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2013 Smart Structures/ NDE

10-14 March 2013

Technical Summaries

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Location
Town & Country Resort
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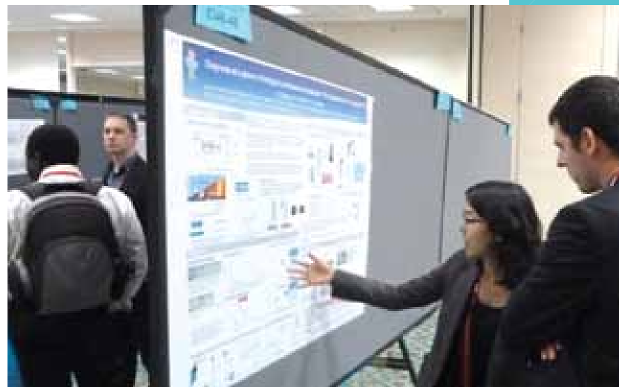
San Diego, California, USA

Conferences & Course
10–14 March 2013

Exhibition
12–13 March 2013



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SPIE Smart Structures/NDE

Technical Program

CELEBRATING 20 YEARS SPIE SMART STRUCTURES/NDE

Conferences & Courses: 10–14 March 2013 Exhibition: 12–13 March 2013
Town & Country Resort and Convention Center, San Diego, California, USA

8686-1, Session KEY

Biomimetic textiles *(Keynote Presentation)*

Michael S. Ellison, Clemson Univ. (United States)

Clothing is quintessentially human. While there are, of course, reports of other species using natural materials for shelter, there are no reports of, for example, monkeys wearing clothing of their own making (the organ grinder man's venerable friend notwithstanding). It is a common belief that animal skins and even vegetation (e.g., fig leaves) were used as body coverings. Whatever their inception, textiles and clothing have been present in human history since the earliest records and reflect both the raw materials available to a people and the technologies that they developed.

In a sense, the archetype of bioinspiration for materials design and use is textiles. The field of biomimesis has spawned many new materials and continues to be a fruitful field of investigation, so it behooves us to explore its roots. This talk begins with an introduction to textiles, in that I have found many preconceived notions about the field that need addressing before the application of biomimetics to textiles can be truly appreciated. Next, naturally enough, some details on fiber and textile science and engineering, and biological concepts that resonate with textiles, are discussed. Some examples of remarkable fibrous materials, including spider silk, and Hagfish slime threads, are presented. Finally, the marriage of biomimesis and textiles is performed and some consequences revealed.

8686-2, Session 1

Bioinspired hydraulic control systems

Michael A. Meller, Ephrahim Garcia, Cornell Univ. (United States)

Hydraulic control is an attractive actuation means due to its high force density and quick response. Some of the major drawbacks of traditional hydraulic systems include system inefficiency and leakage. In order to be more efficient, momentum, gravity, and other forces must be allowed to help translate the hydraulic actuators instead of the actuators always working against these loads. A common example in nature where passive dynamics is utilized to operate at optimum efficiency is the swing phase of the human walking gait. Taking inspiration from this, a spool valve that can actively drive a double-acting hydraulic cylinder in both directions, hold its current position, and dangle has been developed and modeled. The novel feature of this valve is the dangle function which permits the fluid to freely flow between both cylinder chambers and the return reservoir. This yields efficiency gains due to the utilization of passive dynamics rather than only actively driving the actuators. Additionally, leakage can be reduced while attaining more biological motion by implementing fluidic artificial muscles in antagonistic pairs instead of using traditional cylinder actuators. These artificial muscles are almost always actuated pneumatically, and characterization tests of these muscles being utilized hydraulically are reported as well.

8686-3, Session 1

Nonlinear analysis of quasi-static response of pneumatic artificial muscles for agonistic and antagonistic actuation modes

Ryan Robinson, Norman M. Wereley, Univ. of Maryland College Park (United States); Curt S. Kothera, Techno-Sciences Inc. (United States)

Pneumatic artificial muscles (PAMs) have excellent actuator characteristics, including high specific work, specific power, and power density. Recent research has focused on applying such pneumatic actuator technology to robotic or aerospace applications. However, to enable accurate feedback control of systems employing such PAMS, the actuators must be characterized in terms of blocked force, and free contraction over pressures ranging from 1-120 psi. In addition, because these actuators are applied in actuation schemes with bioinspired antagonistic muscle kinematics, the antagonistic force was also characterized, that is, the force was measured when stretching the muscle beyond its resting length in the absence of air pressure. During these experiments, four key nonlinear phenomena were observed: nonlinear PAM stiffness, hysteresis of the force vs. displacement response for a given pressure, a pressure deadband, and antagonistic stiffening. To analyze the nonlinear aspects of PAM response, a nonlinear stress vs. strain model, a hysteresis model, and a pressure bias were introduced into a refined force balance analysis. Parameters of these nonlinear model refinements were identified from measured force vs. displacement data. The improved nonlinear force balance model captures the nonlinear actuation behavior of the PAMs over the operating pressure range. It is also shown that this analysis reconstructs quasi-static PAM response with much higher accuracy than has been previously reported.

8686-4, Session 1

Characterization and modeling of geometric variations in McKibben pneumatic artificial muscles

Erick J. Ball, Yong Lin, Ephrahim Garcia, Cornell Univ. (United States)

This paper presents experimental data on the actuation properties of McKibben muscles constructed with varying bladder pre-strain and thickness. The tests determine quasi-static force-length relationships during extension and contraction, for muscles constructed with unstretched bladder lengths 50%, 67%, and 100% of the stretched muscle length, as well as two different wall thicknesses of the rubber. Existing models do not adequately describe the effects of these variations, making it difficult to determine the best geometry for an application. The quasi-static actuator force and maximum contraction length are found to depend strongly on the thickness and modulus of the rubber, as well as the amount of pre-strain. A model is presented to better predict force-length characteristics from geometric parameters. It accounts for the nonlinear elastic properties of the bladder, friction, and stiffness of the mesh strands and end connectors. It includes axial force generated by stretching the bladder during construction, and it also describes the hoop stress created by radial expansion of the bladder, which partially counteracts the internal fluid pressure that presses outward on the mesh, thus reducing both axial force and friction between the mesh and bladder. The axial force generated by the mesh is found directly from contact forces rather than from potential energy. This method allows the calculation of the tension in each mesh strand, which determines how much they stretch. The model closely matches the experimental data on wall thickness, while the effects of bladder pre-stretching are not fully explained.

8686-5, Session 2

Analysis of fish and bioinspired robotic fish swimming together in a water tunnel *(Invited Paper)*

Giovanni Polverino, Andrea Facci, Paul T. Phamduy, Marco Drago, Kamran Khan, Lu Yang, Maurizio Porfiri, Polytechnic Institute of New York Univ. (United States)

The possibility of integrating biomimetic robots in groups of live social animals may constitute a valuable tool to investigate the bases of social

behavior and explore the fundamental determinants of animal functions and dysfunctions. Here, we investigate the interaction between individual Golden shiners (Notemigonus crysoleucas) and robotic fish swimming together in a water tunnel. The robotic fish is designed to mimic its live counterpart in terms of aspect ratio, body shape, dimension, and swimming pattern. The latter feature is addressed through the design of a miniature multi-link mechanism that allows for replicating the species-specific locomotory pattern of carangiform-subcarangiform swimmers, wherein a large portion of the body undulates to propel the animal.

Fish positional preference with respect to the robot is determined using two orthogonal references, that is, frontal and sagittal planes. The flow structure generated by the robotic fish tail-beat is investigated using a digital particle image velocimetry (PIV) system. Experiments are conducted by systematically varying the color pattern and tail-beat frequency of the robot to offer insight into the role of visual and hydrodynamic cues in shaping fish-robot interactions. Experimental results show that both the robotic fish tail-beat frequency and color pattern influence the positional preference of live individuals. Specifically, fish-robot interaction is maximized when the robot mimics both the visual aspect and swimming pattern of its animal counterpart, that is, when the color of the robot is silver and its tail beat frequency equal to 3 Hz for a flow speed of approximately 10 cm/s.

8686-6, Session 2

Enhanced propulsion from converging radial velocity in jellyfish jetting

Michael Krieg, Doug Lipinski, Kamran Mohseni, Univ. of Florida (United States)

The morphology of the velar cavity opening of jellyfish Sarsia tubulosa is examined as it relates to propulsive performance. Jellyfish propel themselves through the water by successively ingesting and expelling jets of fluid out of the velar cavity. This species creates a distinct high momentum jet with each cycle unlike more oblate species of jellyfish like Aequorea victoria whose wake contains a highly packed array of thin cored vortex rings. The exact shape of a swimming Sarsia tubulosa was captured visually, and exported to a direct numerical simulation (DNS) to recover the motion of fluid around the jellyfish, which was used to determine propulsive efficiency in Sahin et al. (2009), and analyze swimming patterns as they relate to feeding by Lipinski & Mohseni (2009).

Here the velocity field data is analyzed according to a jet control volume analysis (derived in Krieg & Mohseni (2012)) to determine the effect of `nozzle’ morphology on the propulsive jet output. The control volume analysis assumes an axisymmetric inviscid fluid jet allowing the rate at which circulation, impulse, and energy are created, as well as the pressure at the `nozzle’, to be solved in terms of velocity profiles. Viscous losses play an important role at the low Re jellyfish swimming, and are subtracted from the flux of quantities into the domain, resulting in excellent agreement with the bulk quantities. It is observed that converging radial velocity resulting from the conical shape of the `nozzle’ increases the total impulse of the jet by nearly 30% over a parallel jet with identical parameters. The converging radial velocity also nearly doubles the total circulation of the jet which can benefit the feeding at downstream tentacles.

8686-7, Session 2

Effect of oral and tentacle structure on the propulsion and feeding of bio-inspired Mastigias papua robot

Tyler Michael, Alex Villanueva, Pavlos P. Vlachos, Shashank Priya, Virginia Polytechnic Institute and State Univ. (United States)

This study reports progress towards understanding the low energy propulsion mechanisms of Hydromedusa (jellyfish) for developing energy efficient autonomous underwater vehicles (AUV). In conjunction to propulsion, another area of interest in our investigations is the sustainability of AUVs for long periods of time. To achieve this goal, we take inspiration from the constant feeding and energy generation achieved by jellyfish. The feeding mechanism can be used to supply nutrients to the microbial fuel cells within the artificial structure to convert chemical energy into electricity. The Rhizostome model in particular utilizes oral structures comprised of internal channels that capture zooplankton on distal capture surfaces. The effect that the simulated oral arms and terminal clubs have on the hydrodynamics of the AUV must be fully understood. The robot’s physical dimensions were based on the morphology of Mastigias papua with a bell diameter of 16.4 cm. Geometry and structure were derived from literature, live samples, and digitization of video of natural animals. Based upon this data the AUV was molded out of silicone and assembled to achieve jellyfish like architecture. The assembled robot was inserted into a water tunnel to simulate the average swimming velocities of 12 cm/s with minimum and maximum pulsation velocities of 7 and 17 cm/s respectively. A stereo Particle Image Velocimetry (PIV) setup was utilized to resolve the velocity fields around the AUV while varying morphological parameters such as the length of terminals clubs and density of branching from the internal channels of the oral arms. The results of these experiments provide a hydrodynamically optimum configuration for the oral structure and terminal clubs of the Mastigias Papua robot.

Acknowledgement: The authors gratefully acknowledge the financial support from Office of Naval Research.

8686-8, Session 3

Solution-based techniques for bioreplication *(Invited Paper)*

Michael H. Bartl, The Univ. of Utah (United States)

Nature generates structurally complex architectures with feature sizes covering several length scales under rather simple environmental conditions and with limited resources. While we start to better understand the structure-property relationship for many of these biological architectures, in many instances, we still lack the ability to create such hierarchical structures with similar functionalities. In recent years, significant progress in fabricating functional architectures with similar structures as those found in nature has been achieved with bioreplication techniques. Bioreplication combines the strength of two worlds: structural engineering in biology with materials fabrication and processing. Borrowing nature’s structural blueprints as templates enables synthesis of polymeric, ceramic and metallic materials with entirely new nano-to-microstructural features. Such bioreplicated materials are interesting for a range of applications, including optical materials, high surface-area scaffolds in catalysis, and coatings with interesting properties such anti-fouling, superhydrophobicity, and anti-icing. Among the various bioreplication techniques, solution-based methods provide simple, inexpensive routes to generating bioreplicated structures. In this talk, we will give a general introduction into different solution-based bioreplication methods and provide an example for generating three-dimensional photonic-crystal structures based on colored weevil scales. In particular, we will focus on sol-gel chemistry methods and demonstrate how sol-gel parameters can be adjusted to tune properties of bioreplicas (refractive index, filling fraction, type of replica). We will discuss the properties of these new structural materials and show how bioreplication can be used to create new optical materials with fascinating properties.

8686-9, Session 4

Functionalization of biomaterials with metals by atomic layer deposition (ALD) *(Invited Paper)*

Seung-Mo Lee, Korea Institute of Machinery and Materials (Korea, Republic of); Mato Knez, CIC nanoGUNE Consolider (Spain)

Atomic layer deposition (ALD) is a thin film deposition technique, which was developed in the 1970s to meet the needs for processing thin film electroluminescent displays (TFEL). Technically and chemically it is similar to chemical vapor deposition (CVD). However, in contrast to CVD, ALD separates the chemical reaction into two half-reactions. The exposure of the substrate to separate precursor vapors allows for chemical saturation of the substrate surface with a monolayer of the precursors and thus for a precise sub-Å growth control in a cycle-by-cycle manner. In addition, being a non-line-of-sight deposition technique, ALD allows good coating conformality even with 3D nanostructured substrates or structures with a high aspect ratio together with a good capability for upscaling.

A recently evolving application of ALD deals with the modification of phyical properties of soft materials after infiltration of metals by ALD. Although the detailed chemistry behind the approach is barely understood, biological or organic materials, such as spider silk, collagen, or diverse polymers can change their mechanical properties after being treated with pulsed vapors of metal precursors. The toughness of such materials increased by up to 10-fold, outperforming most manmade materials. With such potential to produce (bio)organic-inorganic hybrid materials, the infiltration by ALD promises use in the textile industry or the production of artificial tissues.

The talk will show various approaches towards functionalization of biomaterials through insertion of metals by means of ALD.

8686-10, Session 4

Biomimetic topologically and chemically tuned CVD-grown nanodiamond layers and their biointeractions

Hans J. Fecht, Andrei P. Sommer, Ulm Univ. (Germany)

There is increasing observational evidence for an implication of the order of interfacial water layers in biology, for instance in processes of cellular recognition and during first contact events, where cells decide upon survival or entering apoptosis. Experimental methods allowing access to the order of interfacial water layers are thus crucial in biomedical engineering. Here we show that interfacial water structures can be nondestructively analysed on nanocrystalline diamond. layers having atomic scale roughness and bioinspired surface topography (resembling a “strawberry pattern”). The sampoles have been prepared by a combination of CVD and photolithographyic processes. This approach opens the gate to a new chapter in the design of biomaterials inspired by biomimetic principles. Recent results on the role of topological surface modification and chemical surface termination of stress-free nanocrystalline diamond layers or free-standing films for biocompatible and biomimetic materials will be discussed.

8686-11, Session 4

Biomolecular hydrogel-based lipid bilayer array system

Joseph Najem, Donald J. Leo, Virginia Polytechnic Institute and State Univ. (United States)

Animals have the ability to sense a wide range of stimuli through hair cell receptors. These mechanical sensors are found in a range of animal species especially in the inner ears for vestibular and auditory sensing. For instance, the human cochlea contains around 16,000 hair cells in addition to 135,000 vestibular hair cells. These hairs vary in dimension which provides a wide range of frequency selectivity.

Inspired by the natural hair cell structure and function, recent research in our group has demonstrated that hair-like structures embedded in artificial cell membranes can serve as flow and vibration sensors in a similar fashion to the mechanotransduction system found in the hair cell. In our previous work, artificial hair cell was formed in an open biomolecular unit cell, where the transduction element is an artificial cell membrane, or a lipid bilayer. However, this study motivated the need to develop biomolecular devices featuring arrays of artificial hair-cells that mimic the frequency discrimination properties of the human cochlea.

This work investigates the fabrication of hydrogel based lipid bilayers arrays using micro fabrication technologies that enable high precision in controlling the cell-scale droplets. Arrays of hydrogels that support curved aqueous lenses are deposited on two parallel substrates using photolithography techniques on top of a network of Ag/AgCl electrodes. First step in the fabrication process is to deposit silver electrodes using physical vapor deposition through a mask, a layer of silver chloride is then formed around the silver channels using electroplating. The hydrogel arrays are then achieved by exposing a thin film of photocrosslinkable hydrogel to light through a mask. The last step is to deposit thin aqueous curved lenses on the hydrogel arrays.

Bilayer arrays are formed by using a technique similar to the regulated attachment method (RAM), where mechanical force is used to bring adjacent aqueous lenses in contact. Capacitance and protein gating measurements of the multi array interface bilayer, are used to prove the ability of bilayer formation using arrays of gel-supported aqueous lenses.

8686-12, Session 5

Biomimetic optical sensor for real-time measurement of structural bending deflection *(Invited Paper)*

Susan A. Frost, NASA Ames Research Ctr. (United States); Robert Streeter, Cameron H. G. Wright, Steven F. Barrett, Univ. of Wyoming (United States)

Research at NASA focused on reducing the environmental impact of aviation depends on accurate wing deformation measurements to enable safe and efficient operation of new aircraft configurations. Existing sensor solutions, such as strain gauges, are hindered by high computational requirements. A bio-mimetic vision sensor (based on Musca domestica, the common house fly) for detecting aircraft wing deformation is described. The sensor is a very small, low power device that makes use of revolutionary optical sensor design resulting in significantly improved motion detection capabilities when compared with conventional optical sensors. The simple analog architecture allows for real-time solution at any desired bandwidth to enable accurate measurement of structural bending deflection.

While much of the work to date on compound insect eye based sensors has focused on the apposition compound eye, the neural superposition compound eye has been the basis for previous research by the authors. This paper describes extensions to previous work to create a sensor that includes groupings of photoreceptors with seven parallel optical axes and seven partially overlapping Gaussian response curves. The signals from the six photoreceptors in the “outer ring” of a group are combined using signal routing and analog preprocessing circuitry to create the bio-mimetic equivalent of the laminal cartridge. Any arbitrary number of these artificial ommatidia can be combined to create the desired sensor characteristics for the application. The proposed sensor takes advantage of the motion hyper-acuity inherent in its design to detect extremely small motions, thereby enabling structural deflection measurements.

