify scattering due to the presence of a spherical corrosion pit on the surface of a layer. By using the usual superposition argument, the total field consists of the incident and the scattered field, where the latter is generated by tractions on the surface of the cavity, which are obtained from the stress fields of the incident Lamb wave. In the approximation advanced in this paper these tractions are then represented by body forces in the interior of the intact layer. The acoustic radiation from the resultants of these body forces approximates the scattered field. The resultant forces are decomposed in symmetric and antisymmetric systems, which generate symmetric and antisymmetric radiating modes. The time-harmonic elastodynamic form of the reciprocity theorem is finally employed in an elegant way to obtain an analytical solution to the scattered field amplitudes. As our damage metric we obtain the ratio of scattered to incident Lamb mode amplitudes, which in a closed generalized form include material properties, geometry of the pit and layer, and angular frequency of the incident wave. Results of this study yield graphical representations for the amplitude ratios with respect to pit geometry, and has the potential to lead to a unique solution of the inverse problem.

7984-66, Session 11a

Advanced DPSM approach for modeling ultrasonic wave scattering in an arbitrary geometry

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Several studies are being carried out to diagnose structural damages. The structures are tested by analyzing ultrasonic signals scattered by damages. The interpretation of these signals requires a good understanding of the interaction between ultrasonic waves and structures. Therefore, researchers need analytical or numerical simulations. However, modeling of wave scattering phenomenon by conventional techniques such as finite element method requires very fine mesh at high frequencies necessitating heavy computational power. Distributed point source method (DPSM) is a newly developed robust mesh free technique to simulate ultrasonic, electrostatic and electromagnetic fields. In most of the previous studies the DPSM technique has been applied to model two dimensional surface geometries only. It was difficult to perform the analysis for complex geometries. This technique has been extended to model wave scattering in an arbitrary geometry. In this paper a channel section idealized as a thin solid plate with several rivet holes is formulated. The simulation has been carried out with and without cracks near the rivet holes. Further, a comparison study has been also carried out to characterize the crack. A computer code has been developed in C for modeling the ultrasonic field in a solid plate with or without cracks near the rivet holes.

7984-67, Session 11a

Numerical simulation of guided-wave propagation in composite plates and sandwich structures

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Composite structures are being extensively used in the modern aerospace, civil and transportation industries because of the superior strength to weight ratio, high stiffness, and long fatigue life. The ability to tailor the material properties along different directions also increases the avenues of composites material application. The ever increasing demand for composite structures and the need to ensure the structural integrity necessitates the development of sustainable and efficient

structural health monitoring (SHM) systems. Studies have shown guided waves (GW) as an efficient method for damage detection in metallic structures, which motivates similar research in the field of composite materials. Because of the anisotropy present in the composite materials, the development of the SHM methods are significantly more complicated and challenging than in the case of isotropic materials. A comprehensive understanding of the GW propagation behavior is required to develop a reliable structural health monitoring system.

A complete 3D-elasticity based formulation for GW propagation is intricate for modeling complex composite structures because of the interface conditions and accounting the shape in the formulation. This paper aims to present numerical simulations based on local interaction simulation approach (LISA) to characterize the propagation of GW in composite plates and sandwich structures. The LISA method is based on iterative equations (IE) for "unit cells" that are used to represent/discretize the model. The actual IEs are derived from the elastodynamic equilibrium equations. The coefficients in these iterative equations depend only on the local physical properties. The actual conditions that are enforced at the interface between the cells are continuity of displacements and stresses (sharp interface method). Therefore, changes in stiffness, density, or attenuation can be accounted for as the IE coefficients in adjacent cells with different properties will be different.

The method has been used previously by other researchers, mostly for wave propagation in isotropic plate-like structures and similar study in composites is limited. To get a better perceptive of the propagation behavior of GW in composite structures, simulations based on LISA will be implemented and validated against experimental data and finite element based simulations. Numerical analysis will be carried out for layered composite plates and then enhanced to accommodate complex structures such as composite sandwiches.

7984-68, Session 11a

A parametric study of piezoceramic thickness effect on the generation of fundamental Lamb modes

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Although numerous efforts have been devoted to the application of the structural health monitoring (SHM) concepts to real world problems; there is a shortage in the modeling tools specifically tailored for rapid computer aided design (CAD) of SHM applications. This is due to the fact that the finite element method (FEM), which is the dominant method in the simulation of the wave propagation problems due to its geometric versatility and capability to simulate complex boundary conditions as well as coupling effects, lacks the required computational efficiency for the structural health monitoring applications. This is because of the high frequencies usually utilized in SHM, posing a huge burden on the mesh size to minimize the errors.

Spectral element method (SEM), a variant of the p-type FEM, combines the fast convergence rates associated with the spectral methods with the geometric flexibility of the FEM, thus allowing for more computationally efficient simulation, leading to fast product design cycle. Recently these advantages have drawn the attention of the different researchers in the field of the SHM. The advantage of the SEM as a high accuracy solution method enables the refinement and the testing of different concepts of SHM. One of these concepts is the main focus of the current paper. The presented work is a parametric study of the effect of the piezoceramic (PZT) actuator thickness on the generation of the fundamental Lamb waves S_0 and A_0 in a thin-wall structure, using a tailored SEM solver written in FORTRAN. In order to illustrate the reduction of the computational costs, the results of the study were also compared with similar results obtained from a commercial FEM solver (ANSYS), as well as analytical results based on widely accepted model from the literature. Additionally, some of the cases were validated experimentally using a PZT wafer bonded on a thin aluminum plate and the amplitude of the propagated waves was measured using a laser vibrometer. The experimental results show an excellent agreement with the model results.

7984-69, Session 11a

Guided waves filtering with warped curvelets

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Lamb wave testing for SHM is complicated by multimodal propagation and by reflections caused by discontinuities encountered along the wave path. In this work, the usefulness of the decomposition in Warped Curvelet Frames for the analysis of guided ultrasonic waves is studied.

The Curvelet Transform is a special member of the family of multiscale and multidimensional transforms. Such transformation provides an optimally sparse representation of wave propagators (Candes et al., Comm. Pure Appl. Math., 2005). The transformation acts by expanding the analyzed signal in a tight frame of basis functions named Curvelets. The Curvelet Transform may be effectively combined with the Warped Frequency Transform (De Marchi et al., IEEE TUFFC, 2009) to analyze wave propagation in dispersive media. To perform the curvelet decomposition, efficient discrete algorithms have been implemented. Thanks to the spatial and temporal localization of curvelets, it is possible to decompose waves that are overlapped both in the time/space and in the frequency/wavenumber domain. Thus, the Warped Curvelets decomposition provides a greater flexibility w.r.t. methods which are based on the direct masking of frequency/wavenumber domain (Ruzzene, Smart Mat. Struct., 2007).

Full wavefield data obtained both numerically, from dedicated FEM simulations, and experimentally, with a scanning laser Doppler vibrometer from a 3-mm thick Al plate, were used to validate the proposed approach. The preliminary results show that the proposed decomposition is capable of separating guided waves modes propagating from close acoustic sources. Such capability can be effectively applied for the inspection and characterization of structural components.