8686-13, Session 5

A μ-biomimetic uncooled infrared sensor

Georg Siebke, Siegfried Steltenkamp, Ctr. of Advanced European Studies and Research (Germany)

The beetle Melanophila acuminata detects forest fires from distances of about 80 miles. For the detection of the fire, the beetle uses specialized infrared-sensing receptors. Inspired by this extremely sensitive natural device, we are developing an uncooled IR sensor.

The beetle’s IR receptors are based on a fluid-filled pressure cell. By absorbing IR radiation, the fluid heats up and expands. The receptor senses the ensuing pressure increase using a mechanoreceptor. To discriminate between fast and small pressure signals, evoked by a distant heat source and slow and large background signals, due to changes in ambient temperature, the beetle has developed a sophisticated compensation mechanism.

Our sensor will feature a size of a few mm2 and is fabricated using silicon MEMS. The sensor uses the same mechanism as the beetle's IR receptor, except for pressure sensing. The pressure increase inside the pressure cell deflects a membrane on top of which one electrode of a plate capacitor is located; this evokes changes in capacitance of a few femtofarad. A long and narrow channel connects the pressure cell to a compensation chamber. To the outside, this chamber is sealed by a thin and elastic PDMS membrane. The channel enables the slow transfer of fluid to the compensation chamber while the thin membrane maintains the pressure inside this chamber close to the ambient pressure. Without this mechanism, the high pressure inside the capacitor chamber would destroy the sensor.

This presentation focuses on the technical design and the progress of the manufacturing process.

8686-14, Session 6

Integration and flight test of a biomimetic heading sensor *(Invited Paper)*

Javaan S. Chahl, Univ. of South Australia (Australia); Akiko Mizutani, Odonatrix Pty Ltd. (Australia)

We report on the first successful development and implementation of an automatic polarisation compass as the primary heading sensor for a UAV. Polarisation compassing is the primary navigation sense of many flying and walking insects, including bees, ants and crickets. Manually operated polarimeters were fitted in passenger airliners operating over the arctic prior to the advent of the global positioning system to compensate for the dangerous degradation of conventional navigation sensors in Polar Regions.

The device we developed demonstrated accurate determination of the direction of the Sun, with repeatability of better than 0.2 degrees and linearity of better than 0.5%. These figures are comparable to any solid state magnetic compass, including flux gate based devices. Practical calibration of a polarimeter for navigation required the development of new techniques. Challenges also existed in managing the configuration of optical system, both in terms of intensity of measured skylight and in developing an optical design to exclude direct and reflected sunlight. Integration of the sensor into an integrated flight control sensor suite also required a new approach, and a new understanding of the limits of polarisation sensors.

The performance and characteristics of a calibrated solid state magnetic compass and the polarisation compass will be compared. Flight trials were undertaken in which the output of the polarimeter was the only heading reference used by the aircraft as it flew GPS waypoints and followed heading commands without GPS. The aircraft was fully instrumented with a magnetometer aided attitude reference unit and a GPS unit allowing an assessment of in-flight performance to complement static testing. The use of a biomimetic sensor in this way is a microcosm of the general problem of creating a hybrid system that is partly conventional and partly biomimetic.

8686-15, Session 6

Biomimetic image processing techniques for use on fly-inspired vision sensors

Brian K. Dean, Oakland Univ. (United States); Cameron H. G. Wright, Steven F. Barrett, Univ. of Wyoming (United States)

Previous research efforts in mimicking the compound eye of Musca domestica, the common house fly, in hardware have primarily been focused on optical design. These designs have shown that the fast, analog, parallel and motion hyperacuity properties of the biological system can be mimicked through various optical techniques. However, before the benefits of this type of sensor can be fully realized, a processing system has to be designed that is also fast, analog, and parallel. In addition, this system has to preserve the hyperacuity characteristic of the optical platform. This paper will discuss a processing system that is being investigated for use with two different fly-inspired optical front ends. Techniques for achieving biomimetic light adaptation and edge detection will be discussed, and these techniques will be compared and contrasted with techniques used on traditional imaging systems. It will be shown that the underlying structure that allows for motion hyperacuity can be utilized to improve the accuracy of locating small linear objects such as power lines.

8686-16, Session 6

Geodermis: Biomimicry of distributed sensing for earth-based building

Hae-Bum A. Yun, Univ. of Central Florida (United States); Lakshmi Reddi, Florida International Univ. (United States); Toni-Gaye McCulloch, Bryan Paul, Univ. of Central Florida (United States)

The issue of sustainable development in building engineering has been discussed since the early 90's. The current research seeks to aid in this endeavor by reducing the heating and cooling loads on a building through its envelope, more specifically the wall material. The problem as viewed by most researchers is that the most common building materials, such as concrete and steel, allow for easy heat and mass transfer into buildings. Researchers now look to earth-based materials as passive building materials for increased thermal regulation. The building envelope of earth-based materials is an important buffer for heat and mass transfer into the building environment, but is a part of a bigger picture, which includes hygrothermal loads from the occupants and other facets of the indoor environment, as well as the mechanisms that regulate the indoor environment.

This research looks at the soil-based building materials in different light. Our premise is that an understanding of the analogies between thermoregulatory systems in skin, plant, and soils, would inspire us to use soils as intelligent materials in stabilized earth construction with their pore geometries engineered based on these analogies. This biomimetic approach of developing "geodermis" can be broken into two smaller problems: (1) "sensory/nervous systems" to collect and process surrounding hygrothermal data, and (2) "motor system" for semi-active hygrothermal control with the combination of passive regulation by soil and active regulation based on the information from the sensory/nervous system.

An on-going international collaborative study between the University of Central Florida (UCF) and Florida International University (FIU) in USA, University of Nottingham (UON) in UK, and Auroville Earth Institute (AEI) in India is being conducted for long-term continuous monitoring for earth-based buildings. The field test site is located the AEI, which is located 10 km north of Pondicherry, on the Coromandel Coast of southern India. The climate is tropical with its dry season from January to May and its rainy season from June to December. The temperature ranges from 24°C to 40°C in the dry season. The selection of the AEI as the field site is highly desirable since as a representative of the UNESCO Chair "Earthen Architecture, Constructive Cultures and Sustainable Development," the AEI is known for researching, developing, and promoting earth-based techniques, such as building technologies using compressed stabilized earth blocks (CSEB). A total of 20 temperature and 4 humidity sensors were installed to a building made of the CSEB. A web-based monitoring system was developed to transfer the sensor data from the publisher at the to the server at the UCF. The sensor data are further transferred to the "clients" at FIU and UON for hygrothermal analysis. Using the field monitoring data and hygrothermal analysis results, this paper focuses on the development of sensory/nervous system of geodermis.

8686-17, Session 7

Approaching limits of sensing using neuromorphic noise-exploitation principles *(Invited Paper)*

Shantanu Chakrabartty, Michigan State Univ. (United States)

Neurobiological sensing systems serve as a marvel of nature's engineering by achieving energy efficiency (bits per Joule) that is orders of magnitude superior to its synthetic counterparts. For example, the filiform hair in crickets can sense mechanical stimuli at fundamental limits of noise. The electro-sensitive cells in an electric fish can detect small insects in its environment even in the presence of hydrodynamic disturbances. The auditory sensors in the parasitoid fly Ormia ochracea can precisely localize ultra-faint acoustic signatures in spite of the underlying physical limitations. A common recurring theme amongst the neurobiological sensing systems is the constructive role "noise" plays in signal processing. In man-made sensors, device and sensor noise are typically considered as a nuisance, whereas in neurobiology "noise" has been shown to be a computational aid that enables sensing and operation at fundamental limits of energy efficiency and performance. In this paper, we first describe two important noise-exploitation techniques: (a) stochastic resonance; and (b) noise-shaping and then we discuss how these principles can be used for designing neuromorphic sensors. Within the context of noise-exploitation, we will present a design framework called sigma-delta learning that integrates the noise-exploitation principles within neural dynamics. As a case-study, we describe the application of sigma-delta learning for the design of a miniature acoustic source localizer whose performance matches that of its biological counterpart (Ormia ochracea).

8686-18, Session 7

Bat biosonar as an inspiration for dynamic sensing

Rolf Mueller, Virginia Polytechnic Institute and State Univ. (United States)

Sensory systems found in nature continue to outperform their man-made peers in many respects. In particular, their ability to extract salient information from complex, unstructured environments is often superior to engineering solutions. Bat biosonar is an example for an exceptionally powerful yet highly parsimonious sensing system that is capable of operating in a wide variety of natural habitats and achieve a likewise diverse set of sensing goals. One aspect in which bat biosonar appears to differ from man-made sensing of acoustic or electromagnetic waves is its heavy reliance on diffraction-based beamforming with intricate baffle shapes. Observations of these baffle shapes in live bats with high-speed video have provided evidence for non-rigid baffle deformations that coincide with the diffraction of the outgoing or incoming waves. In horseshoe bats, a bat group with one of the most elaborate biosonar systems, the emission baffles (noseleaves) have been found to twitch in synchrony with each pulse emission. On the reception side, the animals' outer ears can likewise be deformed while the incoming pulses impinge on them. The acoustic effects of the outer ear motions can be characterized using frequency-domain characterizations (beampatterns) revealing significant acoustic effects. However, a time-domain characterization of a biomimetic prototype has shown even stronger effects. Hence, it may be hypothesized that these mobile baffle provide a substrate for a time-variant strategy for the encoding of sensory information - a hypothesis that is well suited for further exploration with bioinspired sensing technology.

8686-19, Session 8

Simulation analysis on the optical role of the various structural disorder in the Morpho butterfly's color *(Invited Paper)*

Akira Saito, Takuto Shibuya, kosei Ishibashi, Megumi Akai-kasaya, Yuji Kuwahara, Osaka Univ. (Japan)

Morpho butterfly's conspicuous blue is well known as an example of the structural color and attracts interest due to a metallic luster produced by their organic body. The blue is produced by their scales containing no pigment. The basis of the color with high reflectance (> ~60%) is then attributed to an interference from a periodic microstructure. However, the blue observed in too wide angle (> ± 40° from the normal) cannot be explained by interference. This mystery has been clarified by a specific nanostructure that contains nano-disorder preventing the rainbow coloration. This principle has been proved successfully by emulating the 3D nanostructures by deposition of multilayer film on a nano-patterned substrate designed with a specific disorder. Such artificial structural color has recently been found to have wide potential applications. However, for the true applications, we need to predict and simulate the coloration and spectra from the nanostructures containing nano-disorder that has long been difficult to treat by analytical calculation. However, the recent FDTD method enabled us to predict the optical properties of the disordered nanostructures by numerical approaches. Thus, we could analyze theoretically the optical roles of the several different kinds of nano-disorders in the Morpho butterfly's scale. These analyses will serve not only to understand the optics on the nano-disorder, but, also to design artificially the specific Morpho-color.

8686-20, Session 8

Optical simulations of biomimetic nanostructures and applications *(Invited Paper)*

Surojit Chattopadhyay, National Yang-Ming Univ (Taiwan); Yi-Fan Huang, National Yang-Ming Univ. (Taiwan)

Many natural surfaces are texturized in the nano-scale to impart certain optical properties, such as anti-reflection, and wetting properties, such as superhydrophobicity in lotus or certain plant leaves. The cornea of the moths or wings of Cicada has tiny conical burls that reduce reflection (in moths) and increase transmission (in Cicada) of the surfaces. We have fabricated nano-tip structures on semiconductor (Si, GaAs, GaP, GaN) surfaces by a top-down type self masked plasma etching process involving a plasma of silane, methane, hydrogen and argon. Biomimetic silicon and GaAs nanotips demonstrated ultra low optical reflectance over a broad spectral range from UV to THz. Since these are subwavelength structures (SWS) we could simulate their optical properties with VASE and FDTD softwares. Selection of suitable models could lead to exact simulation of the experimental data obtained on these surfaces. The anti-reflection properties are explained on the basis of gradient refractive index (GRIN) profiles of these structures. The plasma etching can be tuned with respect to substrate properties to arrive at superior surface designs meeting the application needs. For example, silicon nanotips demonstrated geometry-tunable hydrophilicity (water contact angle, C. A, ~2°) and chemically-tunable hydrophobicity. Substrate properties such as doping, and polarity, could offer interesting photonic and phononic signatures when textured.

Another application of these nanotips is in molecular sensing via surface enhanced Raman scattering (SERS). Optical sensing of DNA has been demonstrated at the sub-picomole level using self assembled silver nanoparticle (AgNPs) decorated gold nanotip (AuNT) arrays. The plasmon field distribution, from FDTD simulation, of such AuNP clarifies why the assembly is a good SERS substrate.

8686-21, Session 8

Progress toward visual decoys to trap the male emerald ash borer

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The Emerald Ash Borer (EAB), Agrilus Planipennis, is an invasive species threatening the ash trees of North America. EABs exhibit a mating behavior in which the flying male will spot a stationary female at rest, then execute a pouncing maneuver where he dives sharply onto the female. It is thought that this pouncing behavior is cued by some visual signal from the elytra of the EAB. Here we present a method for reproducing the elytra of the EAB. These bioreplicated elytra were then used in an experiment which compared four types of bioreplicated EAB decoys with a dead EAB female to determine if the artificial lures were effective at cuing the pouncing behavior in males. Artificial decoys were produced by hot stamping polymer sheets which had a quarter-wave-stack Bragg reflector deposited on its upper surface and a black absorber layer deposited on its lower surface. The negative die used in the hot stamping process was produced by initially coating an EAB with an ~ 500 nm thick evaporated nickel layer which was then reinforced by electroforming and mounted in a steel ring which could be electrically heated. The positive die was produced through successive castings of the negative die; first with a soft polymer and then with a hard epoxy. The positive die was then mounted to a stainless steel plate which was electrically heated. Over 100 artificial lures were produced, demonstrating this technique's industrial scalability. It was found that several variations of artificial decoys produced in this way were more effective than dead EAB females at cuing the pouncing behavior in males.

8686-22, Session 9

Design and simulation of an intra-ventricular assistive device for end stage congestive heart failure patients

Milad Hosseinipour, Mohammad H. Elahinia, The Univ. of Toledo (United States)

In an attempt to produce a less invasive and more suitable alternative for current ventricular assistive devices, this study proposes a novel intra-ventricular VAD for end stage heart failure patients. VADs are approved by FDA as "short-term" to "destination" therapies for patients at NYHA Class IV level as an alternative to heart transplant. While current devices generally need open heart surgery, the flexible structure and thin active membrane, made of Ionic Polymer Metal Composites and Shape Memory Alloys, enables the transcatheter implantation and so eliminating the thoracotomy. Also exerting almost no shear stress on blood cells and having no stagnant points reduces the risk of hemolysis and thrombosis. Hemodynamics of eligible patients is first examined to define the average working conditions and supply needs. Different motion mechanisms are then evaluated to find the one with maximum volume displacement and True Forward Flow (TFF) ratio. As the preliminary evaluation of the device, 1D results of the FEM solution to the governing differential equation of the electrochemical behavior of IPMCs are extended to 3D to check the compliancy of IPMCs with those needs defined by hemodynamics and motions analysis. Although modeling and simulation results provided in this paper are for left ventricle, the same progressive design and test processes are valid for right ventricle.

8686-33, Session PTues

Bionic design and analysis of morphing trailing-edge

Weilong Yin, Harbin Institute of Technology (China)

The flexible trailing-edge actuated by pneumatic muscles is developed from the viewpoint of bionics in this paper. The alternate contraction of pneumatic muscles located on the upper and lower surface makes the deformed wing surface smooth, Continuous and Seamless. The pneumatic muscle with the outer diameter of 4mm is developed. The experimental results show that the maximum output force of pneumatic muscles fibers with the diameter of 4mm is 27N when the air pressure is 0.4MPa and the maximum contraction ratio can reach 26.8%. The mechanical model of the flexible trailing-edge actuated by pneumatic muscles is developed by use of deformation theory of the elastic beam. The effect of the bending deformation on the axial displacement is considered. The numerical results show that the deflection angle of the flexible trailing-edge can be controlled by adjusting the pressure of the pneumatic muscle. The deflection angle of the steel plate with the thickness of 0.6mm can be up to 20° when the pressure of the pneumatic muscle is 0.3MPa.

8686-34, Session PTues

Experimental analysis on the effect of milk fat concentration on light scattering intensity

Jinying Yin, Harbin Institute of Technology (China)

An important indicator that gets more and more attention to measure the quality of dairy products is ingredient content of nutrients in dairy products. One of main component of milk, the concentration of milk fat is of great significance for light scattering measurements. The photomicrograph of the different homogeneous state of milk fat solution with is different concentrations obtained by using high magnification optical microscope. And the particle size distribution of different homogeneous state and different concentrations of milk fat solution are analyzed. Based on the principle of light scattering technique for the detection of milk composition, as well as analysis of the physical and chemical properties of milk fat solution, the energy spectrum, absorbance spectrum, the transmittance spectrum of the different homogeneous state and the different concentrations of milk fat solution are determined by the dual-beam spectrophotometer (TJ270-60). Then the effects of fat solution concentration, particle size distribution and homogeneous state on the light scattering intensity are analyzed. Furthermore, it is derived the relationships among milk fat solution concentration with energy, absorbance and transmittance based on experimental results. This study will bring a progress in processing quality control of product, and contribute to promote the development of China's dairy industry for bringing practical significance and great economic benefits.

8686-35, Session PTues

Inspiration from Morpho wing scales structrue to design advanced optical materials

Wang Zhang, Di Zhang, Shanghai Jiao Tong Univ. (China)

Nature generates 150,000 to 200,000 Lepidoptera species (butterflies and moths). Each has more than one kind of wing scales with three dimensional (3D) complicated sub-microstructures. In this work, we first introduce the fabrication of inorganic oxides replica of the morpho wing scales.

Microstructure characters of original butterfly wing scales were maintained faithfully in this biomorphic inorganic replicas, such as ZnO, TiO_2 and ZrO_2. All these replicas can reflect iridescent visible lights, which can even be observed by naked eyes. The uniform blue colour of Morpho butterflies have been known as interference of light due to the

multilayer of cuticle and air. But the multilayer structure isn't consistent with Morpho's low angular dependence. The irregularity in the lamellae deviation destroys the interference among neighboring ridges, which results in the diffuse reflection in a wide angular range. The wide angular range was investigated using finite-difference time-domain (FDTD)/ particle swarm optimization (PSO) analysis. Using FDTD method different parameters of Morpho's tree-like structure were studied and their contribution to the angular dependence was analyzed. Moreover, the field map of the wide range reflection in a large area was given to confirm the wide angular range.

8686-36, Session PTues

Research on biomimetic material templated from nature materials

Di Zhang, Wang Zhang, Shanghai Jiao Tong Univ. (China)

Biological materials naturally display an astonishing variety of sophisticated nanostructures that are difficult to obtain even with the most technologically advanced synthetic methodologies. Inspired from nature materials with hierarchical structures, many functional materials are developed based on the templating synthesis method. This review will introduce the way to fabricate novel functional materials based on nature bio-structures with a great diversity of morphologies, in State Key Lab of Metal Matrix Composites, Shanghai Jiao Tong University in near five years. We focused on replicating the morphological characteristics and the functionality of a biological species (e.g. wood, agriculture castoff, butterfly wings). We change their original components into our desired materials with original morphologies faithfully kept. Properties of the obtained materials are studied in details. Based on these results, we discuss the possibility of using these materials in photonic control, solar cells, electromagnetic shielding, energy harvesting, and gas sensitive devices, et al. In addition, the fabrication method could be applied to other nature substrate template and inorganic systems that could eventually lead to the production of optical, magnetic. or electric devices or components as building blocks for nanoelectronic, magnetic, or photonic integrated systems. These bioinspired functional materials with improved performance characteristics are becoming increasing important, which will have great values on the development on structural function materials in the near future.

8686-37, Session PTues

Redesigning of industrial product design systems on biological lines

Avinash Raipally, National Institute of Fashion Technology (India)

"Go take your lessons from nature, that?s where our future lies" -Leonardo da Vinci

The design practices currently are being clearly focused on sustainability by trying to reduce carbon footprints and carbon mileage, but there is also an another approach called Biomimicry or Biologically Inspired Design or Biominetics.

Environmental sustainability can be achieved through emulating nature which has been constantly sustaining from millions of years.

The challenge of designs for today's unsustained world is through Biomimicry in a way. The future of product design could sustain if it could be Biommiced through Form and Function inspired by nature and introducing sustainable materials and practices. We could use nature's power and designing technicality for our advantage in product design is the idea.

The literature available in this area for designers in particular is limited at this point. We should be able to develop more theoretical understanding among many disciplines of design and technology- let it be material or fiber, as there is a great potential for the future development of product design through Biomimicry.

"Technology break through not only enhance human power but also teach us how to live in harmony with nature, rather than dominate it" -Janine Benyus

There is also a demanding need for the design scientist's to develop products inspired by nature and explain its advantages of being clever & sustainable to the world. Particularly at this juncture of cross roads the world is today in regard to a sustainable future. We have to be reassessed. The quest for change would definitely be arduous. So there is a need to develop a „model setup? with such products designed which later should inspire the fellow design scientists as well.

The issues relating to sustainable development are substantial, the parameters are numerous and complex, and without any doubt, navigation in sustainable waters is difficult, arbitrating on the relevant decisions to be taken and making sense without compromising ourselves. As Baron de Coubertin so wisely said; "The important thing is to participate." We are in the first stage of a long conquest for the more reasonable and the more sustainable.(Elodie Ternaux, Industry of Nature, 2012, Pg.7)

All life forms on this planet Earth have been working towards their survival and in the process have evolved through millions of years to sustain. Can we challenge this process of evolution? All throughout this survival process, these species have been working towards the growth of the planet through synchronizing with each other in equilibrium, unlike the homosapiens who in one way or the other constantly- knowingly or unknowingly destroying the nature.

The uncertain future of our green planet is a fearing factor what the humankind is facing these days. As design scientist's it is very important for us to create environments which are more suitable and sustainable. So the following design process and methodology could be helpful, useful and meaningful in designing a Bioinspired design.

8686-38, Session PTues

Adhesion performance of gecko-inspired flexible carbon nanotubes dry adhesive

Yang Li, Nanjing Univ. of Aeronautics and Astronautic (China); Geng Xu, Suzhou Institute of Nano-Tech and Nano-Bionics (China); Ling Gong, Nanjing Univ. of Aeronautics and Astronautic (China); Géza Tóth, Univ. of Oulu (Finland); Qingwen Li, Suzhou Institute of Nano-Tech and Nano-Bionics (China); Zhendong Dai, Nanjing Univ. of Aeronautics and Astronautic (China)

Geckos' super switchable adhesive capability to cling to different smooth or rough surfaces is attributed to hierarchical fine structure of gecko foot hairs (microscale setae and nanoscale spatula). Extensive efforts have been made to fabricate gecko-inspired adhesive which can be used for gecko-mimetic climbing robots. Carbon nanotubes (CNTs) are well-known for exceptional mechanical properties and are one of the most outstanding candidates for developing gecko-inspired dry adhesive. Recent experiments revealed that the side contact of CNTs with substrates over a larger contact area could provide a stronger adhesion force than that of a tip contact. However, the limited choice of growth matrix, and the weak interaction between CNTs and matrix could restrict adaptability of CNTs adhesive. In addition, the attaching-detaching laws of CNTs adhesive used for gecko-mimetic climbing robot are also lack of awareness.

In this paper, a CNTs dry adhesive was fabricated by catalytic chemical vapor deposition and was transferred onto flexible polymer substrates with an effective polymer intermediate. Adhesion performance of the CNTs adhesive was measured with an adhesion/friction performance test platform. A pre-drag process was implemented during the test in order to help increasing the side contact area of CNTs. A transferred CNTs array on flexible PET substrate with an increased adaptability was obtained. SEM pictures suggested no obvious structural damage happened after transfer process. The normal and shear adhesion performance were both enhanced dramatically due to the pre-drag process, which had been investigated in gecko adhesive that dragging along the natural curvature of setae is necessary for gecko foot to generate sufficient adhesion. The fabrication and test methods provided here will be useful for the application of CNTs dry adhesive.

8686-39, Session PTues

The driving pattern and safety margin of gekko gecko on slopes

Zhendong Dai, Institute of Bio-inspired Structure and Surface Engineering (China)

Gecko is a kind of sprawled-posture animal, the research on its driving and adhesive pattern is representative to reveal the law of sprawled-posture. Thus scholars have tried to reveal that how gecko moves freely in the space utilizing its superior adhesive setae. An important feature of gecko setae is the frictional anisotropy: along the setal direction of friction. setae can generate frictional adhesion with substrate; conversely, against the setal direction of friction, that generate dry friction. The anisotropy of friction and adhesion ability of gecko setae is an important reason of its excellent performance.

The three-dimensional reaction forces of geckos moving on different slopes were measured using a three-dimensional force-sensors-array. Gecko adhesion process is divided into four phases according to the synchronization of video data. The experimental results show that: the frictional pattern is dry friction between foot and substrate on 0°substrate, safety angle of friction was no greater than 20°; the frictional pattern was frictional adhesion on 90°-180° slopes, safety margin did not exceed the adhesive critical angle (-30°).

Meanwhile from 0° to 90° transitional slopes, gecko adjusts the location of its toes to achieve different frictional pattern among each toe, utilizing anisotropy of the toe setae. This way not only meets the needs of the movement, but also reduces the unnecessary energy loss and improves driving efficiency during locomotion. Above research will inspire design of frictional pattern during gecko-like robots climbing movement, in order to improve the performance of robots and expand its scope of application.

8686-23, Session 10

Microflyers: inspiration from nature *(Invited Paper)*

Jayant Sirohi, The Univ. of Texas at Austin (United States)

Over the past decade, there has been considerable interest in miniaturizing aircraft to create a class of extremely small, remotely piloted vehicles with a gross weight on the order of tens of grams and a dimension on the order of tens of centimeters. These are collectively refered to as micro aerial vehicles, micro air vehicles (MAVs) or microflyers.

Engineers derived inspiration from natural flyers during the early development of heavier-than-air aircraft, al- though modern aircraft have little in common with natural flyers. Because the size of microflyers is on the same order as small birds or large insects, engineers are once again turning to nature for inspiration. Interest in biomimetic mi- croflyers originated in the 1970s[1] and was revived in the 1990s by several government funded research programs[2]. Researchers have developed a variety of microflyer configurations including those based on bioinspired and biomimetic concepts. Bioinspired concepts make use of structural or aerodynamic mechanisms that are observed in insects and birds, such as elastic energy storage and unsteady aerodynamics. Biomimetic concepts attempt to replicate the form and function of natural flyers, such as in flapping wing propulsion.

In addition to the performance limits imposed by the square-cube law, several other challenges appear as the size of an aircraft is decreased. These challenges are related to the behavior of mechanical assemblies, energy storage in batteries, miniaturization of electronics and aerodynamics. The full paper will review recent developments in the area of man-made microflyers. The design space for microflyers will be described[3], along with fundamental physical limits to miniaturizing mechanisms, energy storage and electronics. Key aerodynamic phenomena[4] at the scale of microflyers will be highlighted. Because the focus is on bioinspiration and biomimetics, scaled-down versions of conventional aircraft, such as fixed wing micro air vehicles and micro-helicopters will not be addressed. However, bioinspired and biomimetic microflyer concepts developed by a number of researchers will be described in detail. Modeling of the aeromechanics of flapping wing microflyers will be described. Finally, some of the sensing mechanisms used by natural flyers and are being implemented in man-made microflyers will be discussed.

8686-24, Session 10

Relationship between wingbeat frequency and resonant frequency of the wing in insects

Nam-Seo Goo, Ngoc-San Ha, Hoon Cheol Park, Konkuk Univ. (Korea, Republic of)

Biomimetics is one of the most important paradigms as researchers seek to invent better engineering designs over human history. However, the observation of insect flight is a relatively recent work. Several researchers have tried to address the aerodynamic performance of flapping creatures and other natural properties of insects, although there are still many unsolved questions. One of the questions is how to save energy and enhance performance in insects. There are two major arguments in the explanation: one is that insects could take advantage of a structural property to save energy by matching the resonant frequency of their compliant wings to the wingbeat frequency, the other is that insects could save energy by flapping their wing far below the natural resonant frequencies. Until now, there is no exact conclusion about these arguments because of a few studies of comparative resonant frequency and wingbeats of insects in the literature. Therefore, in this study, we experimentally studied the resonant frequency of four species insects: beetle (Allomyrina Dichotom), cicada (Tibiceninae), dragonfly (Anisoptera) and butterfly (pieridae) and compare the resonant frequencies to the wingbeat frequency. The ratio between wingbeat frequency and the resonant frequency was plotted to wing loading and body mass. We found that the frequency ratio of the wing for force production is in general between 0.3 and 0.6, which suggests that the flapping frequency should be much lower than the natural frequency for the wing to explore the advantages of the passive deformation to save energy.

8686-25, Session 11

Is clicking mechanism good for flapping wing micro aerial vehicle?

Yao Wei Chin, Gih-Keong Lau, Nanyang Technological Univ. (Singapore)

In this paper, a simple clicking compliant mechanism prototype inspired from Dipteran insect thorax is presented. Many had observed and described the click mechanism through insect's anatomy. Through theoretical models and numerical studies, some dismissed its effect on flapping efficiency, while others predicted better thrust generation with it. Without concrete experimental proof, the argument is hypothetical. This work showed the benefits of the click mechanism by experiment, with its simple compliant thorax designed using carbon fiber and polyimide film. The click mechanism system is designed like a thin elastic plate which was compressed until bent, with its center point stable at either the top most extreme or the bottom most extreme positions. 'Clicking' occurs when the plate center is moved forcibly from one extreme to the other. Before it passes the midpoint, the plate center moves slowly as it tends to return to the original extreme and resist the displacement. When moved passed the midpoint, it now tends to move to the other extreme, together with the external force, resulting in a fast, snapping 'click' to the other extreme. Hence, the clicking prototype showed a sudden high increase in wing flap speed when it is moved beyond midpoint towards the other end. It also showed quick wing reversal and is able to produce consistent large wing stroke (~70°). The clicking prototype, which weighs 3.26g, produces a higher thrust of 1.36g at a flapping frequency of 18Hz. In comparison, a 3g non-click prototype of similar configuration produces only 1.17g of thrust at 17.5Hz.

8686-26, Session 11

Bioinspired corrugated wings for micro air vehicles

Javaan S. Chahl, Manas Khurana, Univ. of South Australia (Australia)

The development Micro Aerial Vehicles (MAV) is at the forefront of Aerospace Research, Design and Analysis. Insect flight is a source of inspiration for the development of innovative MAV platforms. Dragonflies exhibit a wide-spectrum of flight modes including extended hover (endurance), to efficient glide (range), and rapid dash phases with multiple degrees-of-freedom (manoeuvre). Insects combine flight performance flexibility with efficiency through morphing of the wing surfaces which match the intended flight mode with precision.

It has previously been shown that airfoils composed of surface corrugations exhibit superior lift-to-drag ratios over conventional airfoils at Reynolds numbers of 8,000.

Reynolds Number has a significant effect on the aerodynamic coefficients in corrugated profiles. There exists a range of Reynolds Numbers where the impact of wing corrugation has a minimal through to significant influence on the aerodynamics. At a given Reynolds Number, flow attachment might be attained due to the trapped vortices in the valleys of the corrugation. Subtle variances in the operating envelope can result in rapid flow separation. Due to these variations it can even be argued that operationally, corrugation is critical only for wing stiffness.

The focus of the presented analysis is to map the efficacy of wing corrugation at the defined Reynolds Number of interest. We will present three critical computational analyses: Sensitivity of airfoil corrugation shape on aerodynamics; Aerodynamics of a corrugated airfoil at different span stations; Comparison of a corrugated airfoil against a conventional airfoil.

8686-27, Session 11

In-flight validated flexible-multibody structural dynamics model of a bioinspired ornithopter

Cornelia Altenbuchner, James E. Hubbard Jr., National Institute of Aerospace (United States)

A large effort is currently underway to understand the physics of avian-based flapping wing vehicles, or ornithopters. Small aerial robots are needed for a variety of civilian and military scenarios. Efforts to model the flight of these vehicles have been complicated by a number of factors, including nonlinear elastic effects, multi-body characteristics, unsteady aerodynamics, and the strong coupling between fluid and structural dynamics. Experimental validation capabilities are crucial in order to achieve accurate simulations. A multi-disciplinary analysis methodology requires the evaluation of tools representing individual disciplines before they can be combined to form a comprehensive model. Analysis of inertial properties and previous fight data has led to the development of a rigid multi-body dynamics model, where the ornithopter is modeled as a collection of chains of rigid body linkages emanating from a central fuselage. In this paper, a flexible multi-body simulation considering fluid-structure interaction and a novel experimental validation methodology is presented. Previous rigid-multi body dynamic models are extended to a flexible multi-body dynamic model. To achieve high fidelity simulation, and considering the flexibility of the flapping wing membrane, a finite element approach with a robust integration of the equations of motions is used. The resulting ornithopter flight simulator is validated with experimental free flight data obtained using 53 tracking points and a Vicon Vision® Motion tracking system.

8686-28, Session 11

Unconstrained vertical takeoff of a flapping-wing system power by on-board batteries

Vu Hoang Phan, Tri Q. Truong, Hoon Cheol Park, Konkuk Univ. (Korea, Republic of)

Insect-mimicking flapping-wing micro air vehicles (FW-MAVs) are more difficult to design than bird-mimicking FW-MAVs, because they have to fly only by wings without control surfaces at tail. For stable forward flight of an insect-mimicking FW-MAV, a pair of wings should be able to flap symmetrically, so that they can create symmetric aerodynamic forces to prevent rolling motion. In addition to this, the system should be assembled such that pitching moment is zero around its center of gravity, which can implement inherent pitching stability.

We have been developing an insect-mimicking flapping-wing system, which mimics flight of a beetle, Allomyrina Dichotom. It can create a large flapping angle of 140 to 160 degrees at a flapping frequency of about 40Hz, which is close to the beetle's flapping frequency. The engineering design of the flapping-wing system has been recently registered as a US patent. The flapping-wing system could successfully demonstrate uncontrolled stable vertical takeoff by applying electric power from an external power supply. The applied voltage of 12V is relatively high, so that a large capacity battery should be used as an independent power source, which increases total weight of the system. In this work, we modified our previous flapping-wing system for flight by on-board batteries and remote power control. A 12:1 gear ratio was adopted to reduce the required power. Forces produced by the flapping-wing system were estimated by Unsteady Blade Element Theory (UBET) and experimented by using a swing test and a loadcell. Finally, we demonstrated stable vertical takeoff of the modified flapping-wing system without any control.

8686-29, Session 11

Unsteady aerodynamics in ornithopter flight

Juan C. Gomez, Cornell Univ. (United States)

This research involves numerically simulating the unsteady aerodynamics generated by flapping wings using a modified quasi 2-D model. This model in its first incarnation was a quasi-steady model that involved modeling the effects of translation and rotation via a rotational lift term. It has been subsequently modified to drop this term and use a dynamic lift term involving the calculation of an ordinary differential equation. The kinematics are handled using modified rotation matrices. Characteristics such as propulsive efficiency are investigated and analyzed over varying parameters, as well as unsteady effects such as dynamic stall. Various wing kinematics are investigated as well.

8686-30, Session 11

An investigation of 6-DOF insect flight dynamics with a flexible multibody dynamics approach

Joong-Kwan Kim, Jae-Hung Han, KAIST (Korea, Republic of)

Flying insects have wings with anisotropic flexibility, and passive deformation of the wings is known to affect overall aerodynamic force and moment generation. Insects can independently control two wings with high degree-of-freedom using various well-developed flight muscles. This complex motion of the wings is not only used as thrust generator, but also takes charge of control force generation.

The passive deformation of the wings has distribution that increases to the direction of distal area, and makes it hard to define a single wing kinematics suitable for a certain flight mode, i.e. hovering. Therefore, previous researches on insect flight dynamics extracted a representative wing kinematics from externally measured data via high-speed-camera recordings. This passive deformation of the wings due to inertial and aerodynamic forces can alter the actual wing motions intended by the insect, therefore externally measured wing kinematics containing effect of aeroelasticity could be different from commanded wing kinematics by the insect to its flight muscles.

Here, we develop a flexible multibody dynamics model of a hovering insect with flexible wings which have similar structural dynamic characteristics that of real insects. Based on this environment, hovering wing kinematics is searched and compared with experimentally measured wing kinematics from other literatures. 6-DOF flight dynamic states and wing kinematics at hovering condition are also compared between an insect model with rigid wings and a model with flexible wings. A qualitative analysis on the 6-DOF flight dynamics is performed, and the effect of wing flexibility to the flight dynamics is addressed.

8686-31, Session 12

Effects of motor protein binding/unbinding on their collective transport

Woochul Nam, Bogdan I. Epureanu, Univ. of Michigan (United States)

Kinesins are nano-sized biological motors which are responsible for active transport in cells. A single kinesin molecule is able to transport its cargo about 1 um in the absence of external loads. However, kinesins perform much longer range transport in cells by working collectively. One of the most important mechanisms involved in this long transport is the binding and unbinding of kinesin to microtubules. Kinesin realize the transport by a repetitive mechanochemical cycle. In this study, the unbinding probabilities corresponding to each mechanochemical state of kinesin are calculated. The statistical characterization of the instants and locations of binding are captured by computing the probability of unbound kinesin being at given locations. The forces acting on kinesins affect binding and unbinding. This effect is also considered in this study. It reveals that the length of the transport is significantly longer when multiple proteins cooperatively transport the same cargo.