7984-70, Session 11a

Modeling of transient Lamb wave propagation in a honeycomb composite sandwich structure

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The primary objective of this study is to develop a theoretical model based on the wavenumber integral representation of the elastodynamic field for fast and accurate calculation of the waveforms generated by localized dynamic loads, such as impact loadings and transducer sources on the surface of honeycomb-composite sandwich plates. The honeycomb composite used in this study has an extremely lightweight and relatively thick regular hexagonal honeycomb core, which is sandwiched between two graphite woven composite skins. The honeycomb core and the composite skins are modeled as homogeneous transversely isotropic materials. The formulation is based on a global matrix method, where the exact displacements and stresses in each layer (skin or core) are represented in the frequency-wavenumber domain in terms of six unknown constants, which are then solved by applying the interface continuity conditions and the stress conditions on the free surfaces. Finally, the spatial and frequency domain solutions to the field variables are computed by using a wavenumber integral technique. Dispersion curves for the composite skin and the sandwich plate are calculated first from the solution to the global matrix, and are found to be vastly different. The response to various surface loadings in the thickness direction is determined in the frequency domain and then transformed to the time domain using the inverse Fourier transform. The results from the theoretical model are compared to those obtained using numerical simulation performed in commercially available finite element software LSDYNA. It has been shown that the model is quite

reasonable in capturing the behavior of the waves in relatively low frequency applications of interests, where the wavelength is larger than the honeycomb cell dimensions. Theoretical modeling indicates that the guided waves have sinusoidal depth dependence in the composite skin but they decay exponentially in the honeycomb core. Thus the guided waves are of the so-called Rayleigh-Lamb (R-L) type. Extension of the model to include disbonds at the core-skin interface and other defects is under way.

7984-71, Session 11b

Model order identification techniques in wind turbine systems using wireless sensor networks

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Wind Turbine Systems is an area of research which is growing up rapidly due to concerns of global energy consumption and sustainability.

Advances in wind turbines technology have promoted a tendency to improve dynamic performance-based efficiency on the structure, often characterized as a high-rise tower. As a result, slender and longer poles, bigger gear boxes, and heavier and thicker blades.

Structural design optimization should account for nonlinear effects such as wind-induced vibrations, unmeasured disturbances, and limitations on the bandwidth imposed by the use of fixed time step criteria to generate experimental data. All these factors contribute to increase the model dynamics complexity, ending up in a higher system model order. Currently research is ongoing in modeling and identification, mainly for controller design, state estimation and structural fault detection/diagnosis. A data-driven post-analysis assessment using made-home wireless sensors technology on a wind turbine experiment performed in University of Michigan is presented.

Eigensystem Realization Analysis is employed to investigate/estimate model order (degree) and State Space Model. Alternative linear system methodologies are elaborated to benchmark the wind turbine modal analysis, such as Frequency Domain Decomposition, Stability, ARX, and Finite Element models. Comparison of the dynamic properties are presented.

7984-72, Session 11b

Wind rotor blade x-ray computed tomography (CT) for in line process control and NDE

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Wind Turbines are designed to harness the Wind's Energy as a green renewable energy source. The Wind energy market is growing at 20% in the US with an US initiative to achieve 20% wind power by 2030. Wind turbines are constructed from major components including wind turbine rotor blades, gear boxes, towers, generators and control systems and sensors. Approximately, 22%-23% of the wind turbines cost is in the three rotor blades. Therefore, Wind Rotor Blade Reliability is a keen issue. Major failures are due to manufacturing flaws and defects, lightning, ice, and over speed conditions.

The Wind Rotor Blade X-ray Computed Tomography (WRBCT) is being developed in a global collaboration with wind rotor blade manufacturers, wind turbine manufactures and Wind Rotor Blade Reliability Consortium. The WRBCT systems are being designed to demonstrate that the systems can detect manufacturing problems at the blade formation process and provide rapid feedback to correct process defects.

The WRBCT will provide 3D x-ray CT density information on the wind rotor blade for 100% inspection and process control feedback at

completion of the blade molding process. The WRBCT is expected to provide solutions to the following manufacturing problems including: 1.) Are the Low/High Pressure shells bonded together properly over the 40 meter to 50 meter length? 2.) Are the Spar Caps and Shear Webs bonded properly? 3.) Are there "Dry Fibers"? 4.) Are there "Fiber Waves" in root sections and spar caps?

The WRBCT system consists of six 250 Kev X-ray sources operated in a pulsed mode to scan blades of 3.2 meter chord length and 50 meter long. The WRBCT structure with a 4 meter aperture has a 300 Kev multislice CT detector with real-time data acquisition and reconstruction. The WRBCT data can be used for semi-automated defect image processing, which provides the operator precise location for reworking the blade on the manufacturing floor. The WRBCT is designed to perform 100% inspection of wind turbine blades and provide a certification report for process quality improvement.

Design simulations and X-ray CT Imaging have been performed for Fiber Glass composite materials used in 1.5 MW wind turbine systems. These simulations included x-ray penetration, density levels for fiber glass, resins, voids, and path lengths through wind rotor blades geometry. Also the WRBCT design with multiple X-ray sources to operate 24/7 and scan 3-6 rotor blades in 24 hours. The imaging chain of the Multi-Source X-ray System and multi-slice 300 Kev detector system are designed to detect voids of 1mm in rotor blades with 3.2 meter max chord lengths. The WRBCT's 3 dual tube x-ray source blocks (6 x-ray tubes) and OSEM 3D targeted FOV reconstruction allow isotropic multi-planar viewing and image processing of rotor blades' volume. The WRBCT system is being design and implemented as a consortium effort for the wind industry to improve wind rotor blade reliability.

7984-73, Session 11b

High-temperature monitoring of condensed water in steam pipes

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An effective in-service health monitoring system is needed for steam pipes to track through their wall the condensation of water. The system is required to measure the height of the condensed water inside the pipe while operating at temperatures that are as high as 250°C. The system needs to be able to make real time measurements while accounting for the effects of water flow and cavitation. For this purpose, ultrasonic waves were used to perform data acquisition of reflected signals in pulse-echo and via autocorrelation the data was processed to determine the water height. Transmitting and receiving the waves is done by piezoelectric transducers. Using transducers with Curie temperatures that are significantly higher than 250°C allowed performing the required task. This paper reports the results of the feasibility study that is intended to establish a health monitoring systems.

7984-74, Session 11b

Combined acoustic emission and guided wave monitoring of fatigue crack growth on a full scale pipe specimen

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The existing nuclear power plant (NPP) in-service inspection (ISI) regime prescribes a periodic and localized inspection methodology. This approach assumes that degradation evolution is slow and linear. However, experience with in-service degradation has shown that rapidly-growing cracks, including several varieties of stress corrosion cracks (SCCs), can grow through a pipe in less than one fuel outage cycle after they initiate. The existence of these quickly-growing degradation mechanisms challenges the philosophy underlying periodic and localized

examinations. A move from periodic local inspections of welds to global continuous monitoring would greatly improve crack detection, especially for slow-to-initiate but rapidly-growing flaws.