8686-32, Session 12

Using cellular energy conversion and storage mechanics for bio-inspired energy harvesting

Eric C. Freeman, Michael K. Philen, Donald J. Leo, Virginia Polytechnic Institute and State Univ. (United States)

Novel biologically-inspired energy harvesting devices based on cellular mimics used for converting mechanical, chemical, photo, and thermal stimuli into appropriate electrochemical responses are studied. Recently our group has developed a biomolecular unit cell consisting of encapsulated bilayer membranes stabilized between two hydrophilic compartments. The bilayer membrane enables stimuli-responsive control of ion transport between the chambers. The goal of this work is to develop devices that use ion concentration gradients for generating current and replenish these ionic gradients through utilizing external stimuli.

The proposed systems will be constructed using biomolecular unit cells that incorporate stimuli-responsive channels for controllable transport. These systems are highly tailorable as their performance is dependent on the electrolyte concentrations, the lipid properties, and the type of proteins included in the unit cell. These systems also exhibit collective properties where the configuration of a system including multiple unit cells may allow for abilities not exhibited in the single unit cell such as signal rectification. This paper provides an overview of the various pathways that may be used for energy conversion in these systems, and focus on the development of a next-generation unit cell model that accounts for the complex interlinking of the mechanical, chemical, and electrical conditions.

The findings from this model will then be used to determine how to optimize the performance and efficiency of these cellular energy harvesters, and findings from the experiments will be used to validate and further refine the model. The result is the creation of first-generation cellular energy harvesters and energy stores that may be used for power advanced cellular machines.

Conference 8687: Electroactive Polymer Actuators and Devices (EAPAD) XV

Monday - Thursday 11–14 March 2013

Part of Proceedings of SPIE Vol. 8687 Electroactive Polymer Actuators and Devices (EAPAD) 2013

8687-1, Session 1

Compliant mechanisms: ideal opportunity for integrated sensors and actuators *(Keynote Presentation)*

Larry L. Howell, Brigham Young Univ. (United States)

Compliant mechanisms provide alternate solutions for transferring or transforming motion, force, or energy. Rather than using traditional components like bearings and hinges, compliant mechanisms rely on the deflection of flexible members for their mobility. This enables the integration of multiple functions into simple topologies. The functionality of future compliant mechanisms may be enhanced by embedding sensors and actuators, resulting in monolithic devices capable of complex tasks. Compliant mechanisms show promise for addressing many pressing needs that are not easily solved through traditional approaches. These include next generation medical implants that closely mimic the biological systems that they replace, mechanical devices in the micro and nano size scales, high precision systems, and hyper-compact devices for space craft.

8687-2, Session 1

High-performance electrolyte-free torsional and tensile carbon nanotube hybrid muscles *(Invited Paper)*

Márcio D. Lima, The Univ. of Texas at Dallas (United States); Na Li, The Univ. of Texas at Dallas (United States) and Nankai Univ. (China); Mônica J. Andrade, Shaoli Fang, Jiyoung Oh, The Univ. of Texas at Dallas (United States); Geoffrey M. Spinks, Univ. of Wollongong (Australia); Mikhail E. Kozlov, Carter S. Haines, Dongseok Suh, The Univ. of Texas at Dallas (United States); Javad Foroughi, Univ. of Wollongong (Australia); Seon-Jeong Kim, Hanyang Univ. (Korea, Republic of); Yongsheng Chen, Nankai Univ. (China); Taylor Ware, The Univ. of Texas at Dallas (United States); Min Kyoon Shin, Hanyang Univ. (Korea, Republic of); Leonardo D. Machado, Univ. Estadual de Campinas (Brazil); Alexandre F. Fonseca, Univ. Estadual de São Paulo (Brazil); John D. Madden, The Univ. of British Columbia (Canada); Walter E. Voit, The Univ. of Texas at Dallas (United States); Douglas S. Galvão, Univ. Estadual de Campinas (Brazil); Ray H. Baughman, The Univ. of Texas at Dallas (United States)

New electrolyte-free muscles that provide fast, high-force, large-stroke torsional and tensile actuation are described, which are based on guest-filled, twist-spun carbon nanotube yarns. Actuation of hybrid yarns by electrically, chemically, and photonically powered dimensional changes of yarn guest generates torsional rotation and contraction of the helical yarn host. Over a million reversible torsional and tensile actuation cycles are demonstrated, wherein a muscle spins a rotor at an average 11,500 revolutions/minute or delivers 3% tensile contraction at 1,200 cycles/minute. This rotation rate is 20 times higher than previously demonstrated for an artificial muscle and the 27.9 kW/kg power density during muscle contraction is 85 times higher than for natural skeletal muscle. Applying well-separated 25 ms pulses yielded 0.104 kJ/kg of mechanical energy during contraction at an average power output of 4.2 kW/kg (four times the power-to-weight ratio of common internal combustion engines). Demonstrations include torsional motors, contractile muscles, and sensors that capture the energy of the sensing process to mechanically actuate. Improved control and large rotational actuation, along with long cycle life and tensile contractions up to 9%, suggest the use of these yarn actuators in medical devices, robots, and shutters, for which shape memory alloys are currently employed, as well as extension to microvalves, mixers, smart phone lenses, positioners and even toys and intelligent textiles.

8687-3, Session 1

A unified model of actuation in ionic electroactive polymers

John D. Madden, The Univ. of British Columbia (Canada)

The field of electroactive polymer actuators (EAPs) has been neatly classified by Bar-Cohen into electronic and ionic EAPs. Ionic EAPs are further classified by the materials employed - including conducting polymers, carbon nanotubes, and ionic polymer metal composites. It is shown that despite employing very distinct materials, these three 'classes' of actuator very likely all share the same underlying actuation mechanism, and are thus different implementations of the same physical effects. This realization should help in obtaining new actuators featuring the best properties of each actuator material. It will also help in the sharing of ideas and models.

In all three actuators ions are inserted or removed upon a change in electrochemical potential. The ion insertion is achieved via electrochemical double layer charging within the material or by a pseudo-capacitive mechanism. In all materials strain is proportional to the density of ions inserted, suggesting a first order description involving a proportionality between strain and stored charge (the strain to charge ratio). The deformation achieved per ion is approximately proportional to the ion size, plus entrained solvent. Application of a load leads to insertion of expulsion of ions, producing a sense voltage that is proportional to the load and the strain to charge ratio. Examples of how this basic capacitive/charge insertion model applies to the three forms of electroactive polymers are presented to make the case for a unified model.

8687-4, Session 2

Reactive actuators and sensors integrated in one device: mimicking brain-muscles feedback communication *(Invited Paper)*

Toribio Fernández Otero, Jose G. Martinez, Univ. Politécnica de Cartagena (Spain)

Artificial muscles based on conducting polymers, fullerene derivatives, carbon nanotubes, graphenes or other carbon derivative molecular structures are electro-chemo-mechanical actuators. Oxidation and reduction reactions drive most of the volume variation and the concomitant actuation: movement rate and displacement.

(Pol*)s + n(A-)sol + m(S) [(Pol)n+(A-)n(S)m]gel + ne- (1)

According with Chemical Kinetics, under flow of a constant current (constant reaction rate) any working or surrounding variable influencing the reaction (ox or red) rates will be sensed by the muscle potential (or by the consumed energy) evolution, E(t), during actuation. The theoretical description of this evolution has now been attained:

Where ic determines the rate of the movement; the consumed charge, ict, defines the displacement, characterizing the movement. Eq. 2 also includes working and surrounding variables: electrolyte concentration, [A-]; temperature, T; driving current, I; and mechanical conditions, V and ka. When the device senses the mechanical conditions (pressure, strain, or trailed weights and obstacle for muscles) becomes an mechano-chemo-electrical sensor. Both, theoretical description and experimental results will be presented in order to illustrate the good agreement between theoretical and experimental results. As conclusion, any actuator (artificial muscle, battery, smart window or mirror, smart membrane, smart drug delivery systeme) based on electrochemical reactions in carbon derivative materials will sense working and surrounding variables while working. Only two connecting wires contain, simultaneously, actuating (current) and sensing (potential) signals. Those constitute new feedback intelligent and biomimetic devices opening new technological borders and mimicking natural muscles/brain communication.

T. F. Otero, J. J. Sanchez and J. G. Martinez, J. Phys. Chem. B 2012, 116, 5279-5290; J. Phys. Chem. B 2012. DOI:10.1021/jp302931k. and Electrochim. Acta. DOI:10.1016/j.electacta.2012.03.097.

8687-5, Session 2

Self-sensing ionic electromechanically active actuator with patterned carbon electrodes

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In comparison to other ionic electromechanically active polymers (ionic EAP), carbon-polymer composite (CPC) actuators are considered especially attractive due to possibility of producing completely metal-free devices. However, mechanical response of ionic EAP-s is—in addition to voltage and frequency—dependent on environmental variables such as humidity and temperature. Therefore, similarly to other EAPs, one major challenge lies in achieving controlled actuation of the CPC sample. Due to their size and added complexity, external feedback devices (e.g. laser displacement sensors and video cameras) tend to inhibit the application of micro-scale actuators. Hence, self-sensing EAP actuators—capable for simultaneous actuation and sensing—are often desired. A thin polyvinylidene fluoride-co-hexafluoropropylene film with ionic liquid (EMIBF4) was prepared and masked coincidently on opposite surfaces prior to spray painting carbide-derived carbon electrodes. The purpose of masking was to create different electrically insulated electrodes on the same surface of polymer in order to achieve separate sections for actuator and sensor on one piece of CPC material. Solution of electrode paint consisting of carbide-derived carbon, EMIBF4 and dimethylacetamide was applied to the polymer film. After removing the masking tape, a completely metal-free CPC actuator with sophisticated electrode geometry was achieved to foster simultaneous sensing and actuation, i.e. self-sensing carbon-polymer actuator was created.

8687-6, Session 2

Fabrication and characterization of a two-dimensional IPMC sensor

Hong Lei, Xiaobo Tan, Michigan State Univ. (United States)

Ionic polymer-metal composites (IPMCs) have inherent sensing and actuation properties. An IPMC sensor typically consists of a thin ion-exchange membrane, chemically plated with electrodes on both surfaces. Such IPMC sensors respond to deflections in the beam-bending directions only and thus are considered one-dimensional. In this paper, a novel IPMC sensor capable of two-dimensional sensing is proposed by plating two pairs of electrodes on orthogonal surfaces of a Nafion beam that has comparable thickness and width. The fabrication method is reported along with the characterization of the fabricated sensor. Experimental results show that the proposed IPMC sensor can be used for 2D flow and displacement sensing with promising applications in artificial lateral line systems and biomimetic whiskers.

In the fabrication process Nafion solution is first cast and solidified, and the resulting structure is then cut to form beams with square cross-sections. In particular, the sample we fabricated has cross section of 1mm by 1mm and the length of 15mm. Platinum electrodes are then plated on four side surfaces of the Nafion beam, with insulation from each other. The fabricated IPMC sensor are shown to respond to the 2D mechanical stimulus within the cross-section plane, and separate sensor signals are collected from the two pairs of the parallel electrodes. The response (short-circuit current) of the fabricated IPMC sensor is characterized both in air and in water, to verify the 2D sensing capability and examine the correlation between the two sensor signals.

8687-7, Session 2

Conducting polymers are simultaneous sensing actuators

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Conducting polymers are the electrochemomechanical actuators having the ability to sense the surrounding variables simultaneously. The sensing and actuating signals are sent /received back through the same two connecting wires in these materials. The sensing ability is a general property of all conducting polymers arises from the unique electrochemical reaction taking place in them. This is verified for two different conducting polymers here – for an electrochemically generated polypyrrole triple layer bending actuator exchanging cations and for a chemically generated polytoluidine linear actuator exchanging anions. The configuration of the polypyrrole actuator device corresponds to polypyrrole-dodecyl benzene sulfonate (pPy-DBS) film/tape/ pPy-DBS film in which the film on one side of the triple layer is acted as anode and the film on the other side acted as cathode simultaneously, and the films interchanged their role when move in the opposite direction. The polytoluidine linear actuator was fabricated using a hydrogel microfiber through in situ chemical polymerization. The sensing characteristics of these two actuators were studied as a function of their working conditions: applied current, electrolyte concentration and temperature in aqueous electrolytes. The chronopotentiometric responses were recorded by applying square waves of electrical currents for a specified time. For the pPy actuator it was set to produce angular movement of ± 45° by the free end of the actuator, consuming constant charges of 60 mC. In both the actuators the evolution of the muscle potential along the electrical current cycle was found to be a function of chemical and physical variables acting on the polymer reaction rates: electrolyte concentration, temperature or driving electrical current. The muscle potential evolved decreases with increasing electrolyte concentrations, increasing temperatures or decreasing driving electrical currents. The electrical energy consumed during reaction was a linear function of the working temperature or of the driving electrical current and a double logarithmic function of the electrolyte concentration.Thus, the conducting polymer based actuators exchanging cations or anions during electrical current flow is a sensor of the working physical and chemical conditions which is a general property. We propose that any reactive device based on the same material and reaction (batteries, smart windows, electron-ion transducers, and so on) will sense surrounding conditions.

8687-8, Session 4

Electroactive polymer and shape-memory alloy actuators in biomimetics and humanoids *(Invited Paper)*

Yonas T. Tadesse, The Univ. of Texas at Dallas (United States)

There is a strong need to replicate natural muscles with artificial materials as the structure and function of natural muscle is optimum for articulation. Particularly, the cylindrical geometry of the fiber in the natural muscle promotes the critical investigation of cylindrical and other geometries of the artificial muscles in the design phase of certain platforms. Biomimetic robots and Humanoid Robot heads with Facial Expressions (HRwFE) are some of the typical platforms that can be used to study the geometrical effects of artificial muscles. It has been shown that electroactive polymer and shape memory alloy artificial muscles and their composites are some of the candidate materials that may replicate natural muscles and showed promise for biomimetics and humanoid robots. The application of these materials to these systems reveals the challenges and associated technologies that need to be developed in parallel. This paper will focus on the computer aided design (CAD) models of conductive polymer and shape memory alloys in various

biomimetic systems and Humanoid Robot with Facial Expressions (HRwFE). The design of these systems will be presented in a comparative manner primarily focusing on three critical parameters: the stress, the strain and the geometry of the artificial muscle.

8687-9, Session 4

Directional underwater sensor based on ionic electroactive polymer device

Reza Montazami, Maziar Ashuri, Ruisi Zhang, Wangyujue Hong, Abbey Machtemes, Iowa State Univ. (United States); Nichelle'Le Carrington, Savannah State Univ. (United States)

The functionality of ionic electroactive polymer (IEAP) sensors is due to the mobility of ions within the ionic membrane and ionic polymer-metal composite (IPMC). The ions are sourced by uptake of electrolyte (aqueous or ionic liquid) into the IPMC, and are mobilized when subjected to an external mechanical stimulus. Thus far, the common understanding of the sensing mechanism in IEAP sensors has been that mobility of ions provided by the electrolyte is the primary origin of the electrical signal. Nafion, used as the backbone structure of most IEAP sensors, is an ion permeable polymer with sulfonate end groups and proton counterions. In this work, we have shown that the counterions of Nafion have significant effect on the performance of IEAP sensors and that both signal magnitude and temporal response are closely related to the type of counterions of Nafion. We have studied samples consisting of Nafion in its original (protonated) form and Nafion with 1-ethyl-3-methylimidazolium (EMI) counterions and have shown that the counterions participate in the sensing process and influence the performance of the IEAP sensors. Also, we have investigated directionality of the sensing under water. We have fabricated sensors capable of directional sensing under water. To further scrutinize the relation between polymer counterions and ions sourced by electrolytes, samples with proton (H) or EMI counterions were tested with different electrolytes.

8687-10, Session 4

Electroactive polymer (EAP) mobility device

Mark C. Stasik, Jay R. Sayre, Megan S. Moore, Battelle Memorial Institute (United States); Chuck A. Plaxico, RoadSafe LLC. (United States)

Ionic Polymer-Metal Composites (IPMCs) are a class of Electroactive Polymers (EAPs) that bend and exert force in response to an applied voltage <5 volts. In this work, a design is presented where IPMCs are used to accomplish rotary motion. A unique feature is that EAP actuation is used in conjunction with gravity to cause rotation. This idea could be used to create a self-driven roller device. Such a roller could resemble a wheel with a circular or cylindrical geometry, or a sphere capable of rolling in all directions. Numerical simulations were performed that show that a 2-D roller device can accomplish rolling motion as a result of IPMC actuation. Experimental data on both the deformation and force-generation ability of fabricated IPMCs was used to drive the numerical simulations of the device. A possible application of this roller mechanism could be a mobility device on the centimeter scale that can transport a ~10g payload to a target destination.

8687-11, Session 4

Electroactive polymer-based anthropomorphic robot finger system

Baek-Chul Kim, Hanjoung Cho, Seunghoon Shin, HyungSeok Lee, Hyungpil Moon, Hyoukryeol Choi, Ja Choon Koo, Sungkyunkwan Univ. (Korea, Republic of)

Robot finger system based Electroactive Polymer(EAP) will be introduced in this paper. The study of various devices using EAP has been going. As a result, the new concept about small and lightweight devices that can replace previous devices was announced. However, it is completely difficult that EAP devices replace to current device due to the low driving performance and environmental constraints. Most of developed EAP devices is to integrate in narrow space and to reduce the weight. The example of actual system made by integrating these devices is rare. In this study, an anthropomorphic robot finger system was manufactured by integrating the developed EAP devices. The system is composed of many devices a tactile sensor like human skin, a force/torque sensor and a linear actuator for artificial muscle that is made by using EAP. We evaluated each device by integrating a system and verified the performance of entire system. Through this, we will present the vision of EAP devices.

8687-12, Session 4

Power electronics concepts for driving EAP stack actuators

Lars Eitzen, Jürgen Maas, Ostwestfalen-Lippe Univ. of Applied Sciences (Germany)

Compared to single layer EAP actuators, stack actuators exhibit advantageous properties such as large displacements at acceptably low operating voltages. Therefore, EAP stack actuators seem to be a promising option for the successful use in commercial applications.

For an energy-efficient operation of EAP stack actuators or EAP actuators in general an adequate power electronics with high voltage capability is indispensable. Depending on the specific application, the use of different converter topologies combined with suitable control concepts has to be considered.

In this contribution three different general converter concepts for driving EAP stack actuators will be investigated: The investigation of unidirectional concepts comprises converter topologies only capable of charging an actuator. Bidirectional converter concepts allow the bidirectional operation of EAP actuators using one single bidirectional converter topology, which can both charge and discharge an EAP actuator. Hybrid converter concepts include structures consisting of two single converter topologies. Using a hybrid converter approach might result in advantageous properties of the overall converter system compared to a bidirectional converter concept.

For each general converter concept, different converter topologies are evaluated regarding their general suitability. The most promising topologies are analyzed in detail, suitable control schemes are selected and the converter prototype design is addressed.

For the evaluation, simulation and experimental results of the respective prototypes will be presented and potential application cases for the experimentally investigated prototypes will be stated.

8687-13, Session 4

Understanding efficiency limits for dielectric elastomer driver circuitry

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Dielectric elastomers (DEs) can theoretically operate at efficiencies greater than that of electromagnetics. This is due to their unique mode of operation which involves charging and discharging a capacitive load at medium voltages. Efficient recovery of the electrical energy stored in the capacitance of the DE is essential in achieving favourable efficiencies as actuators or generators. This is not a trivial problem because the DE acts as a voltage source with a low capacity and a large output resistance. These properties are not ideal for a power source, and will reduce the performance of any power conditioning circuit utilizing inductors or transformers. This paper briefly explores how circuit parameters affect

the performance of a simple inductor circuit used to transfer energy from a DE to another capacitor. Experiments have revealed a decrease in performance at higher voltages when there is a large series resistance. In one experiment, adding a series resistance to the circuit caused an efficiency reduction of 12% at 1kV but 32% at 3kV. These results reveal the significance of DE electrical parameters on the efficiency of the overall DE device. These parameters must be taken into account when designing the driving circuitry to maximize performance.

8687-96, Session 4

Progress toward EAP actuators for biomimetic social robots

David F. Hanson Jr., Hanson Robotics, Inc. (United States) and Nanyang Technological Univ. (Singapore) and The Univ. of Texas at Arlington (United States)

The author presents novel research and development in social robots, with walking bodies, grasping hands, and expressive faces, describing how each actuation domain could benefit from EAP actuation. The author then describes experiments in developing the robots for EAP actuation, and proposes future work for practical convergence of EAP capabilities and the actuation requirements for social robotics.

8687-15, Session 5

Finite element modelling of the sensing and energy harvesting performance in ionic polymer metal composites

Barbar J. Akle, Wassim Habchi, Lebanese American Univ. (Lebanon)

Ionic Polymer Metal Composite (IPMC) is an Electro-Active Polymer (EAP) that is used as an electro-mechanical sensor and being investigated as an energy harvester. The IPMC transducer is proved to be inefficient as an energy harvester due to the small amount of voltage it generates when deformed. This study explores this problem by developing a fully-coupled 2D mechano-chemo-electrical finite element model that predicts the sensing behaviour in IPMC. The electro-chemical element is modelled based on the Nernst-Planck and Poisson's equations. The chemo-mechanical coupling is due to the change in the concentration of ions upon deforming the sensor. This paper is focused on developing methods to control the amount of voltage and current the IPMC sensor can generate. The developed FEM model is used to assess the effects of increasing the thickness of the transducer and of manipulating the architecture of the high surface area electrodes. The IPMC transducer is simulated and experimentally tested using two electrical boundary conditions: the open circuit voltage or the short circuit current. All numerical results are supported by experimental data. The results are shown to be in good agreement with model predictions.

8687-16, Session 5

Autonomous dielectric elastomer generator using electret

Cong Thanh Vu, G2Elab (France); Claire Jean-Mistral, Institut National des Sciences Appliquées de Lyon (France); Alain Sylvestre, G2Elab (France)

Dielectric elastomers can work as a variable capacitor to convert mechanical energy such as human motion into electrical energy. Nevertheless, scavengers based on dielectric elastomers require a high voltage source to polarize them, which constitutes the major disadvantage of these transducers. We propose here to combine dielectric elastomer with an electret, providing a quasi-permanent potential, thus replacing the high voltage supply. Our new scavenger is fully autonomous, soft, lightweight and low cost. The structure is thus composed of a dielectric elastomer (Polypower from Danfoss) and an electret developing a potential of -1000V (Teflon from Dupont). The transducer is designed specifically to scavenge energy from human motion. Thus, it works on pure-shear mode with maximum strain of about 50% and it is textured in 3D form because electret is non deformable. Thanks to an appropriate electromechanical analytical model, an energy density of about 1.5mJ.g-1 is expected on an optimal electrical load. However, for practical applications, this energy is difficult to achieve due to the existence of residual air gaps of approximately 500µm between the dielectric elastomer and the electret at maximum strain. Consequently, optimization of the 3D form was proposed to enhance scavenged energy. Lastly, experiments were carried out in order to validate our model. Our new autonomous dielectric generator can produce about 0.55mJ.g-1 on a resistive load of 99MΩ, nine times more than those obtained by piezoelectric polymers, and can further be optimized by enhancing the performance of dielectric elastomer such as dielectric permittivity or by increasing the electret potential.

8687-17, Session 5

Oscillating-water-column wave-energy-converter based on dielectric elastomers

Marco Fontana, Rocco Vertechy, Massimo Bergamasco, Scuola Superiore Sant'Anna (Italy)

Ocean-wave power is a very persistent and highly spatially concentrated form of renewable energy. To date, the development of cost effective Wave Energy Converters (WECs) is hindered by inherent limitations of available material technologies. State of the art WECs are indeed based on traditional mechanical components, hydraulic transmissions and electromagnetic generators, which are all made by stiff, bulky, heavy and costly metallic materials. As a consequence, existing WECs result in being expensive, difficult to assemble, sensitive to corrosion and hard to maintain in the marine environment.

Thanks to their lightness, low cost, easy manufacturability/workability and high corrosion resistance, Dielectric Elastomer (DE) transducers could be an enabling technology for the development of next generation WECs.

In this context, this paper focuses on Oscillating-Water-Column (OWC) type WECs, and analyzes the viability of using DE transducers as power-take-off systems. In traditional OWC devices, Wells turbines are used to convert into electricity the variable pressure that is generated by the oscillation of the free surface of a water column in a submerged closed chamber. In the DE-based OWC proposed here, the Wells turbine is replaced by a properly-shaped deformable DE membrane.

Regarding paper structure, the first sections introduce the working principle of OWC devices and discuss possible layouts for their DE-based power-take-off system. In the subsequent sections a simplified model of DE-based OWC devices is described along with an appropriate control strategy aiming at the maximization of the energy produced.

8687-18, Session 5

Soft 3D printed energy harvesters

Thomas G. McKay, The Univ. of Auckland (New Zealand); Peter Walters, Univ. of the West of England (United Kingdom); Jonathan M. Rossiter, Univ. of Bristol (United Kingdom); Benjamin M. O'Brien, Iain A. Anderson, The Univ. of Auckland (New Zealand)

Dielectric elastomer generators (DEG) provide an opportunity to harvest energy from low frequency and aperiodic sources. Because DEG are soft, deformable, high energy density generators, they can be coupled to complex structures such as the human body to harvest excess mechanical energy.

However, DEG are typically constrained by a rigid frame and manufactured in a simple planar structure. This planar arrangement is unlikely to be optimal for harvesting from compliant and/or complex structures. In this paper we present a soft generator which is fabricated using a 3D printing process. This capability will enable the 3-dimensional structure of a dielectric elastomer to be customised to the energy source, allowing efficient and/or non-invasive coupling.

This paper demonstrates our first 3D printed generator which includes a diaphragm with a soft elastomer frame. When the generator was connected to a self-priming circuit and cyclically inflated, energy was accumulated in the system, demonstrated by an increased voltage.

Our 3D printed generator promises a bright future for dielectric elastomers that will be customised for integration with complex and soft structures. In addition to customisable geometries, the 3D printing process may lend itself to fabricating large arrays of small generator units and for fabricating truly soft generators with excellent impedance matching to biological tissue. Thus comfortable, wearable energy harvesters are one step closer to reality.

8687-19, Session 5

Electroactive polymers for gaining sea power

Benedikt Scherber, Matthias Grauer, Bosch Rexroth AG (Germany); Istvan Denes, Robert Bosch GmbH (Germany)

Because of the quest for sustainability companies are going to make new energy-sources accessible worldwide. With consideration of current energy policies they often focus on renewable energies. Using sea power is very popular and qualified as well because of its constant availability in contrast to the unstable sources like sun or wind. For the presented new technology the up and down moving waves are delivering the power, not the sea current. With this technology conventional hydraulic energy converters are replaced by a new budding technology. The context of checking and testing has shown that electro-active polymers are the best choice for gaining sea power. The forecasted advantages of the usage of polymers are lower production costs and that they are more durable in comparison to former hydraulic systems. Core of the new technology is an all new silicon-based material: an electro-active polymer (EAP), which Bosch is currently working on together with the worldwide leader in silicon developing and production.

The principle of effect is that the material changes its shape by applying a voltage. These materials are often used as actuators or sensors. By inverting this process (deforming the material, not applying a voltage) an electronic charge transport is generated within the EAP with a following separation of charge. This occurred potential difference can be taken and saved by power electronic units. The new materials and technologies for producing these materials are reviewed and tested currently to guarantee their suitability for those tasks. To use this form of energy production reasonably and efficiently many of these actuators are stacked to so-called EAP-stacks. This EAP-stack is compressed by the transfer of wave motion and the help of the wave energy converter. Thereby a voltage is generated by electronic displacement in each EAP-actuator. After relaxation of the whole EAP-stack energy can be saved in a capacitor with the help of a power electronic unit.

For this special application an all new construction will be developed by the Bosch Rexroth AG. This construction is based on the competence Bosch Rexroth has so far in relation to sea power. It contains the body, the energy converter which consists of the EAP-stack and a mechanical system for keeping the electronics apart from sea water. Additional to this, the corresponding power-electronic unit which uses the power-difference between charging and discharging to gain energy is part of the wave energy harvesting system. By using the demonstrator model in a wave-channel the possibility of energy generation out of sea waves will be simulated and proved. Because of the cooperation between institutes and companies along the whole value chain the view of specialists is secured.

The observation of the project beginning with the material production and manufacturing along the components and system development to the prototype shows a closed and stable base for a concept for a new technology.

The article for the SPIE 2013 describes the essential steps of this research and presents a new technology for gaining sea power.

8687-20, Session 6

Platform-based design of EAP transducers in Danfoss PolyPower A/S

Rahimullah Sarban, Danfoss PolyPower A/S (Denmark); Tómas V. Gudlaugsson, Technical Univ. of Denmark (Denmark)

Electroactive Polymer (EAP) has gained increasing focus, in research communities, in last two decades. Research within the field of EAP has, so far, been mainly focused on material improvements, characterization, modeling and developing demonstrators.

As the EAP technology matures, the need for a new area of research namely product development emerges. Product development can be based on an isolated design and production for a single product or platform design where a product family is developed. In platform design the families of products exploits commonality of platform modules while satisfying a variety of different market segments. Platform based approach has the primary benefit of being cost efficient and short lead time to market when new products emerges.

Products development based on EAP technology is challenging both technologically as well as from production and processing point of view. Both the technological and processing challenges need to be addressed before a successful implementation of EAP technology into products. Based on this need Danfoss PolyPower A/S has, in 2011, launched a EAP platform project in collaboration with three Danish universities and three commercial organizations. The aim of the project is to develop platform based designs and product family for the EAP components to be used in variety of applications. This paper presents the structure of the platform project as a whole and specifically the platform based designs of EAP transducers. The underlying technologies, essential for EAP transducers, are also presented. Conceptual design and solution for the concepts are presented as well.

8687-21, Session 6

Dielectric elastomer energy harvesting undergoing electromechanical phase transition

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Applied to voltage, a dielectric elastomer membrane may deform into a mixture of two states under certain conditions. One of which is the flat state and the other is the wrinkled state. In the flat state, the membrane is relatively thick with a small area, while on the contrary, in the wrinkled state, the membrane is relatively thin with a large area. The coexistence of these two states may cause the electromechanical phase transition of dielectric elastomer. The phase diagram of idea dielectric elastomer membrane under unidirectional stress and voltage inspired us to think about the liquid-to-vapor phase transition of pure substance. The practical working cycle of a steam engine includes the thermodynamical process of liquid-to-vapor phase transition, the fact is that the steam engine will do the maximum work if undergoing the phase transition process. In this paper, we investigated the phase transition process under certain conditions, some similar conclusions as the liguid-to-vapor phase transition and the typical steam power cycle are got. Energy converted in an electromechanical cycle undergoing electromechanical phase transition is much larger than that in an electromechanical cycle including only one state. We think these results can guide the design and manufacture of energy harvesting equipments.

8687-22, Session 6

Optimized energy harvesting materials and generator design

Christian Graf, Ostwestfalen-Lippe Univ. of Applied Sciences (Germany); Julia Hitzbleck, Torsten Feller, Karin Clauberg, Joachim Wagner, Jens Krause, Bayer MaterialScience AG (Germany); Jürgen Maas, Ostwestfalen-Lippe Univ. of Applied Sciences (Germany)

Electroactive polymers are soft capacitors made of thin elastic and electrically isolating films coated with compliant and conductive electrodes offering a large amount of deformation. These unique properties enable the industrial development of highly efficient and environmentally sustainable (wave) energy converters, which opens the possibility to exploit a large renewable and inexhaustible energy source that is widely unused otherwise. The well-known energy harvesting principle is based on a sequence of stretching, charging, relaxing and discharging.

Compared to other electroactive polymer materials, polyurethanes, whose formulation has been systematically modified and optimized for energy harvesting applications, have certain advantages. The inherently higher dipole content results in a significantly increased permittivity and the dielectric breakdown strength is higher, too, whereby the overall specific energy is better by at least factor ten. In order to reduce conduction losses on the electrode, a highly conductive bidirectional stretchable electrode has been developed. Other important material parameters like stiffness and bulk resistivity have been optimized to fit the requirements. To realize high power energy harvesting systems, substantial amounts of material are necessary, which opposes special attention to the mechanical design of the generator. Different measures have been studied to e.g. reduce the defect occurrence and electrical connection.

The accompanying optimization studies of the energy harvesting cycle result in an optimal exploitation of the material and converter. In the final paper the material requirements, the generator design, the test procedures and the optimized energy harvesting cycle are presented in detail, always supported by meaningful measurement results.

8687-23, Session 6

Comparison of dielectric electroactive polymer generators' energy harvesting cycles

Emmanouil Dimopoulos, Ionut Trintis, Stig Munk-Nielsen, Aalborg Univ. (Denmark)

Research over the dielectric electroactive polymer (DEAP) generator's energy harvesting cycles has attracted much of the scientific interest over the past few years. Indicatively, several publications have thoroughly discussed and compared the 'Constant Charge', 'Constant Voltage' and 'Constant E-field' cycles, mainly based though, on idealized theoretical models. In addition, the optimum way to scavenge electric potential energy from a DEAP generator, during its relaxation phase, has itself concentrated a significant part of the scientific research, indicating that the 'Constant E-field' cycle is the most energy efficient one. Yet, it has not been possible until present to validate those theoretical outcomes with experimental measurements.

In this paper all three energy harvesting cycles are exhaustively compared, by means of energy efficiency, losses and more, based for the first time upon experimental results generated by the laboratory setup in Aalborg University. Further, the interdependence between the system's energy conversion efficiency, i.e. mechanical energy converted into electrical energy, and the operating energy harvesting cycle is thoroughly investigated and discussed.

8687-24, Session 6

Modular dc-dc converter system for energy harvesting with EAPs

Lars Eitzen, Jürgen Maas, Ostwestfalen-Lippe Univ. of Applied Sciences (Germany)

Energy harvesting with EAPs requires an energy-efficient power electronics providing a bidirectional energy transfer and operating voltages of up to several kilovolts.

A possibility to achieve a high energy-efficiency for high voltage conversion is the use of a modular converter system consisting of several bidirectional converter modules, which are connected in series on the converter output side and in parallel at the input side. Since each converter stage provides only a part of the overall converter output voltage, the converter module output voltages can effectively be reduced by choosing the number of cascaded converter modules appropriately. This allows the use of standard semiconductor switches with superior electrical characteristics compared to high voltage semiconductors, enabling a high energy-efficiency. Because of the output voltage reduction for each module, also smaller passive components such as inductors can be used.

Since EAP devices exhibit a mainly capacitive behavior and a limitation of the operating current is required for electrode protection, the utilized converter structure/topology has to be operated as a controllable current source on the lowest control level, which is achieved by operating the converter modules of the modular converter system with a subordinate closed-looped current control scheme. In order to avoid voltage unbalances among the single converter modules, a method for voltage balancing and a control scheme for closed-loop voltage control have to be implemented, which will be presented in the final paper.

For the validation of the proposed modular converter system, experimental results of a realized prototype in closed-loop operation are presented.

8687-25, Session 6

Maximizing the energy density of dielectric elastomer generators using equi-biaxial loading

Jiangshui Huang, Samuel Shian, Zhigang Suo, David R. Clarke, Harvard Univ. (United States)

Dielectric elastomer generators (DEGs) for harvesting electrical energy from mechanical deformations have been demonstrated but the energy densities achieved are still small compared with theoretical predictions. In this presentation, we show that significant improvements in energy density (550mJ/g with an efficiency of 9.3%), can be achieved by using an equi-biaxial mechanical loading configuration, one that maximizes the capacitance changes. Quantification of the energy contributions indicate that attaining higher conversion efficiencies is currently limited by viscous losses within the acrylic elastomer suggesting that higher conversion efficiencies with other elastomers can be attainable.

The basic concept of mechanical energy harvesting with a dielectric elastomer sheet is a straightforward electromechanical cycle leading to a voltage step-up: a sheet is stretched, electrical charge at low voltage is placed on either side using compliant electrodes, the circuit disconnected, the stretch is released causing the sheet's initial thickness to be recovered separating the charges which can then be drawn off at higher voltage.

Integral to maximizing the energy conversion is the amount of mechanical energy that can be stored elastically in the elastomer sheet during stretching. We show that this can be maximized by equi-biaxial loading. Furthermore, as the electrical capacity varies with the fourth power of the mechanical stretch, the design of the mechanical loading system is the key to enhanced performance. Details of our dielectric elastomer generator will be described as well as the procedures we use for quantifying its performance. Designs based on the same optimization of the mechanical loading will be described for harvesting energy from ocean waves and wind.