Acoustic emission (AE) and guided wave ultrasound (GWUT) are two measurement methodologies that stand out as possible techniques for monitoring reactor piping for cracking in real time. Significant efforts to develop AE as a global on-line monitoring tool for degradation in NPP components were initiated at the Pacific Northwest National Laboratory (PNNL) in the 1970's and sustained through the early 1990's. Ultimately, the effects of excessive signal interference within a noisy reactor environment prevented the application of AE for global on-line monitoring. However, AE has proven to be an effective tool for more favorable applications including crack monitoring during hydrostatic testing of the reactor pressure vessel and for leak detection.

GWUT is an active inspection technique and is particularly effective at detecting changes in the boundary of components with simple geometries. In NPPs, GWUT methods have been used to inspect baffle bolts and hold promise as an effective approach for inspecting steam generator tubes and buried piping. One difficulty in employing GWUT methods is that the test component usually supports multiple complex modes, complicating the analysis of the measurement data.

The development of inspection technologies that are minimally intrusive and increasingly effective is needed to ensure long term operation of the current fleet of commercial NPPs in a safe and economical manner. A combination of AE and GWUT monitoring approaches is evaluated in this paper for eventual global on-line monitoring applications. Efforts to monitor fatigue crack growth in situ on a full scale pipe section using both AE and GWUT transducers have been initiated at PNNL. The experimental configuration is described and the results of these tests are discussed.

7984-75, Session 11b

Investigating the use of advanced health monitoring systems in oil and gas pipelines infrastructures

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Oil and gas pipelines are important parts of energy and materials transmission and hence, they are vital for the economy of countries. Millions of miles of pipelines are currently functioning around the world for this purpose and such networks of pipelines are constantly expanding due to increase in the economical growth of societies.

In order to have a proper maintenance in place and to prevent any malfunctioning that might develop, health monitoring is necessary while the pipelines are in operation. In this paper, the significance of pipelines and their maintenance is explained. Then, an explanation of health Monitoring (HM) is provided and its various normal and advanced methods and objectives are outlined. HM is regarded as a major component of any successful maintenance in industrial applications and infrastructures. It involves the process of monitoring defined parameters having impact on sound operation of that system such that a significant change in any parameter is indicative of a developing failure.

In this investigation, advanced modern methods including custom-designed utilization of Ultrasonic testing method particularly designed for industrial applications in oil and gas pipelines will be introduced. A practical hands on procedure of monitoring pipelines considering their health status with regard to discontinuities and defects will be the direct outcome of this study. Finally, findings of the conducted experimental studies herein will be presented.

7984-76, Session 12a

Resource-efficient wireless monitoring based on mobile agent migration

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Wireless sensor networks are increasingly adopted in many engineering applications such as environmental or structural monitoring. Having proven to be low-cost, easy to install and accurate, wireless sensor networks serve as a powerful alternative to traditional tethered monitoring systems. However, due to the limited resources of a wireless sensor node, one critical problem is the power consuming transmission of the collected sensor data. This paper presents a new approach towards resource-efficient wireless sensor networks based on multi-agent technology. In order to reduce the quantities of measured data to be communicated and to economically utilize the restricted computing resources, mobile software agents are embedded in the wireless sensor nodes. These agents are designed to autonomously collect, analyze, condense and communicate the data sets. Thereby, the software agents located on a sensor node continuously execute relatively simple but resource-efficient algorithms such as regression or modal analyses. If having detected (potential) anomalies, specific algorithms and further knowledge is required for a more comprehensive interrogation of the data sets. Thus, specialized software agents are requested to physically migrate from connected computer systems, or adjacent nodes, to the respective sensor node. Possessing the required expert knowledge and algorithms, a migrating agent is capable of appropriate decision-making executed directly on the sensor node. As a consequence, the quantities of communicated measured data are largely reduced, and the probability of data loss during transmission is lowered significantly. This paper will present a prototypical test implementation demonstrating the deployment of multi-agent technology in wireless sensor networks. Specifically, the design and implementation of autonomous mobile agent migration will be elucidated in detail. Furthermore, performance tests will be shown comparing the implemented agent-based approach to conventional solutions.

7984-77, Session 12a

Hierarchical fiber-optic-based sensing system for impact damage monitoring of large-scale CFRP structures

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Existing structural health monitoring systems using fiber-optic sensors are highly sensitive to damage in aerospace carbon fiber reinforced plastic (CFRP) structures. However, when the optical fiber sensor networks are applied to large-scale structures for monitoring randomly induced damage such as impact damage, they are unsatisfactory in the following three properties; repairability, redundancy, and monitorable area. It is difficult to repair and reconnect broken optical fibers in damaged areas. And a failure at only one point on the optical fiber may lead to a breakdown of the entire sensing network. Furthermore, since the fiber-optic-sensing obtains one-dimensional strain and temperature information along the thin optical fiber, damage far from the sensing fiber can not be detected. This study proposes a novel hierarchical sensing concept excelling in these three aspects and establishes an impact damage detection system based on Comparative Vacuum Monitoring (CVM) technique, which was originally developed by Structural Monitoring Systems in Australia. In the hierarchical system, numerous three-dimensionally constructed sensing devices are distributed throughout the structure and are connected with the fiber-optic network through transducing mechanisms. The devices are bonded on the structural surface or embedded in the structure and detect damage. Meanwhile, the fiber-optic network attached on the structural back surface gathers the damage signals from the distributed devices and transmits the damage information to a measuring instrument. This

study begins by developing the distributed devices and the fiber-optic network, followed by validation of the proposed hierarchical system using a CFRP skin-stringer fuselage demonstrator. Finally, the superiority of the hierarchical sensing concept is discussed and clarified through comparison of the proposed system with existing ones.

7984-78, Session 12a

Defect characterization using two-dimensional arrays

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The application of ultrasonic arrays for non-destructive evaluation has seen a dramatic increase in recent years. A two-dimensional (2D) array allows both volumetric inspection and advanced defect characterization because a defect is illuminated over a range of angles. The complete ultrasonic response of a defect is defined by its scattering matrix, which describes the amplitude of the reflected wave caused by a plane incident wave as a function of incident angle, scattering angle and frequency. Because a 2D array has a finite-sized aperture, only part of the scattering matrix can be captured using the array data and this limits the accuracy of defect characterization. A larger aperture permits better characterization. The fundamental challenge associated with truly 2D arrays, capable of full 3D imaging, is due to the number of elements required to produce an aperture of sufficient size to allow adequate defect characterization. In this paper quantitative comparison of 2D arrays with different element layouts is performed. Model and experimental results are shown that illustrate the imaging performance of two 3 MHz arrays: a conventional 11x11 matrix array and a 128-element array with optimized pseudo-random element positions. A technique for extracting the scattering matrix from the raw 2D array data is also presented. The approach is based on the reversibility of the imaging algorithm. The method is tested on experimental data for characterization of various volumetric defects.