8687-26, Session 6

Electrode effect on the cellulose piezo-paper energy harvester

Lindong Zhai, Sangdong Jang, Jaehwan Kim, Zafar Abas, Inha Univ. (Korea, Republic of); Heung Soo Kim, Dongguk Univ. (Korea, Republic of); Joo-Hyung Kim, Chosun Univ. (Korea, Republic of)

The potential of cellulose based Electro-active paper (EAPap) for harvesting energy by ambient vibration with different metal electrodes will be investigated under sinusoidal input excitation. Although piezopolymers have smaller value of electro-mechanical coupling constants as compared to the piezoceramics, but are very flexible, which motivates to use these materials as potential source for energy harvesting. Cellulose based Electro-active papers are deposited with different metal electrodes like aluminum, gold, silver and nickel The fabricated samples will be tested with aluminum cantilever beam under an input excitation. The effect of area of electrodes will be investigated by comparing the output voltage at the different values of area of electrodes ranging from 400mm2 to 1200mm2. In order to observe the effect of electrodes area the average output voltage will be plotted at different values of electrode area. An attempt will also be made to investigate work function effect on the output voltage from the EAPap specimens. From the experimental results the potential of EAPap as a flexible energy harvester will be optimized by considering the parameters like size effect, electrodes area, sensitivity and shielding effects.

8687-89, Session PTue

Hot-embossing of microstructures on addition-curing polydimethylsiloxane films

Sindhu Vudayagiri, Liyun Yu, Suzan S. Hassouneh, Anne L. Skov, Technical Univ. of Denmark (Denmark)

The aim of this research work is to establish a hot-embossing process for addition curing vinyl terminated PDMS (polydimethyl siloxane) which are thermosetting elastomers, based on the existing and widely applied technology for thermoplasts. Addition curing silicones are shown to possess the ability to capture and retain an imprint made on it 10-15 minutes after the gel-point at room temperature. This property is exploited in the hot-embossing technology.

In the large scale manufacture of dielectric electroactive polymers (DEAPs) by Danfoss Polypower A/S, the surface of the PDMS elastomer films are imparted with micro-scale corrugation lines which enhance the performance of the films as actuators and generators due to the directional anisotropy and it allows for high strains of the metallic electrodes. The films are currently made on a specially designed carrier web which imparts the corrugated structure to the films. The elastomer mixture is applied on the carrier web and it is left to cure on the web. The cured elastomer film is then peeled off the web to allow for the deposition of electrodes. This process is expensive, as it requires miles of carrier web to make the films. Therefore an alternative process to make thin, corrugated elastomer films is required to make the DEAP technology economically competitive with other actuator, generator and sensor technologies. The hot-embossing process is one of the simplest, most cost-effective and time saving alternative method for replicating micro-structures on addition-curing PDMS films.

8687-90, Session PTue

Evolutionary algorithms for the multi-objective optimization of stacked dielectric elastomer actuators

Aaron D. Price, ABB AG Corporate Research Ctr. (Germany)

Dielectric elastomer stacks are a particularly promising configuration of electroactive polymer actuators due to their uniquely favorable balance of output force and stroke capabilities. These performance characteristics are highly dependent on many interrelated factors including layer geometry, mechanical and electrical properties of the electrode and dielectric layers, driving voltage, and the ancillary electrical system and interconnection behavior. Furthermore, these considerations are often made more complex by varying environmental factors encountered in service. Thus, the specification of an optimal actuator design remains a challenging task when the competing objectives of performance and cost must be mutually satisfied. Simulation of the electromechanical actuation response of stacked dielectric elastomers in three dimensions is an intensive and time consuming process, and hence the computational effort required to survey the complete design space is prohibitive.

This study aims to efficiently elucidate the relationship of these design factors on actuator performance by means of the application of evolutionary optimization algorithms in conjunction with a coupled multi-physics finite element simulation to predict the dynamic performance of silicone- and polyurethane-based dielectric stacks. Alternative approaches to define the design of experiments (which form the starting set of designs required by optimization algorithm) are described, followed by the specification and application of a multi-objective evolutionary (genetic) algorithm that features the biologically inspired aspects of elitism and reproduction including crossover, mutation and selection. This approach serves to rapidly identify the optimal actuator design without the computational expense of simulating the entire design space.

8687-91, Session PTue

Anticipating electrical breakdown in dielectric elastomer actuators

Daniel Muffoletto, Kevin M. Burke, Jennifer Zirnheld, Univ. at Buffalo (United States)

The output strain possible in a dielectric elastomer actuator is in direct proportion to the square of the applied electric field. However since the likelihood of electric breakdown, and thus the irreversible destruction of the actuator, increases with this applied field, systems employing dielectric elastomer actuators often heavily derate the maximum operating electric field to a value much below the absolute electric breakdown field, so that even as the device ages and becomes more susceptible to breakdown, failure due to breakdown remains unlikely. In an effort to sense the strength of the dielectric material so that stronger yet safe electric fields are applied to the actuator, partial discharge testing detects the charge that is released when localized instances of breakdown partially bridge the insulating gap, and can be used to assess the health of an insulating system. The results of testing entire dielectric elastomer assemblies using complaint electrodes, and the impact of using interpenetrating polymer networks to prestrain dielectric samples are explored.

8687-92, Session PTue

Actuators based on intrinsic conductive polymers/carbon nanoparticles nanocomposites

Sergio Bocchini, Istituto Italiano di Tecnologia (Italy); Daisy Accardo, Istituto Italiano di Tecnologia (Italy) and Politecnico di Torino (Italy); Mariangela Lombardi, Politecnico di Torino (Italy) and Istituto Italiano di Tecnologia (Italy); Paolo Ariano, Istituto Italiano di Tecnologia (Italy)

Highly conductivite and soluble polyaniline /carbon nanoparticles nanocomposites have been successfully synthesized by in-situ chemical oxidation polymerization using polyelectrolyte poly(styrenesulfonate) (PSS) as surfactant agent and ammonium peroxodisulfate (APS) starting from non-toxic N-phenil-p-phenylenediamine (aniline dimer) with a new synthesis in emulsion. The use of surfactant agent allows the inclusion of carbon nanoparticles such as carbon nanotubes and graphene that was produced in-situ by graphene oxide reduction with the monomer itself. The resulting nanocomposites show a higher conductivity due to the synergism between conductive polymer and carbon nanoparticles. Bimorph solid state ionic actuators were prepared with these novel nanocomposites using different polymer membranes and a ionic liquid.

The main novelties of this work are the production of polyaniline using a new emulsion synthesis, the feasibility to obtain well-dispersed polyaniline/carbon nanoparticles nanocomposites, the production of graphene nanoparticles from graphene oxide without the use of further reducing agents and new actuators based on the nanocomposites prepared.

8687-93, Session PTue

Kinetics evaluation of using biomimetic IPMC actuators for stable bipedal locomotion

Milad Hosseinipour, Mohammad H. Elahinia, The Univ. of Toledo (United States)

Ionic conducting polymer-metal composites (IPMC) are revolutionary actuators that can act as artificial muscles in many robotic and microelectromechanical systems. The electrochemical-mechanical behavior of these materials has been modeled by some black or gray box models. An FEM solution to the governing partial differential equation of IMPC and a 2D extension of the results using a thermostructural model are already published. This model was employed to study the stability of a bipedal gait on a seven degree of freedom IPMC-actuated biped model. In this study the theoretical predictions of the FEM and thermostructural models are first verified by experimental data. The dynamic equations of motion of the bipedal gait are then solved to find the internal forces and torques acting on the links. The feasibility of using IPMCs as joint actuators is evaluated by considering the blocking force and force-to-mass ratio limitation of these materials. This study will complement the previous work by adding kinetic results to the kinematic data.

8687-94, Session PTue

The effects of electrode surface morphology on the actuation performance of IPMC

Kwang Jin J. Kim, Univ. of Nevada, Las Vegas (United States)

It is generally understood that increasing the specific surface area of the electrodes of IPMC leads to improved electromechanical performance of the material. Most physics based models compensate the effect of high surface area of the electrodes by increasing both diffusion constant and dielectric permittivity values, while using flat electrode approximation in calculations. Herein, a model was developed to take into account the shape and area of the electrodes. High surface area of the electrodes in the model was achieved by generating Koch fractal structure – different generation depths and both unidirectional and random directional generations were studied. The preliminary calculations indicate that increasing the generation depth of fractals, thus surface area of the electrodes results in more overall transported charge during the actuation process. Based on the model, the effect of the specific surface of the electrodes on the electromechanical performance was experimentally investigated. IPMCs with different Pt or Pd electrode structures were prepared and their electromechanical, -chemical and mechanical properties were examined and discussed. The methods to manipulate the surface structure of Pt or Pd electrodes were proposed.

8687-95, Session PTue

Scalable low nDOF hp-FEM model of IPMC actuation

David Pugal, Univ. of Nevada, Reno (United States); Alvo Aabloo, Univ. of Tartu (Estonia); Kwang Jin J. Kim, Univ. of Nevada, Las Vegas (United States)

IPMC actuation is described with a system of partial differential equations – the Poisson's equation, the Nernst-Planck equation, and the Navier's equations for the displacement field. In such systems, one physical field can be very smooth while others are not. This can possibly result in very large problem size in terms of number of degrees of freedom (nDOF) when implemented with the finite element method (FEM). Furthermore, finding an optimal mesh is challenging due to the fact that the physical fields are time dependent. In order to overcome these deficiencies, hp-FEM was used to solve the system of equations. The hp-FEM is a modern version of the FEM that is capable of exponential convergence (the approximation error drops exponentially as new degrees of freedom are added during adaptivity). It is shown how the multi-meshing allows reducing the problem size in terms of nDOF; also, how the solution domain that describes IPMC can be scaled without a significant increase in the nDOFs and solution time. The model was implemented in Hermes that is a free hp-FEM solver.

8687-98, Session PTue

Development of an active isolation mat based on dielectric elastomer stack actuators for mechanical vibration cancellation

Roman Karsten, Helmut F. Schlaak, Technische Univ. Darmstadt (Germany)

Nowadays, for active attenuation of mechanic vibrations on sensitive devices usually voice-coil, pneumatic, or piezo-electric actuators are used. The main disadvantages of these actuator types are high complexity and costs and also high energy consumption.

A promising alternative is the use of dielectric elastomer stack actuators (DESA). The dielectric elastomer actuator is built like a parallel plate capacitor. It consists of two compliant electrodes and a soft silicone in between which is used as a dielectric and as a return spring. High strain and dynamics allow deploying DESA for active attenuation of low frequencies up to 100 Hz. Higher frequencies are eliminated passively due to the silicone damping behavior.

This paper describes the development of an active isolation mat for the cancelation of vibrations on sensitive devices with a mass of up to 500 g. Vertical disturbing vibrations are attenuated actively while planar vibrations are damped passively. The dimensions of the investigated mat are 200 x 200 x 25 mm^3. The mat contains 5 DESA. Depending on system's requirements, the size of the mat and number of the actuators can be easily changed.

The design and the optimization of the active isolation mat are realized by Ansys FEM software. The best performance shows a DESA with air cushion mounted on its circumference. The deployed DESA has 40 mm electrode diameter and 50 layers. In this application the planar strain of DESA is used. Within the mounting encased air increases static and reduces dynamic stiffness. Experimental results show that the vibrations with amplitudes up to 200 µm can be actively eliminated.

8687-99, Session PTue

Strain-enhanced nanoparticle electrostrictive polymer blends for actuator applications

Boscij Pawlik, Christian Schirrmann, Kirstin Bornhorst, Florenta Costache, Fraunhofer-Institut für Photonische Mikrosysteme (Germany)

The electrostrictive poly(vinylidene fluoride-trifluoroethylene-1,1-chlorofluoroethylene) – P(VDF-TrFE-CFE) terpolymer exhibits higher field-induced strain and larger dielectric constant (> 50) than most materials. In this paper we show that the strain of this terpolymer can be increased even more by mixing it with nanoparticles of high dielectric constant.

First, high dielectric constant nanoparticles such as $BaTiO_3$ were mixed with the terpolymer in different weight fractions. The blend's newly acquired properties, as compared to the polymer matrix, such as crystallinity and phase transitions were analyzed by means of X-ray diffraction and differential scanning calorimetry (DSC).

We further examined the electric field-induced strain in thin films made from terpolymer or nanoparticle / terpolymer blends. For this examination, thin films were prepared by spin coating, they were subsequently annealed and structured metallic electrodes were deposited on both sides of the films to form an actuator-type structure. To minimize the effects of nanoparticle clustering observed in the nanoparticle / terpolymer blend thin film, an optimum annealing temperature as well a minimum film thickness were deduced from surface topology inspection using atomic force microscopy (AFM).

Measurements of electric-field induced strain in these thin films were carried out with a Michelson interferometric set-up. The results show that, for the same applied electric field, the electrostrictive strain increases with increasing the nanoparticle content in the blend.

The importance of these blends properties for micro-actuators design and applications will be discussed.

8687-100, Session PTue

Dielectric strength of elastomer membranes: from electromechanical instability to bulk breakdown

Alexander Kogler, Andreas Tröls, Richard Baumgartner, Rainer Kaltseis, Reinhard Schwödiauer, Ingrid Graz, Siegfried G. Bauer, Johannes Kepler Univ. Linz (Austria)

The dielectric strength of elastomers strongly depends on experimental measurement conditions. We show here an experimental approach to determine the dielectric strength of elastomer membranes. We investigate the dielectric breakdown in pre-stretched dielectric elastomers as a function of the stretch ratio. Without clamping the membrane the breakdown is caused by the electromechanical pull-in instability. Higher breakdown voltages are achieved by clamping the pre-stretched elastomer membranes, coming closer to the materials limited bulk breakdown. VHB and natural rubber are used as materials for the breakdown study. We discuss and compare our measurements with available experimental data and conclude that breakdown voltages of dielectric elastomers are determined by experimental constraints. Our results may find applications in the design of dielectric elastomers actuators and energy harvesters and form the basis for theoretical calculations of the maximum energy of conversion in dielectric elastomer energy harvesting.

8687-101, Session PTue

DEAP high-level product architecture

Tómas V. Gudlaugsson, Niels H. Mortensen, Technical Univ. of Denmark (Denmark); Rahimullah Sarban, Danfoss PolyPower A/S (Denmark)

DEAP technology has the potential to be used in a wide range of applications. This poses the challenge to the DEAP component manufacturers to develop components for a wide variety of products. Danfoss Polypower A/S is developing a DEAP technology platform, which can form the basis for a variety of DEAP technology products while keeping complexity under control. High level product architecture has been developed for the mechanical part of DEAP transducers, as the foundation for platform development.

A generic description of a DEAP transducer forms the core of the high level product architecture. This description breaks down the DEAP transducer into organs that perform the functions that may be present in a DEAP transducer. A physical instance of a DEAP transducer contains a combination of the organs needed to fulfill the task of actuator, sensor, and generation. Alternative principles for each organ allow the function of the DEAP transducers to be changed, by basing the DEAP transducers on a different combination of organ alternatives.

A model providing an overview of the high level product architecture has been developed to support daily development and cooperation across development teams.

The platform approach has resulted in the first version of a DEAP technology platform, on which multiple DEAP products can be based. The contents of the platform have been the result of multi-disciplinary development work at Danfoss PolyPower, as well as collaboration with potential customers and research institutions. Initial results from applying the platform on demonstrator design for potential applications are promising.

8687-102, Session PTue

Fabrication of stable reduced-graphene oxide dispersions in various media and their transparent conductive electrode for the dielectric elastomer actuators

Chong Min Koo, Kyungho Min, Min Ho Kim, Il Jin Kim, Soon Man Hong, Ji Young Jung, Won Jun Na, Korea Institute of Science and Technology (Korea, Republic of)

In this presentation , we demonstrate an easy way to prepare a stable reduced graphene oxide (RGO) dispersion in aqueous or organic media by simple adjustment of the degree of reduction and pH of RGO dispersion, and a subsequent fabrication of transparent conductive RGO electrode for dielectric elastomer actuators using a spray coating technique. RGOs were prepared using a hydrazine reducing agent from graphene oxide (GO), which was oxidized from graphite via a modified Hummers' method. The degree of reduction determined the surface properties, such as atomic composition, surface polarity and potential of RGO platelets. In addition, pH significantly affected the surface potential of graphene dispersion. The fine adjustment of degree of reduction and pH of RGO dispersion made production of fine RGO dispersions in aqueous, and organic media such as ethanol and DMF, possible without any aid of dispersing agents. The stable RGO dispersion using volatile ethanol medium provided a unique advantage to be spray-coated into uniform transparent conductive RGO thin electrode films on various dielectric elastomer substrates even at room temperature.

8687-103, Session PTue

Validated numerical simulation model of a dielectric elastomer generator

Florentine Foerster, Holger Moessinger, Helmut F. Schlaak, Technische Univ. Darmstadt (Germany)

Dielectric elastomer generators (DEG) produce electrical energy by converting mechanical to electrical energy. Efficient operation requires homogeneous deformation of each single layer. However, by different

internal and external influences like supports or the shape of a DEG deformation will be inhomogeneous and hence negatively affect the generated electrical energy. Optimization of the deformation behavior leads to improved efficiency of the DEG and thereby to higher energy gain.

In this work a numerical simulation model of a dielectric elastomer generator is developed using the FEM software ANSYS. The analyzed multilayer DEG consists of 50 dielectric layers with layer thicknesses of 50 ?m. The elastomer is PDMS while the compliant electrodes are made of graphite powder.

In the simulation the real material parameters of the PDMS and the graphite electrodes need to be included. Therefore, the mechanical and electrical material parameters of the PDMS are determined by experimental investigations of test samples while the electrode parameters are determined by numerical simulations of test samples.

The numerical simulation of the DEG is carried out as a coupled electro-mechanical simulation for the three different energy harvesting cycles: constant charges, constant voltage and constant field.

Finally, the derived numerical simulation model is validated by comparison with electro-mechanical characterization results of the real DEG and analytical calculations. First comparisons of the determined results show good accordance with regard to the deformation of the DEG.

Based on the validated model it is now possible to optimize the DEG layout for improved deformation behavior.

8687-104, Session PTue

Silver nanowires embedded gel electrodes

Yuta Abe, Jin Gong, Hidemitsu Furukawa, Yamagata Univ. (Japan)

In recent years, organic electronic devices have achieved the tremendous development. Organic light-emitting diodes (OLED) are famous organic electronic devices. OLED have been widely used in our life, mostly in displays of smartphones and illuminations. In addition, OLED also have promising applications in new fields of solar panels, wearable display, and so on. However, currently indium tin oxide (ITO) is often used to make electrode of the organic electronic devices, and ITO has two main disadvantages of expensive and hard. Many researchers have made various efforts to improve the performance of the electrode. In particular, it has been reported that single-walled carbon nanotubes electrode was prepared successfully which having better performances compared to ITO electrode. However, their electric conductivity is not enough high to drive the large-scale organic electronic devices. In this study, we aimed to develop flexible polymer gel electrode consisting of silver nanowires. Firstly, we synthesized silver nanowires by using polyvinylpyrrolidon(PVP), potassium bromide(KBr), ethylene glycol(EG), silver chloride(AgCl), silver nitrate($AgNO_3$) as materials. Secondly, we observed morphology of silver nanowires by scanning electron microscope. Finally, flexible conductive films were developed by introducing silver nanowires into polymer gels, and we measured their mechanical properties and electric conductivity. Silver-nanowire electrode is considered that it can be granted a high conductivity and flexibility. We expect the flexible and conductive gel films have quite new applications in many new fields like health and care, robot, mechanical engineering, ect.

8687-105, Session PTue

Polarizability investigation of 1-butyl-3-methylimidazolium cation in electroactive ionic liquid-cellulose gel actuator

Wissawin Kunchornsup, Anuvat Sirivat, Chulalongkorn Univ. (Thailand)

Due to internal rotation of the polar atomic groups and non-centrosymmetry of its molecules, cellulose can be utilized towards piezoelectric applications. However, the dissolution of cellulose is limited by the high inter- and intra-molecular interactions via the hydroxyl group. One of the novel cellulose solvent is 1-butyl-3-methylimidazolium Chloride (BMIM+Cl-) ionic liquid; it can be used in dissolving and gelling a micro-crystalline cellulose. The thermal gravimetric analysis shows the degradation of obtained BMIM+Cl- cellulosic gel revealing both the degradation temperature of BMIM+Cl- and micro-crystalline cellulose , implying the miscible state of the gel. To investigate 1-butyl-3-methylimidazolium cation as an actuating ion, the dielectric permittivity (?´r) measurement is used to investigate the polarizability of the gel. ?´r versus frequency indicates the domination of ionic polarization over electronic polarization because the BMIM+Cl- cellulosic gel is an ionic rich gel, especially with BMIM+ free cation. Attenuated total reflectance incorporated Fourier transform infrared spectroscopy (ATR-FTIR) is used to investigate the distribution of DMAc bounded BMIM+ free cation showing stronger peaks of 1618, 1506, and 1402 cm-1. It is suggested that the DMAc bounded BMIM+ free cation preferably migrates towards the surface under 1 kV/mm of electric field strength, proving the existence of polarizability. The polarizability of the BMIM+Cl- cellulosic gel is further confirmed by Atomic Force Microscopy (AFM) which provides the topological, electrostatic, and overlapped images. They indicate the gel non-smooth surface, consisting of channels of the BMIM+ cation agglomeration and agglomerated charges topology.

8687-106, Session PTue

A comparison study of ionic polymer-metal composites (IPMCs) fabricated with Nafion and other ion exchange membranes and their suggested applications

Jiyeon J. Park, Viljar Palmre, Univ. of Nevada, Reno (United States); Kwang Jin J. Kim, Univ. of Nevada, Las Vegas (United States); Dongsuk Shin, Department of Bioengineering, Rich University (United States); Daniel H Kim, Memorial Hermann Health System, Department of Neurosurgery, University of Texas (United States)

Ionic polymer-metal composites (IPMCs) have been and still are one of the candidates with a huge potential to be used as an actuator. So far, the most commonly used ion exchange membrane is Nafion and many studies have been conducted with it for IPMC applications. There are a number of commercially available ion exchange membranes in the market besides nafion, but only a few to none studies have been done on those membranes to be used in IPMC. Therefore, in this study, three other commercially available membranes, (1) CMI7000S (Membranes International Inc.) and (2) fumapem F-14100 (fumatech) are selected to be used in the fabrication of IPMCs and their performances are compared to nafion by carrying out various characterizations such as DSC, Ionic Exchange Capacity (IEC), displacement measurement, and more. In addition, the downside of one of properties of nafion is that it limits its performance at the temperature higher than 100 ºC. Hence, those listed membranes are tested at high temperature and observed if they bring out better performance at higher temperature than nafion and can potentially broaden the field of IPMC applications.

8687-107, Session PTue

Sulfonated styrenic pentablock copolymer/ silicate nanocomposite membranes and their IPMC transducers

Chong Min Koo, Jang-Woo Lee, Seunggun Yu, Soon Man Hong, Il Jin Kim, Jin Hong Lee, Santosh Yadav, Korea Institute of Science and Technology (Korea, Republic of)

A novel ionic thermoplastic elastomer, poly((t-butyl-styrene)-b-(ethylene-r-propylene)-b-(styrene-r-styrene sulfonate)-b-(ethylene-r-propylene)-b-(t-butyl-styrene)) (tBS-EP-SS-EP-tBS; SSPB) pentablock copolymer,

and its nanocomposites with sulfonated montmorillonite (s-MMT) have been investigated as polymer electrolytes for ionic polymer-metal composite (IPMC) actuators. The SSPB pentablock copolymer formed a well-defined microphase-separated nanodomain morphology on the several tens nanometer scale. Selectively sulfonated styrene (SS) middle blocks formed ionic conduction channels through which mobile ions are transported. The functionalized MMTs were homogeneously distributed in the SSPB/s-MMT nanocomposites and had the intercalated morphology. The resulting SSPB and SSPB/s-MMT nanocomposite IPMCs revealed not only higher tensile moduli but also higher ionic conductivities than conventional Nafion polymer electrolyte IPMCs. Among the IPMCs, the SSPB/s-MMT nanocomposite-based IPMCs with the developed morphology registered the best actuation performance in terms of bending displacement and blocking force, comparable to a typical Nafion-IPMC.

8687-124, Session PTue

Improvement of foamed ionic polymer metal composites actuator

Chuljin Kim, Kyung Soo Lee, Byung Chul Kweon, Sung Woon Cha, Young-Pil Park, Yonsei Univ. (Korea, Republic of)

In order to improve the actuation performance, the foamed IPMC was carried out researches on. The foamed IPMC is manufactured from the foamed membrane with micro-sized cells that are formed by the microcellular foaming process (MFPs). The MFPs is a technology that forms micro-sized cells in the plastics. Traditionally, in order to increase the driving force, the method of increasing the thickness of IPMC is widely used. Thick Nafion is fabricated by the casting process and foamed. With the increase of the thickness, the change of the foaming characteristic is researched. The optimal condition to of making the foam is found and the correlation between the performance and the thickness are researched.

8687-27, Session 7

Fast miniaturized and manufacturable µm-to cm-scale dielectric elastomer actuators *(Invited Paper)*

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

We report on recent work at the EPFL-LMTS on arrays of miniaturized dielectric elastomer actuators (DEAs) with kHz response. Our goal is highly integrated flexible systems with dozens to thousands of distributed fast actuators and sensors, with feature sizes down to a few µm to enable complex systems such as A4-sized haptic (braille) screens with rapid refresh rates or reconfigurable microfluidic chips.

Our first emphasis is on careful material choice for the elastomer membrane and for the electrode material to achieve both high strain (80%) and also millisecond response time. We report on different silicones and compare compliant electrodes fabricated by low-energy ion-implantation and by a stamping technique with a carbon powder – PDMS composite. We conclude which combination offers the best strain, lack of viscoelasticity (mechanical quality factor), patternability and manufacturability for different applications.

We then discuss the important role uniaxial and biaxial pre-strain has on silicone devices, in allowing much larger uniaxial strain by anisotropically stiffening the elastomer and in increasing electrical breakdown field.

We present a wide range of different DEA devices we have fabricated, based on 10 to 60 µm thick membranes of different silicones. We present our latest data on arrays of µm scale devices to apply mechanical strain to biological cells, arrays of micropumps for chip-scale fluid pumping, using a zipping-type actuators, tunable lenses, miniaturized DEA rotary motor, and an optimized minimum energy structure bending actuator for soft robotics used as a compliant grabbing system.

8687-28, Session 7

Modeling of mechanical properties of stack actuators based on electroactive polymers

Dominik Tepel, Christian Graf, Jürgen Maas, Ostwestfalen-Lippe Univ. of Applied Sciences (Germany)

Dielectric elastomers are thin polymer films belonging to the class of electroactive polymers, which are coated with compliant and conductive electrodes on each side. Due to the influence of an electrical field, dielectric elastomers perform a large amount of deformation. Because single-layer actuator films are not suitable for the positioning applications, novel energy-efficient multilayer-actuators are utilized to enlarge the displacement and force at a consistent high strain. In the multilayer-technology many actuator films are connected mechanically in series, building up a stack actuator, which elongates in the case of a charged EAP capacitance. The contribution of this paper is to present a model of the mechanical behavior of the actuator.

At first a holistic electromechanical model of a single actuator film and a stack actuator without constraints is derived. To enable a linear positioning and a force transmission when embedding the stack actuator into a mechanical system, stiff end caps are mounted on the upper and lower side. Due to these stiff end caps bulges occur at the free surfaces of the EAP-material, which are calculated and considered in the model for a round and rectangular stack acutuator geometry. Based on the calculation of the lateral bulges, the strain of each stacked film is calculated for the round stack actuator geometry. Finally the analytic actuator film model as well as the stack actuator model are validated by comparing them to numerical FEM-models in ANSYS.

8687-29, Session 7

Electrical modeling of dielectric elastomer stack transducers

Henry Haus, Marc Matysek, Holger Moessinger, Helmut F. Schlaak, Technische Univ. Darmstadt (Germany)

Dielectric elastomer stack transducers (DEST) with up to 100 layers are fabricated in an automated process. While the dielectric layers are homogeneously spin coated films the electrodes are fabricated by spray coating conductive particles. Consequently, the electrodes cannot be assumed as ideal as a continuous electrode. The resulting electrical field driving the actuator will strongly depend on the distribution of conductive particles.

First we show the influence of the particle concentration in the electrode area on the resulting electrical field distribution. Parameters like film thicknesses, particle size and local distribution of conductive material are considered. As a result we conclude fabrication requirements allowing to drive the actuator efficiently.

In a second step we expand this model to a multi-layer system. We derive an expression describing the system's dynamical behavior as a function of fabrication (layout, sheet and interconnection resistance), material (breakdown strength, permittivity) and driving (voltage) parameters.

To be able to validate the model we need to properly characterize actuators. Besides established methods for external characteristics like the frequency response we use new methods to determine internal parameters like the resistance of the interconnections which can heavily influence the actuator's performance.

Finally, we validate the model by comparing theoretical results with electro-mechanically measurements of different sample stack transducers. We see good coherence for our electrical model. Furthermore, the method to determine the interconnection resistance delivers results which correspond to the observed behavior.

8687-30, Session 7

Modelling of dielectric elastomer loudspeakers including dissipative effects

Benny Lassen, Univ. of Southern Denmark (Denmark)

This contribution presents a theoretically investigation of dielectric elastomer loudspeakers similar in design to the loudspeakers studied at SRI International more than 10 years ago. Additionally the more recent designs suggested by Christian Graf and Jürgen Maas are considered. The main emphasis of the contribution is on the effect of dissipative effects, specifically viscoelastic effects and radiative losses.

The starting point of the theoretical model is a free-energy description and include hyper-elastic contributions. In the designs considered in this work the dielectric elastomer material is subject pre-strain which has been applied either by subjecting the membrane to an applied back pressure, or simply applying a biaxial mechanical pre-strain. The membrane is then actuated relative to this pre-strain by the application of an applied ac voltage. The nonlinear equations are linearized around the given pre-strain in order to perform relatively fast calculations of the mechanical impedance of the structure.

8687-31, Session 7

Modeling of roll-actuators based on electroactive polymers

Thorben Hoffstadt, Christian Graf, Jürgen Maas, Ostwestfalen-Lippe Univ. of Applied Sciences (Germany)

Dielectric electroactive polymers are thin films made of elastomeric material coated with compliant and conductive electrodes. Since they offer a large amount of deformation these materials have high potential for actuator- and also generator-applications.

By winding up an EAP-film a roll-actuator can be realized, which elongates axially, if the EAP's capacitance is charged electrically. The contribution of this paper is related to the modeling of the mechanical and electrical behavior of this actuator-type to obtain a coupled model.

The hyperelastic material properties are considered within the mechanical model, which is based on the calculation of the Cauchy-stresses depending on the strain of the material. Besides the Cauchy-stresses the electrostatic pressure caused by the charge on EAP's capacitance have to be considered. This stress is obtained from the electrical model, which besides of the capacitance consists of a resistance in parallel, describing the non-ideal insulating behavior of the polymer, and a series resistance, taking into account that the electrode is not ideal conducting.

Since the electrical parameters and therefore the electrostatic pressure also depend on the strain of the actuator, the mechanical and electrical model can be combined so that a electromechanically coupled dynamic model is obtained, which calculates the actuator force depending on the strain and the applied electrical voltage.

The derived model is based on idealized conditions regarding the actuator setup, which will cause deviations between the model and a realized actuator. Therefore electrical and mechanical boundary effects are explained and implemented finally.

8687-32, Session 7

A comparison of the electromechanical characteristics of dielectric elastomer minimum energy structures (DEMES) and planar dielectric elastomer actuators (p-DEAs)

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Dielectric elastomer actuators are considered as promising candidates for robotic elements (Anderson et al., J Appl Phys, 2012). To this end, planar dielectric elastomer actuators (p-DEAs) and dielectric elastomer minimum energy structures (DEMES) are applicable. However, the knowledge of their electrical and mechanical characteristics is of major importance for engineering. Therefore we study p-DEAs and DEMES by impedance spectroscopy and dynamic capacitive extensometry (DCE). The boundary conditions with regard to p-DEAs (free and fixed boundaries) and the electrode material (carbon black powder, silicone oil – carbon black powder mixture) are varied. DCE is an electrical technique for in situ monitoring of the actuators during dynamic high voltage actuation (Buchberger et al., Proc I2MTC, 2012). DCE was developed based on works of Gisby et al. (Proc SPIE, 2011) and Keplinger et al. (Appl Phys Lett, 2008). The electrical characteristics of the p-DEAs and DEMES are related to their transient stretch in response to high voltage driving signals. We present electrical equivalent circuit models of the actuators, the frequency ranges in which they are applicable and effects of aging on the equivalent circuit models. By DCE we study the transient viscoelastic stretch response of the actuators, the state of the compliant electrodes and their percolation limit, the response time of the actuators and their movement behavior. By this measurement data p-DEAs and DEMES can be compared. Furthermore we give information about the power consumption of the fabricated actuators. In future we plan to measure the influence of temperature on the equivalent circuit models.

8687-33, Session 7

Novel silicone compatible cross-linkers for controlled functionalization of PDMS networks

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Polydimethylsiloxane (PDMS) is one of the most used materials for DEAP applications due to its good thermal stability, high efficiency and fast response [1]. To obtain high actuation strain of DEAPs, the activation voltage is in general too high for many practical applications. One method to lower the activation voltage is to increase the dielectric permittivity of the elastomer. This work presents new functional PDMS materials for DEAP applications with increased dielectric permittivity. The permittivity is enhanced by grafting of functionalities such as dipoles to a novel silicone compatible cross-linker. This novel cross-linker allows for orthogonal chemistry and contains both vinyl groups for cross-linking reactions with hydride-terminated PDMS and an azide functionality that opens up for click reactions. In this case, the copper-catalyzed cycloaddition of an azide group and an alkyne (CuAAC) forming a 1,4-disubstituted-1,2,3-triazole [2,3]. Incorporation of functionality at the cross-linking point allows for controlled and well distributed modification of the PDMS network. Even very small loadings, e.g. 1 wt%, of incorporated dipoles have led to a large increase in the dielectric permittivity.

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8687-34, Session 8

Novel silicone elastomer formulations for DEAPs

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(Denmark)

We demonstrate that the force output and work density of polydimethylsiloxane (PDMS) based dielectric elastomer transducers without any prestretch can be significantly enhanced by the addition of high permittivity titanium dioxide nanoparticles which was also shown by Stoyanov et al[1] but for pre-stretched elastomers. Furthermore the novel elastomer matrix is optimized to give very high breakdown strengths. We obtain an increase in the dielectric permittivity of a factor of approximately 2 with a loading of 12% TiO_2 particles compared to the pure modified silicone elastomer with breakdown strengths remaining more or less unaffected by the loading of TiO_2 particles. Breakdown strengths were measured in the range from approximately 80-150 V/µm with averages of the order of 120-130 V/µm for the modified silicone elastomer with loadings ranging from 0 to 12%.

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8687-35, Session 8

Snap through instability of dielectric elastomers coupling polarization saturation and strain stiffening

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When a dielectric elastomer with randomly oriented dipoles is subject to an electric field, the dipoles will rotate to and align with the electric field. The polarization of the dielectric elastomer may be saturated when the voltage is high enough. In a dielectric elastomer, each individual polymer chain has a finite contour length. When subjected to a mechanical force, the end-to-end distance of each polymer chain increases and eventually approaches the finite contour length, setting up a limiting stretch. On approaching the limiting stretch, the elastomer stiffens steeply. We develop a thermodynamic constitutive model of dielectric elastomers undergoing polarization saturation and strain-stiffening, which include both nonlinear elastic and dielectric behavior. Analytical solutions have been obtained for situations incorporating strain-stiffening effect and polarization saturation effect. The numerical results reveal the marked influence of the extension limit and polarization saturation limit of elastomer material on its snap through instability. The developed thermodynamic constitutive model would be helpful in future to the research of dielectric elastomer based high-performance transducers.

8687-37, Session 8

Effects of filler modification and structuring on dielectric enhancement of silicone rubber composites

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Addition of particulate fillers such as Silica or Titania improves dielectric properties of silicone rubber. Modification of filler surfaces enhances dielectric permittivity of silicone rubber as well as possibility of structuring filler particles in the direction of an applied electric field. By modification and structuring fillers in the polymer matrix dielectric properties of the composite changes to a great extent. It was shown that although Titania has much higher dielectric permittivity than Silica, they perform similarly in this regard since the dominant mechanism in improving dielectric properties and structuring of filler particles is the inter-facial polarization rather than intrinsic properties of filler.

8687-38, Session 8

Fast triggering of instabilities in balloon membranes by dielectric elastomer actuators

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Balloons are known to show a mechanical snap-through instability. We present theory and experiment to show that the instability can be triggered remotely by a dielectric elastomer membrane to safely harness giant voltage-triggered deformation. We mount a dielectric elastomer membrane and a passive balloon membrane on a chamber of suitable volume into a stage near the verge of the mechanical balloon instability. By applying suitable voltages to the dielectric elastomer membrane actuator bistable operation of the balloon is achieved. The dielectric elastomer actuator is working in a safe regime above the snap-through instability and well below the breakdown voltage. The balloon instability is fast due to the use of low viscoelastic natural rubber. VHB is used for the dielectric elastomer actuator. We demonstrate bistable operation with small and large volumes of the rubber balloon and have achieved large volume changes around 1600% at frequencies up to 9 Hz. The remote operation of the balloon actuator suggests applications in Braille and haptic displays when miniaturized. There is also potential to use the large volume changes for the movement of soft robots.