7984-79, Session 12b

Development of a ferromagnetic polymeric metal detector system

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Currently metal detectors operate on three basic technologies: very low frequency (VLF), pulse induction (PI), and beat-frequency oscillation (BFO). Besides, these different types of sensors appear in everyday life as either a walk-through or hand held device. They are commonplace in airports, libraries, prisons, stores and shops. However these devices share some disadvantages. First, they are relatively bulky and large. Second, they are highly affected by the interference caused by the surrounding electronics. If these devices are used in a hospital or laboratory setting, where space is limited and equipment is prone to electromagnetic interference, these detectors often fail. This paper presents a novel metal detector using a fiberoptic magnetostriction sensor. The metal sensor uses a fiber-optic Mach-Zehnder interferometer with a newly developed ferromagnetic polymer as the metal sensing material. This polymeric magnetostrictive fiber-optic metal sensor is small in size, simple to fabricate, and resistant to RF interference (which is common in typical electromagnetic type metal detectors). The detector utilizes a simple DC magnetic field detection scheme and a Mach-Zehnder fiber optic interferometer for metal detection. The basic concept of the metal detection is based on monitoring strain-induced optical path length change in the interferometer stems from the magnetic field induces magnetostriction effect. The magnetostrictive device can produce polarized magnetic fields that have temporal characteristics, similarly generated from walk-through metal detectors system. In this paper, characteristics of the material being sensed and magnetic properties of the ferromagnetic polymers will be discussed. Finally, the preliminary results on the different metal material detection will be discussed.

7984-80, Session 12b

Customization and calibration of BOTDR sensors for underground structural health monitoring

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In recent years, it is becoming more common to use fiber optic sensors (FOS) for structural health monitoring (SHM), especially in the civil engineering field. A number of surface-mountable FOS sensor systems have been developed in the past years, among which the Brillouin Optical Time Domain Reflectometry (BOTDR) system has received much research attention in terms of technology development and application. Different from the traditional monitoring instruments, the BOTDR system provides distributed, long distance, real-time, interference free and high accuracy/precision measurement data. However, there is still a gap between the lab experiments and field applications. Limited research has been conducted on how to maximize its possible applications due to its brittle and fragile material nature. This article focuses on specific methods developed to evaluate the whole sensing chain, with an emphasis on (i) the design requirements and selection criteria for optical fiber-based sensor protection, (ii) the commercially-available optoelectronic instruments and sensing cable, and (iii) the customization range for sensor protection systems that are manufactured involving stainless steel, fiber reinforced composites and concrete. The feasibility of manufacturing the sensor protection systems using these materials is also demonstrated. A number of additional considerations for a successful pairing of these two must be taken into account for successful field applications. These considerations are further developed within this article and illustrated with practical applications of SHM for underground structures, making use of distributed temperature and strain sensing based on Brillouin scattering in optical fibers.

7984-81, Session 12b

Fiberoptic microphone using a polymeric cavity

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It is difficult to accurately and cheaply record audio from microphones while maintaining high quality. In this study, we report the development of an elastomer based fiberoptic Fabry-Perot microphone. The sensor comprises an air-spaced optical cavity formed between the diaphragm and the cleaved end of a single-mode fiber sealed to the sensor by in this case by a molded polymer sleeve. The Fabry-Perot cavity is low finesse, typically less than 10%, and the intensity of the reflected signal follows an approximately sinusoidal response as the cavity length changes in response to external pressure changes. The unique design is in its use of polymer and molding design for the cavity instead of traditional semiconductor material and fabrication so that the cavity can be assembled and aligned with the optical fiber quickly and accurately. The experiments performed on the sensor show good signals and flat frequency response to pressure waves generated by a speaker.

7984-82, Session 13a

Investigation of born approximation applied to non-destructive evaluation of concrete media

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The Born Approximation as a forward model of elastic wave scattering in the context of Impact Echo testing of concrete is investigated in this

paper. The ability of a forward model to realistically simulate the physics of a system is particularly important when the forward model is used as part of an inverse solution. A two-dimensional Finite Difference in Time Domain (FDTD) model for elastic wave propagation in an infinite, homogeneous and isotropic concrete medium is developed to generate the synthetic scattering data for comparison with the Born Approximation model. The scattering by air voids that are typically present in damaged civil engineering structures is considered. Two types of scatterer shapes are considered in this study: horizontal elongated cracks and air voids with compact shapes.

The change in the correlation coefficient, that measures the mismatch between the Born approximated and the synthetic data, is more pronounced for horizontal scatterers than compact ones with increasing size of the scatterers. The change in the time delay associated with the arrival of the maximum amplitude of the cross-correlation function between the waveforms is also more for horizontal scatterers. These observations imply that within limits of a low scatterer dimension and interrogating wavelength ratio (maximum ratio < 0.28), the Born Approximation is able to simulate a compact air void better than a horizontal elongated one. This knowledge provides useful insight on Born Approximation as part of an inverse solution towards imaging of air voids of various shapes in a damaged civil engineering structure.

7984-83, Session 13a

A comparison of data-driven methodologies for the detection of nonlinearities

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Experimental data from a three-story frame test-bed structure, that has been tested at the Los Alamos National Laboratory (LANL) is used to evaluate and compare, in a statistical framework, the robustness and effectiveness of four data-driven vibration-based approaches for detecting and locating asymmetric impact-type nonlinearities. A movable and adjustable bumper assembly (a "snubber") is used to vary the severity and location of the nonlinearity introduced in the test structure. Each of the implemented data-driven methodologies are, respectively, based on: an autoregressive (AR) model, a two-stage model combining an autoregressive (AR) model and an autoregressive model with exogenous inputs (ARX), a general time-domain multi-degree-of-freedom system identification method (GeneralID), and a non-parametric chain-like system identification approach (ChainID). The results of this experimental study show that the methodology based on the chain-like system identification provide the best robustness and reliability for detecting and localizing the impact-nonlinearities in the presence of modeling, measurement, and data processing errors.

7984-84, Session 13a

Acoustic emission monitor and evaluation method of steel corrosion damage for reinforced concrete

D. Li, Dalian Univ. of Technology (China)

Current study is aiming at making an in-depth research about the characteristics of the AE signals produced during the steel corrosion of reinforced concrete. Continuous AE measurement is conducted to monitor the accelerating steel corrosion of reinforced concrete in different levels of corrosion rates. Wavelet analysis is used to analyze the AE data supplementing other methods such as parameter analysis and waveform analysis. The research shows that the corrosion process can be divided into four stages and AE technique can be used to detect the slight corrosion in the first stage. Wavelet analysis can help us to acquire the singular signals in each stage by wavelet transform and the time-frequency distribution. The combination of wavelet analysis,

parameter analysis and waveform analysis is shown successful for the research about the characteristics of the AE signals in each stage. From these results, a great promise for AE technique to monitor the corrosion process in reinforced concrete is clarified. And the combination of different methods for signal analysis especially wavelet analysis is more reliable to the study about the characteristics of the AE signals.

7984-85, Session 13a

Monitoring the lifting construction of the steel roof of Tianjin Jinmen Hotel

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Abstract: Tianjin Jinmen Hotel is the highest building in Tianjin. The roof for which is over 550 tons, and will be lifted to the 14th floor with 59.22 m. So it is crucial to ensure safe and stable in the three lifting process.

(1) Preparing stage: multi-channel dynamic resistance strain gauge are applied to monitor deformation and internal force of the whole structure in site. Over 20 strain gauges are placed on the important bars to monitor the initial stress, and to avoid that to be damaged.

(2) Uplifting stage: In this stage, more attention are put to study the internal stress of structures and acceleration difference among uplifting points, while multi-channel dynamic resistance strain gauge and wireless sensor technology are used to record data and to give correction order timely for error operation.

(3) Fixing stage: During the final stage, the roof will be welded and fixed on the main body of the building. And impact loads, caused by construction, and environmental loads-wind and snow, play important role to suffer the roof structure.

Test data show that it is fairly important to control both of the uplifting acceleration and the velocity difference at various upgrading points.

7984-86, Session 13b

Statistical quantification of the uncertainty in transmissibility-based features for satellite structural condition evaluation

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A rapid state awareness check-out (~days) for the next generation plug-and-play (PnP) satellites is anticipated by Air Force, in which the fastener connection quality is one of the major concerns. In this paper, we consider a SIMO identification model and adopt transmissibility-based features to evaluate the fastener preload levels, and regard the change of features as the damage indicator. There will be both inherent randomness in the system identification process and the uncertainty caused by noise (or other types of operational sources). The uncertainty of transmissibility will affect the feature interpretation, which specifically leads to false-positive (Type-I) errors. We develop the statistical model for the distribution of transmissibility via auto-power density estimation and Chi-square bivariate derivation, and the analytical power density function and confidence interval are given in the end of this paper. Monte Carlo simulations are implemented to validate the statistical model, with testing on a representative structure.

7984-87, Session 13b

Characterization of satellite components assembly for responsive space applications

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The rapid deployment of satellites is hindered by the need to flight-qualify their components and the resulting mechanical assembly. Conventional methods for qualification testing of satellite components are costly and time consuming. Furthermore, full-scale vehicles must be subjected to launch loads during testing. The focus of this research effort was to assess the performance of Structural Health Monitoring (SHM) techniques to replace the high-cost qualification procedure and to localize faults introduced by improper assembly. SHM techniques were applied on a small-scale structure representative of a responsive satellite. The test structure consisted of an extruded aluminum space-frame covered with aluminum shear plates, which was assembled using bolted joints. Multiple piezoelectric patches were bonded to the test structure and acted as combined actuators and sensors. Piezoelectric Active-sensing based wave propagation and frequency response function techniques were used in conjunction with finite element modeling to capture the dynamic properties of the test structure. Areas improperly assembled were identified and localized. This effort primarily focused on determining whether or not bolted joints on the structure were properly tightened.

7984-88, Session 13b

Time-frequency and space-wavenumber analysis for damage inspection of thin-walled structures

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Today's advancement in full-field non-contact dynamic measurement technologies enables fast and accurate vibration measurements of time-varying operational deflection shapes (ODSs) of thin-walled structures (i.e., 1-D and 2-D structures). Scanning laser vibrometers and camera-based motion analysis systems are two prominent examples. The measured data from such a system contain detailed information about the measured structure, but the amount of data is often huge and how to efficiently and accurately extract clear system dynamic characteristics and health information is very challenging. Here we present a methodology for damage inspection of thin-walled structures that combines a boundary-effect evaluation method (BEEM) for space-wavenumber analysis of ODSs and a conjugate-pair decomposition (CPD) method for time-frequency analysis of time traces of measured points.

The BEEM analyzes space-domain data for damage inspection of large one- and two-dimensional structures. Damage introduces new boundaries to a structure, and influences of boundaries on steady-state high-frequency ODSs are spatially localized effects. The BEEM is a signal processing method that takes advantage of these localized effects in performing area-by-area extraction of damage-induced boundary effects from steady-state ODSs to reveal damage locations. The BEEM decomposes an ODS into central and boundary solutions by using a sliding-window least-squares data-fitting technique. Numerical and experimental results show that boundary solutions are excellent damage indicators because of Gibbs' phenomenon, and the central solutions can be used to clearly identify actual boundary conditions. Except for experimental ODSs of the damaged structure the method requires no model or historical data for comparison. Experimental results of many one- and two-dimensional structures validate the high sensitivity and accuracy of BEEM for detection and estimation of multiple small defects in structures.

The CPD method analyzes time-domain data for offline damage inspection and online health monitoring of dynamical systems. Responses of damaged dynamical systems are often nonlinear and nonstationary. For a nonlinear non-stationary signal, empirical mode decomposition (EMD) uses the apparent time scales revealed by the signal's local maxima and minima to sequentially sift intrinsic mode functions (IMFs) of different time-varying scales, starting from high- to low-frequency ones. For offline detailed damage inspection, CPD uses one or more pairs of windowed adaptive harmonics and function orthogonality to track time-varying frequency and amplitude of each IMF. Because CPD processes only time-domain data, it is free from the

edge effect caused by Gibbs' phenomenon and other mathematical and numerical problems caused by the use of Hilbert transform. Hence, results from CPD are valuable for accurate identification of dynamical systems. For parametric identification, one can compare the time-varying frequency and amplitude from CPD with those from perturbation analysis to determine the type and order of nonlinearity and system parameters. For online health monitoring, CPD tracks the instantaneous frequency of an arbitrary signal without signal decomposition by processing three or more most recent data to estimate its instantaneous frequency and amplitude. Numerical and experimental results show that CPD is versatile for system identification, damage inspection, and health monitoring of different linear/nonlinear dynamical systems.

7984-89, Session 13b

Likelihood tests for localizing damage using ultrasonic guided waves

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Presented is a new approach to damage localization for guided wave structural health monitoring (GWSHM) in plate-like structures. In this mode of SHM, transducers actuate and sense guided waves in order to detect and characterize the presence of damage. The approach is based on a generalized likelihood test using a simple stochastic model of the GWSHM process. Most current GWSHM approaches suffer in the presence of secondary reflections from the structure's geometry, which corrupt the images used for localization. The presented likelihood test is derived based on the anticipation of these secondary reflections and its performance is instead enhanced by their presence. Also introduced are two statistics-based methods for evaluating localization performance: the localization probability density function (LPDF) estimate and the localization operating characteristic (LOC) curve. Using an ensemble of measurements from an instrumented plate with stringers, the performance of the likelihood test is compared to that of seven existing localization methods. The likelihood test proved superior in all test cases and was particularly effective in localizing damage using very sparse arrays.

7984-90, Session 14a

Fatigue and fracture assessment of cracks in bridge elements using acoustic emission

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Single edge notches provide a very well defined load and fatigue crack size and shape environment for estimation of the stress intensity factor K , which is not found in welded structures. ASTM SE(T) specimens do not appear to provide ideal boundary conditions for proper recording of acoustic wave propagation and crack growth behavior observed in the field, but do provide standard fatigue crack growth rate data. A modified version of the SE(T) specimen has been examined to provide small scale specimens with improved acoustic emission characteristics while still maintaining accuracy of fatigue crack growth rate da/dN versus stress intensity factor. The specimens represent a steel beam flange subjected to pure tension, with a surface crack growing transverse to a uniform stress field. Testing of small scale single edge notch tension specimens is done to assess load ratio effects, and crack length effects on fatigue life of the specimens. Focus is on tests conducted at high R ratio to maintain similitude with conditions found in welded structures in the field. SIF models are extended to include expressions for crack tip opening displacement measured experimentally with clip gauge. Correlation between fatigue crack growth, stress intensity factor and Acoustic Emission data is developed. Analytical and numerical studies of stress intensity factor are developed consistent with the experimental program. ABAQUS finite element software is utilized for stress analysis of crack tips.

Performed under the support of the U.S. Department of Commerce, National Institute of Standards and Technology, Technology Innovation Program, Cooperative Agreement Number 70NANB9H9007."

7984-91, Session 14a

Feasibility of self-powered wireless smart sensor network for a long-term structural health monitoring

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Wireless smart sensor networks (WSSNs) are one of the recent remarkable advances in the field of structural health monitoring. In an effort to implement full-scale WSSNs on a bridge, a total of 70 sensor nodes were deployed in the 2nd Jindo Bridge located in South Korea in 2009. The long-term operation of the full-scale structural health monitoring (SHM) system on the bridge was achieved involving many efforts to autonomously control the sensor network. The data from the deck, cables and pylons were acquired and modal analysis was successfully carried out. However, those sensor nodes were powered by high capacity batteries and consequently they required regular replacement, once a month, for long-term continuous and stable operation.

To address power issues on sensor nodes, the need for self-powered system arose and alternative power sources such as solar power and wind-generated power as well as power saving strategy have been carefully examined. As a result, in 2010, totally 113 sensor nodes have been deployed with energy harvesting devices and power saving software. In this study, the feasibility of the self powered system utilizing multi-scale power management strategy for wireless smart sensor nodes is investigated through long term experimental power consumption data on the bridge.

7984-92, Session 14a

Correlation between damage detection and observed damage for a full-scale four-story steel building during the collapse test

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A full-scale four-story steel building was tested on the shaking table of the 2007 E-defense project on September, 2007. During the shaking table tests, the building was damaged progressively through various levels of seismic excitations, and finally collapsed on the first floor. To evaluate the modal parameters, the continuous ambient vibration tests were conducted before and after the seismic excitations and a series of ambient vibration record through the test is obtained. At various levels of damage due to the seismic excitations, low-amplitude white noise excitations were applied to the building and the response of the building was measured. The stochastic subspace identification (SSI) method is then applied to identify the modal parameters (natural frequencies, damping ratios and mode shapes) of the building based on measured data from ambient vibration tests and low-amplitude white noise excitation tests at various damage states of the building. This paper focuses on detecting damage of this building based on changes in identified modal parameters. A sensitivity-based finite element model updating strategy is applied to identify (detect, localize and quantify) the damage in the building at each damage state considered. The residuals used in the updating procedure are based on the identified natural frequencies and mode shapes for the first three longitudinal modes of the building. At last the correlation between the damage detection results and the actual damage observed in the building (from pictures, video cameras, and inferred from strain sensors) is carefully examined. They do not exactly coincide but the concentration regions of damage are highly consistent with each other.

7984-93, Session 14a

Variability in dynamic characteristics of the Sutong cable-stayed bridge under routine traffic conditions

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In the field of structural health monitoring, techniques based on vibration monitoring often evaluate the possible degradation or destruction of the structure by measuring changes of modal parameters. But an important problem the techniques have to face is that modal parameters may vary under different environmental conditions or operation conditions, such as traffic loads, wind loads, temperature and so on. The normal variation of structure under routine operation is prone to mask or confuse the variation caused by structural changes in physical properties. Therefore, it is essential for bridge health monitoring to quantize the variability in dynamic characteristics of routine operation and distinguish it from the changes caused by structural damage. Recently many studies have been carried out for the variation of dynamic parameters under different environmental conditions. But investigation of ultra long span cable-supported bridges is still lacking. The Sutong Bridge is the first-built cable-stayed bridge with a thousand-meter scale main span. Its variability in dynamic characteristics under routine traffic conditions is focused and investigated. Before the bridge was open to the traffic, field vibration test was carried out. Acceleration responses of the main girder and the two towers were measured and precise dynamic characteristics of the bridge were identified as a reference. Then in the subsequent different seasons of the operational phase, vibration monitoring of the bridge was performed and dynamic characteristics of the bridge under different environmental conditions were estimated by using the enhanced frequency domain decomposition method and the stochastic subspace identification technique. The variability in dynamic characteristics was discussed and some valuable information was provided for the application of the vibration-based health monitoring techniques.

7984-94, Session 14a

Moving forces identification based on structure health monitoring data for cable-stayed bridge with regularizations

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A new approach suitable for cable-stayed bridge is presented in this paper. Moving force identification method for cable-stayed bridge was seldom reported. In previous research bridges were modeled as Timoshenko beams or orthotropic plates, while cable-stayed bridge can't be modeled as beams or plates. The reduced finite element model is adopted for the girder of cable-stayed bridge in this paper to reduce the scale of problems, and the cables are modeled as elastic supports to girder finite element model. According to D'Alembert principle the equation of motion of girder finite element model can be established, from which the forces are derived, given measured (or identified) time-varying cable forces and accelerations by accelerometers on girder. However this is typically an inverse and ill-posed problem, because the measured global variables is not so sensitive to local loads such as vehicle loads for a large-span bridge meanwhile the noise plays an essential role in measured in-field data. The regularization methods are adopted for solving the ill-posed problem. In field structural health monitoring data as well as the numerical simulations are used to verify the method.

The main contributions of this paper are: a. to propose a method for identifying moving forces on cable-stayed bridge; b. the in-field data from Nanjing Yangtze River Bridge No.3 structural health monitoring system are used to identify the moving forces; c. Several regularization methods such as Tikhonov, TSVD, generalized GTSVD and iterative regularization methods are adopted, and the results from different regularization methods are compared.

7984-95, Session 14b

Application of the multi-scale finite element method to wave propagation problems in damaged structures

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This work illustrates the possibility to extend the field of application of the Multi-Scale Finite Element Method (MsFEM) to structural mechanics problems that involve localized geometrical discontinuities like cracks or notches. The main idea is to construct finite elements with an arbitrary number of edge nodes that describe the actual geometry of the damage with shape functions that are defined as local solutions of the differential operator of the specific problem according to the MsFEM approach. The small scale information are then brought to the large scale model through the coupling of the global system matrices that are assembled using classical finite element procedures. The efficiency of the method is demonstrated through selected numerical examples that constitute classical problems of great interest to the structural health monitoring community.

7984-96, Session 14b

Lattice dynamics approach to determine the dependence of the time-of-flight of transversal polarized acoustic waves on external stress

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The lattice dynamics approach can also be interpreted as a discrete and strictly periodic lumped circuit. In that case the modeling represents a finite element approach. In both cases the properties relevant for wavelengths large with respect to the periodic structure can be derived from the respective limit relating also to low frequencies. The model representing a linear chain with stiffness to shear and additional stiffness introduced by extensional stress is presented and compared to existing models, which so far represent each only one of the effects treated here in combination. Additionally included in the modeling are effects caused by anharmonicity. Whereas an extension caused by pulling will soften the shear stiffness by anharmonic effects, the inherent stress will stiffen the chain. For a string this effect is well known from respective musical instruments. The counteracting effects are discussed and compared to respective experimental results

7984-97, Session 14b

Porosity estimation using wave propagation based methodology for structural health monitoring of a composite beam

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Porosity is one of the most common imperfections in composites reinforced with continuous fibers and practically it is difficult to control the amount of porosity content in composites. With the increasing use of composites as structural materials in aerospace and other industries, there is a growing need for the estimation of porosity as part of the structural health monitoring and structural integrity evaluation. In this paper, a wave propagation based method is presented for the estimation of porosity in a laminated composite beam, where the effective mechanical properties of the porous composite beam is obtained using a modified rule of mixture approach. The properties, thus obtained are used in the conventional spectral finite element model to obtain the high frequency responses of the structure. The model is first validated, using the experimentally obtained results for a CFRP laminate and then

it is used for characterizing the effect of the amount of porosity on the different parameters involved in the propagation of waves through the porous laminate. In the present work, we use the variation of velocity response with the change in porosity, as a parameter to estimate the porosity content in a structure. The experimentally measured velocity response from the structure will be recorded and compared with the velocity response obtained from the numerical model, for finding the porosity content in a structure by solving a nonlinear optimization problem. In the optimization problem, the squared difference in the two responses represent the cost function, which needs to be minimized.

7984-98, Session 14b

Health monitoring of composite structural components using frequency response function curvature method

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Development of efficient methodologies to determine the presence, location, and severity of hidden damage in critical structural components is an important task in the design and construction of structural health monitoring (SHM) systems in aging as well as new structures. Application of modal identification techniques considering changes in natural frequencies and mode shapes due to appearance of damage have been found to be challenging. As a result, methods based on the use of frequency response functions (FRFs) are developed due to their effectiveness for reliable damage monitoring in most applications. The paper emphasizes the need of a unified procedure to improve the reliability of the defects detection capability based on FRF and aid in the development of autonomous health monitoring systems for defects-critical structures. In this paper, the approximate location and severity of an unknown defect is determined using frequency response function curvature (FRFC) method. FRF is a transfer function, expressed in the frequency domain which depends on the physical properties of the structure. The FRFC method compares the undamaged and damaged states of the structure for a range of frequencies by calculating the changes in the curvature due to its sensitivity to the presence of damage. The method has been extended to detect localized impact damage in composite and sandwich plates. Simulations are carried out using commercially available finite element software, ABAQUS, and the results are validated with the available literature. A damage index (DI) is calculated using FRFC data at a number of control points (CPs) showing significant increase in the index with the level of damage, and more importantly, the increase is pronounced at CPs closer to the damage location. The method is found to be conceptually simple and accurate, and can be effectively used in structural damage detection.

7984-99, Session 14b

Elastic wave propagation based autonomic self-diagnosing for AFM with pyramidal indenter

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Atomic-force microscope (AFM) is an important tool in the studying the surface properties of materials at sub-angstrom levels. They are also extensively employed in studies at nano-scale like nanoindentation, etc. The accuracy in measurements depend on the radius of AFM indenter tips and spring constant of indenter. The average radius of indenter tip is taken as specified by the manufacturer. This specification is based on nominal figures representing an average for a batch of microfabricated tips. Thus calibrating radius of AFM indenter tips is of significance.

AFM is operated in two modes: contact and non-contact. During operation in contact mode, the tip adheres to the sample surface with a finite force and is dragged across the surface. The contact occurs over a finite area and the finite adhesion forces deform the indenter tip and the surface. In non-contact mode for force versus distance measurements,

the indenter tip is suspended 40 - 50 angstrom above the surface and long ranged van der Waals forces deflect the tip. The tip deflection used for measurements is influenced by tip sharpness. AFM indenter tips undergo continuous degradation in sharpness during usage. Hence monitoring of indenter tip health is of significance. Several NDE schemes based on spring models have been demonstrated in literature. This work is motivated by lack of analytical closed-form solution based autonomic diagnosing methodology.

In this work, we have developed self-diagnosing system based using elastic wave propagation. Waves are generated through the AFM indenter using a wave source. The reflected waves from the tip are recorded by the receiver. A one-to-one correspondence is demonstrated between tip deformation and shift in resonant frequency of deformed indenter (w.r.t. the healthy indenter). The model is computationally demonstrated using Spectral Element Method and compared with analytical closed form solutions obtained by solving the wave equations. The developed formulations are implemented as a computer module with GUI to provide self-diagnosing for AFM systems. Overall this work provides an effective mathematical tool for self-health monitoring of AFM indenters.

7984-100, Session 15

Lamb wave interaction with aerospace aluminium stringer feet

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Acoustic Emission has shown itself to be a valuable technology for reliably detecting damage initiation and growth in large structures. Monitoring of such structures, throughout its life, is possible with sparse sensor arrays. However aerospace structures can be complex environments containing many structural features, the most common being stringers. Stringers are arranged in a way that they can span the length of the wings or fuselage, separated by less than 200mm in certain cases. Therefore it is inevitable that propagating Lamb waves will interact with multiple stringers within their sparse array. Although the following study will be considering the effect of guided Lamb waves (5-cycle Hanning windowed sinusoidal signal), it is used here to simulate an Acoustic Emission event. For the purposes of the following investigation only the stringer foot has been investigated, ignoring the stringer blade found in common I-beam stringers. This has been carried using strips of sheet metal, to act as the stringer foot, conformed to a large sheet, acting as the wing or fuselage skin. A large panel has been selected to minimise the effects of edge reflections and to allow the two fundamental Lamb wave modes to separate before reception. Aluminium is currently the most common material used for aerospace stringer manufacture and has therefore been used for all tests described.

Preliminary work has shown that stringer foot height has a noticeable impact on Lamb wave propagation, for typical aerospace arrangements. A reduction in transmitted signal amplitude was noted as the stringer thickness was increased. However a local maximum was seen when the stringer foot thickness was equal to that of the plate thickness. The work presented herein discusses quantitative analysis of stringer interaction with the fundamental lamb wave modes. The effect of the stringer as a feature has been divided into three main interactions; stringer dimensions, coupling media and riveting. Each of these interactions has been investigated to determine their quantitative effect on transmission and reflection of the fundamental Lamb wave modes, in Aluminium plates.

A thorough investigation of transmission and reflection coefficients has been conducted, to assess the effect of stringer foot thickness relative to plate thickness, within the range of typical aerospace structures. To maintain consistent results, all investigations relating to the stringer foot thickness were carried out using consistent coupling agent thickness and type. Each stringer then had a consistent pressure applied and left to cure for an equal amount of time. Subsequent work was conducted to investigate the relative transmission and reflection coefficients using; standard ultrasonic coupling gel, silicon adhesive and typical aerospace sealant.

To further improve the accuracy of these results the stringers were then attached to the panel using equally spaced bolts, torqued to represent the pressure experienced by stringers in a typical aircraft wing. Significant numbers of rivets are used to attach stringers to the wing or fuselage skin in aerospace structures. Closely spaced holes drilled during the process of riveting the stringer to the structure have however shown effects on transmitted signal amplitude due to grating effects, as described in Scholey et al. Additional care was taken to position sensors in a way that they will not be affected by any grating effects.

7984-101, Session 15

Assessing the value of information for long-term structural health monitoring

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In the field of Structural Health Monitoring, tests and sensing systems are intended as tools providing diagnoses, which allow the operator of the facility to develop an efficient maintenance plan or to require extraordinary measures on a structure. The relevance of these systems depends directly on their capability to guide towards the most optimal decision for the prevailing circumstances, avoiding mistakes and wastes of resources. Though this is well known, in most studies only the accuracy of information gained from sensors is quantitatively and objectively estimated, e.g. assessing the precision of the sensors or the sensitivity of the measuring principle to relevant damage scenarios, while economical or convenience criteria are evaluated separately, with only marginal and heuristic connections with the outcomes of the monitoring campaign. Nonetheless, the concept of "Value of Information" (Vol) provides a rational approach to rank measuring systems according to a utility-based metric, which fully includes the decision making process affected by the campaign. This framework allows, for example, an explicit assessment of the economical convenience of adopting a sensor depending on its precision.

In this paper we outline the framework for assessing the Vol, as applicable to the ranking of competitive measuring systems. We will present applications related to the mitigation of seismic risk, and specifically discuss issues related to the non-linearity of the cost-to-utility function, to the case of the sequential decisions in long-term monitoring, and to the adoption of approximate numerical methods for computing the Vol.

7984-102, Session 15

Lamb wave based detection of damage in a stiffener bonded to a plate

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Stiffener is one of the major components of aircraft structures to increase the load carrying capacity. Damage in the stiffener, mostly in the form of crack is a usual problem in aerospace structures. Stiffener is bonded to the inner side of the aircraft panel which is not accessible for immediate inspection. A sensor-actuator network can be placed on the outer side of the panel that is accessible. Ultrasonic lamb waves are transmitted through stiffener using the sensor-actuator network for detecting the presence of damages. The sensor-actuator network is placed on both sides of the stiffened section on the accessible side of the plate. Detecting damage in stiffener by using this technique has significant potential for SHM technology. Wavelet based damage parameter correlation studies are carried out. In the proposed scheme, with increase in damage size along the stiffener, it is found that the amplitude of the received signal decreases monotonically. The advantage of this technique is that stiffened panels need not be disassembled in a realistic deployment of SHM system.

7984-103, Session 15

Analysis of instantaneous phase of guided ultrasonic waves in metallic structures with composite repair patches

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Lamb wave inspection is one of the most widely used damage detection techniques based on ultrasonic waves. Many signal processing techniques have been developed for extraction of signal features related to damage. The majority of these investigations focus on amplitude analysis. The paper analyses Lamb wave instantaneous phase. The Hilbert transform is used to obtain signal instantaneous characteristics. Application examples are related to smart structural repair. Cracked metallic plates are repaired using smart composite patches instrumented with low-profile, surface bonded piezoceramic transducers. The study demonstrates that phase information from Lamb waves is very useful for monitoring structural repair.

7984-104, Session 15

CUDA technology for ultrasonic guided wave simulations

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Guided ultrasonic waves (e.g. Lamb waves) are widely used in Structural Health Monitoring applications for inspections of large plate-like structures. Wave propagation phenomena associated with guided ultrasonic waves are difficult to model for complex engineering structures. Various simulation algorithms used in practice are not accurate and very expensive computationally. The paper demonstrates new parallel computation technology offered by modern Graphics Processing Units (GPUs) and Compute Unified Device Architecture (CUDA) used in low-cost graphical cards available in standard PCs. Such systems enable calculations of very large models (more than 107 elements) in minutes. Different simulation algorithms have been implemented and used for wave propagation simulations. The paper demonstrates the application of the Local Interaction Simulation Approach (LISA) and the Elastodynamic Finite Integration Technique (EFIT). Simulation results are validated experimentally using dispersion curve examples. The approach presented in the paper can be linked with classical finite element multi-physics modelling tools allowing for accurate modelling of piezoceramic transducers used for actuation and sensing. Application examples are related to structural damage detection.

7984-105, Session 15

Utilization of wavelet analysis for determination of back wall effects in health monitoring of small coupons

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Contemplating into why different results are obtained from similar wave propagation experiments of acoustic emission conducted by a host of researchers from industry to academe in light of environment's geometry have been subjects of many studies. One such difference has been observed while using small coupons or belts as experiment samples in comparison with bigger or wider sheets in industrial scale. The difference in question; is perhaps more noticeable here and could be better justified than in any other application.

A principal contributor to the existence of such differences is known as Back Wall effect. This phenomenon, in addition to strengthening the signal energy and increasing the number of peaks with higher thresholds of signal recording, changes the frequency value of the analyzed signal within the designated time frame. Furthermore, upon careful analysis, it has the capability of providing related information as to reasons behind yielding different outcomes of similar experiments.

In this investigation, simulation of similar conditions are carried out by generating acoustic waves within an aluminum sheet to study the Back Wall effect received from the outermost wall through wavelet analysis. An assortment of geometries will be considered and a range of available shape of already available sheets will be chosen from. Obtained results from this investigation however, will not be limited to small coupons or belts alone and are extendable to long sheets at the time of sensor installation at sidewalls.

1-Directoe & Associate Professor 2-Ph.d. Graduate Student

7984-110, Session 15

The Smartbrick wireless sensor node for high-resolution structural health monitoring

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This paper introduces a wireless sensor node for the SmartBrick platform, which provides a low-cost and autonomous method for structural health monitoring. Design and testing of the SmartBrick base station have been described in previous publications. The SmartBrick sensor node presented in this paper leverages the Zigbee short-range communication capabilities of the base station to increase the monitoring range of the system. The primary function of the node is to interface to humidity, temperature, tilt, strain, and vibration sensors and transmit their values to the base station via Zigbee. The GSM modem included in the base station has been omitted from the sensor node, in order to reduce cost, form factor, and power consumption. Long-range communication of data and alerts will be through the base station, which serves as the gateway to the outside world, and relays remote configuration and maintenance commands to the sensor nodes.

One of the primary motivations behind development of the sensor node is high-resolution monitoring of strain. Each wireless sensor node will be able to measure strain from 16 different locations on a structure, by multiplexing these gauges to the same signal conditioning circuit, which drastically reduces the number of nodes required for monitoring an area. Data collection can take place at regular intervals, or when triggered by events of interest. Each sensor node includes sufficient memory to store a day's data, although the system default is to transmit the collected data to the base station once per hour.