8687-109, Session 8

Multilayer stack actuator made from new prestrain-free dielectric elastomers

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Dielectric elastomers have attracted increasing attention for basic research and product development. However, the best performing materials reported so far are commercial products manufactured for unrelated applications. Prestretching is commonly employed to obtain high actuation strain and energy density. The limited knowledge of the polymers' chemical structure makes it difficult to re-formulate the polymers for significantly improved overall material performance. We report to the synthesis of new acrylate-based dielectric elastomers that exhibit high actuation strain without prestretrching. Mixtures of commercial acrylate monomers and other additives are copolymerized by UV-initiated radical polymerization to form thin dielectric elastomer membranes. The processing is readily scaled up to fabricate multilayer stacked actuators with 10% linear actuation strain.

8687-39, Session 9

Field-distribution in EAP-transducers with diagonal-edge contacts

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Dielectric electroactive polymers are soft capacitors made of thin elastic and electrically isolating films coated with compliant and conductive electrodes, which belong to a new class of smart materials, whose functional principle is based on electrostatic forces. They can either be used as actuators to provide considerable stretch ratios or as generators to convert mechanical strain energy into electrical energy based on an electrostatic energy converter concept. Since the polymer material and also the covering compliant electrodes have non-ideal electrical properties, such as, respectively, finite resistivity and conductivity,

design rules are usually required to optimize the devices. The electrode conductivity combined with the polymer resistivity causes a voltage drop along the electrode surface, reducing the energy gain in case of energy harvesting applications or actuation force in case of actuator applications.

In a previous contribution, it could be shown that the voltage drop can be calculated analytically in the case of opposite contacts with respect to the axis of film thickness. For this case, important design rules for the optimal placement of electrode contacts were derived. However, the technically important option with diagonal contacts with respect to the axis of film thickness has not been considered. Therefore, an equivalent network model has been developed to calculate the voltage distribution. The detailed modeling approach and simulation results will be presented in the final paper. Based on this model, it is possible to derive design rules for the electrodes of generators and actuators in order to increase the EAP transducer performance.

8687-40, Session 9

Uncertainty quantification and stochastic-based viscoelastic modeling of finite deformation elastomers

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Model uncertainty is a well known issue in formulating continuum scale models based on the unknown molecular and microstructure evolution in large deformation elastomers. The quantification of a stochastic model that includes probability distributions of critical underlying molecular constitutive behavior is not trivial. This is particularly challenging in identifying rate-dependent deformation over a broad range of deformation rates. To address this problem, a Bayesian statistical analysis is applied to modeling the viscoelastic behavior of an elastomer material commonly used in smart structure applications, VHB 4910. Probability distributions are identified using simplified viscoelastic model assumptions and a Bayesian statistical analysis. The probability distributions for individual stretch rates are then used to construct a total distribution describing the viscoelastic behavior. We show that by incorporating these probability distributions into a stochastic based homogenized viscoelastic model, excellent fits to the constitutive behavior are obtained in comparison to uniaxial experiments when the model is coupled to an Ogden hyperelastic stress.

8687-41, Session 9

More than 10-fold increase in the actuation strain of dielectric elastomer actuators

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Prestretching the elastomer is a known technique to enhance the actuation strain of dielectric elastomer actuators as it thins down the membrane and suppresses the instability mode. This is reasonable for VHB based elastomers sold with predefined initial thickness. But with silicone elastomers, any thickness can be manufactured and the desired final thickness of the device determines the initial thickness before prestretching. In this case, biaxially prestretching is a disadvantage, as it stiffens the hyperelastic membrane and increases the required voltage to reach the same actuation strain of a device with a nonstretched membrane. In this paper, with theoretical modeling, we explain that uniaxial prestretching is the effective technique to enhance the actuation strain of dielectric elastomer actuators with predefined device thickness. The membrane stiffens in direction of prestretch and remains soft in the other direction, leading to higher actuation strain in the nonstretched direction and smaller strain in the prestretched direction. This also leads to anisotropic strain profile. To validate the theoretical analysis, we have fabricated 2 x 2 mm2 actuators by patterning perpendicular compliant electrodes on both layers of a silicone elastomer using a pad printer. The elastomeric membrane is prestretched with different ratios and the effect of isotropic and anisotropic prestretch is investigated on device's performance. The maximum actuation strain is increased more than 10 folds by uniaxially prestretching the silicone membrane compared to a nonstretched membrane.

8687-42, Session 9

Enhancement of the dielectric properties of dielectric elastomers by Janus particle fillers

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Dielectric elastomers respond to an electric field by changing their shape due to electrostatic attraction within the elastomer. Because they are flexible, affordable, and easily-fabricated, they are good candidates for electro-mechanical materials. The electromechanical mechanism of dielectric elastomers is described by the Maxwell equation that relates the elastic and dielectric properties of the material. However, most polymers exhibit a low Young's modulus coupled with a low dielectric constant. Thus, high dielectric constant fillers are used to solve this problem.

Silica particles carry a slight negative charge on their surface when immersed in an aqueous electrolyte and as a result responded to an electric field. In our studies, we have modified silica particles with a neutral thin gold layer on one hemisphere. Due to the discontinuous surface charge, these modified silica Janus particles can be aligned in an E-field when dispersed in an elastomer, resulting in the generation of a highly localized dipole moment that efficiently enhances the overall dielectric constant of the material. In addition, we have observed that the Janus modification leads to a reduction of the conduction loss of the composite compared to the increased loss when other conductive materials are used as fillers.

In our research, silica Janus particles are mixed with an EGPEA monomer precursor. The cured p(EGPEA) are swelled with toluene, which leads to an enlargement of the polymer matrix. Then, an electric field is used to align the Janus particles within the swollen matrix. The cap alignment and rotation of the Janus particles is monitored using optical microscopy. The p(EGPEA) actuators with aligned Janus particles have very high dielectric constants, resulting in a high compressive strain when an external electric field is applied.

8687-43, Session 9

Very-high breakdown field strength for dielectric elastomer actuators quenched in dielectric liquid bath

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Dielectric elastomer actuators (DEAs) are prone to premature failure at a lower driving voltage, as compared to the ultimate breakdown voltage, which limits the work life and the actuation performance. Prestretch was well-known to increase the breakdown strength of elastomers by preventing pull-in instability, during which the actuated dielectric film lost tension and buckles. However, dielectric film may fails beyond the pull-in voltage. It remains a question if DEAs could survive the pull-in instability. In this work, we showed that DEAs, which were immersed in a silicone oil bath ((Dow Corning Fluid 200 50cSt).), can survive the pull-instability and operates beyond the pull-in voltage. Membrane DEAs (VHB4905), which were pre-stretched biaxially at 200% strain and immersed in the oil bath, sustained a very high electric field (>800 MV/m) without breakdown, and they demonstrated areal strains up to 140%. The achieved field strength in the immersion is approximately two times larger than that in the air (450 MV/m). This is achieved because the dielectric liquid bath help to quench the localized electrical breakdown, which would have discharged

sparks and burnt dielectric film in the air. The oil immersion promises to extend the safe operation of DEA up to a very high electric field.

8687-44, Session 9

Optimized flexible electrode for EAP (electroactive polymer)

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In this paper, the optimized flexible electrode was studied for electro EAP (electro-active polymer).

Not only an electrode but also elastomer determines the properties of EAP. The electrode should have a low modulus and electrical resistance.

Typically, the conductive grease and rubber were used for electrode, however the conductive grease has a problem for molding and the case of conductive rubber is difficult for extension.

Therefore, in this paper the electrode with low electrical resistance, easy flexibility and extension is developed.

First, the flexible silicone rubber was made by adding the RTV (room temperature vulcanization) thinner.

Second, to provide the conductivity for flexible silicone rubber both the conductive CB (carbon black) and MWCNT (multi-walled carbon nanotube) were filled. The carbon particles were dispersed with an overhead stirrer and ultrasonic device.

The mechanical (modulus, elongation) and electrical (surface and volume resistance) properties of the flexible electrode were investigated experimentally.

The experimental results showed that the electrical resistance decreases with increasing CB and MWCNT content compared to the pure silicone rubber.

The modulus of optimized flexible electrode was 0.05 MPa when the CB content, MWCNT content, and thinner content is 20 phr, 2.5 phr, and 80 phr, respectively. And the surface resistance of that was 100 ? at the same condition.

The actuating capability of the EAP with optimized flexible electrode was confirmed using the 3M 4910 elastomer.

It is believed that the EAP based on flexible electrodes are expected a field of applications in artificial muscles, artificial skin, artificial hearts, etc.

8687-45, Session 9

New operating limits for applications with electroactive elastomer: effects of the drift of the permittivity and the electrical breakdown

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Dielectric elastomer generators are a promising solution to scavenge energy from human motion, due to their lightweight, high efficiency, low cost and high energy density. Performance of a dielectric elastomer used in a generator application is generally evaluated by the maximum energy which can be converted. This energy is defined by an area of allowable states and delimited by different failure modes such as: electrical breakdown, loss of tension, mechanical rupture and electromechanical instability, which depend deeply on dielectric behaviors of the material. However, there is controversy on the dielectric constant (permittivity) of usual elastomers used for these applications. This paper aims to investigate the dielectric behaviors of two popular dielectric elastomers: VHB 4910 (3M) and Polypower (Danfoss). This study is undertaken on a broad range of frequency and temperature. We focus on the influence of pre-stretch in the change of the dielectric constant. An originality of this study is related to the significant influence of the nature of compliant electrodes deposited on these elastomers. Additionally, the electrical breakdown field of these two elastomers has been studied as a function of pre-stretch and temperature. Lastly, thanks to these experiments, analytic equations have been proposed to take into account the influence of the temperature, the pre-stretch and the nature of the compliant electrodes on the permittivity. These analytic equations and the electrical breakdown field were embedded in a thermodynamic model making it possible to define new limits of operation closer to the real use of these elastomers for energy harvesting applications.

8687-46, Session 10

Electrochemistry of electromechanical actuators based on carbon nanotubes and ionic liquids *(Invited Paper)*

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In this paper, we have developed electrochemical equivalent circuit model of the electromechanical actuator composed of the ionic liquid (IL) gel electrolyte layer sandwiched by the electrode layers based on single-walled carbon nanotubes (SWNTs) and ILs (bucky-gel actuator). The model is composed of the resistance of ionic gel electrolyte layer and the impedance of electrode layer. The electrode impedance is the transmission line circuit composed of a distributed double-layer capacitance, a distributed Faraday impedance of redox reaction and a distributed resistance of ion-conductive pore. The electrochemical model can be applied to the electromechanical effect only due to the electric double-layer (DL) charging, or due to both the DL charging and redox reaction of SWNTs.

We have found that the electromechanical response of the bucky-gel actuator is originated by the dimensional changes of both electrode layers due to the electric double-layer charging on the surface of the SWNTs. We have also found that the redox reaction of the SWNTs contributes to the electromechanical effect of the bucky-gel actuator under appropriate conditions. We carried out the electromechanical measurements and electrochemical impedance measurement of the bucky gel actuators. The proposed model was compared with the experimental results.

8687-47, Session 10

Development of piezoresistive PVDF-nanocomposites for strain sensing

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The emergence of novel electronic systems and their requirements have necessitated the evolution of new material classes. The traditional electronic semiconductors and components are shifting from silicon based substrates to polymers and other organic compounds. Sensor components are no exceptions, where compliant polymeric materials offer the possibility of flexible electronics. This paper examines the fabrication and characterization of piezoresistive nanocomposites for strain sensing applications. The matrix material employed was Polyvinylidene Fluoride (PVDF). The PVDF phase was reinforced with conductive particles, in order to form a conductive filler network throughout the nanocomposite. Multiwall carbon nanotubes (MWNT), graphene nanoplatelets (GNP) and carbon black (CB) were chosen as conductive particles to form the networks. The composites were prepared by melt mixing the PVDF and conductive particles in compositions ranging from 0.5 to 26 wt% conductive particle in PVDF.

The dielectric permittivity and electrical conductivity of the composites was characterized and the electrical percolation behavior of PVDF nanocomposites fitted to the statistical percolation model. Scanning electron and atomic force microscopy were employed to understand the morphology of the filler networks in the nanocomposites. Quasi-static piezoresistance of the nanocomposites was characterized using a custom-built force-resistance measurement setup under compressive and tensile loading conditions.

8687-48, Session 10

Improving dry carbon nanotube actuators by chemical modifications, material hybridization, and proper engineering *(Invited Paper)*

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Low voltage, dry electrochemical actuators can be prepared by using a gel made of carbon nanotubes and ionic liquid.[1] Their performance can be significantly improved by combining physical and chemical modifications with a proper engineering. We demonstrated that multi walled carbon nanotubes can be effectively used for actuators preparation;[2] we achieved interesting performance improvements by chemically cross linking carbon nanotubes using both aromatic and aliphatic diamines;[3] we introduced a novel hybrid material, made by in-situ chemical polymerization of pyrrole on carbon nanotubes, that further boost actuation by taking advantage of the peculiar properties of both materials in terms of maximum strain and conductivity;[4] we investigated the influence actuator thickness showing that the generated strain at high frequency is strongly enhanced when thickness is reduced. To overcome limitations set by bimorphs, we designed a novel actuator in which a metal spring, embedded in the solid electrolyte of a bimorph device, is used as a non-actuating counter plate resulting in a three electrode device capable of both linear and bending motion. Finally, we propose a way to model actuators performance in terms of purely material-dependent parameters instead of geometry-dependent ones.[5] Our latest advances on CNT actuators will be given and discussed.

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8687-49, Session 10

Measuring the bending of asymmetric planar EAP structures

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In order to describe electro active polymer (EAP) systems with nanometer-thin films but areas of square centimeter for applications such as artificial sphincters, characterization methods with nanometer resolutions are needed. Optical methods are usually restricted to sub-micrometer limited by wavelength. Hence, we propose the use of a cantilever bending system revealing a resolution of 2.8 nm at the deflection of the free end. Based on estimations this method allows us to detect bending of planar asymmetric EAP-structures applying voltages well below 1 V. Here we have considered structures of silicone layers thinner than 800 nm and polyetheretherketone (PEEK) substrate, films with thicknesses between 6 and 25 µm. Knowing the deflection of the cantilever free end, conclusions on the Maxwell power could be made (cp. [1]). This method should become the basis to analyse low voltage, dielectric EAP-structures to reach nanometer scale stack actuators for artificial sphincter applications.

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8687-50, Session 10

Fabrication of shape-memory nanofibers by electrospinning method

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Nafion as a promising material is considered in lots of fields involving functional composite materials, sensors and actuators, smart textiles and so on. Nanofiber having shape memory effect is a novel smart material. The fiber spinning technique of electrospinning is optimized in order to prepare unidirectional aligned, structurally oriented, and mechanically useful fibers with diameters in the nanoscale range. Nanometer-sized fibers with big surface area and loose structure can expand the scope of application. In this paper, a series of smart Nafion nanofibers with shape memory effect were successfully obtained via an electrospinning technique. TGA was used to text their thermal properties. SEM was applied to investigate the morphology and structure of Nafion nanofibers. And the structure change taking place in the electrospinning process was discussed. The mechanical properties of Nafion nanofibers were examined through tensile tests. The shape memory effect tests were evaluated in a fixed force controlled tensile tests. It was found that the fibers showed an excellent shape memory property. It was significant to expand the technical potential for shape memory polymers.

8687-51, Session 10

Silica reinforced polypropyleneoxide network: a novel silicone-resembling elastomer with enhanced dielectric properties

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A novel very soft elastomeric material for EAP purposes is investigated. The elastomer consists of silica reinforced polypropyleneoxide which are crosslinked into an elastomer. The dielectric permittivity was measured in the range of epsilon=6-12 at 1 Hz and even higher with high-permittivity titaniumoxide particles added, breakdown strengths around 60 V/microns and Young's moduli slightly lower than the commonly used silicone elastomer Elastosil RT625. The response time is similar as for silicones, but the viscous loss is slightly higher as the crosslinking reaction is not complete. Compared to silicone this material has favorable properties especially in the low-frequency range where very high dielectric permittivities are measured.

Furthermore the PPO elastomer opens up for more easily modifications of the elastomer backbone compared to the traditional silicone elastomers.

8687-52, Session 11

Characterization and modeling of humidity-dependence of IPMC sensing dynamics

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Ionic polymer-metal composites (IPMCs) have intrinsic actuation and sensing capabilities, and they need hydration to operate. For an IPMC sensor operating in air, the water content in the polymer varies with the humidity level of the ambient environment, which leads to its strong humidity-dependent sensing behavior. However, the study

of this behavior has been very limited. In this paper, the influence of environmental humidity on IPMC sensors is characterized and modeled from a physical perspective.

Specifically, a cantilevered IPMC beam is excited mechanically at its base inside a custom-built humidity chamber, where the humidity is feedback-controlled by activating/deactivating a humidifier and a dehumidifier properly. We first obtain the empirical frequency responses of the sensor under different humidity levels, with the IPMC base displacement as input and the tip displacement and short-circuit current as outputs. Based on physics-based model for a given humidity level, we then curve-fit the measured frequency responses to identify the humidity-dependent physical parameters, including moment of inertia and Young's modulus for the mechanical properties, and effective dielectric constant, ionic diffusivity and charge-stress coupling constant for the mechanoelectrical dynamics. These parameters show a clear trend of change with the humidity. By fitting the identified parameters at a set of test humidity levels, the humidity-dependence of the physical parameters is captured with polynomial functions, which are then plugged into the physics-based model for IPMC sensors to predict the sensing output under other humidity conditions. The latter humidity-dependent model is further validated with experiments.

8687-53, Session 11

Charge dynamics of ionic polymer metal composites in response to electrical bias

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Ionic polymer metal composites (IPMCs) are a novel class of electroactive materials which find application as sensors, actuators, and energy harvesters. IPMCs are fabricated from an electrically charged polymer membrane which is infused with a solvent, neutralized by mobile counterions, and plated by noble metal electrodes. Electrode deposition generally results in the formation of a heterogeneous layer, wherein metal particles are dispersed within the polymer matrix. Such layer has conductive and dielectric properties and we refer to it as the "composite layer".

Here, we analyze the effect of the composite layer on the response of IPMCs to voltage inputs consisting of an arbitrarily large DC bias and as small AC signal. We model the IPMC as a stacked sequence of five homogeneous layers, wherein the polymer core is separated from the metal electrodes by two composite layers. The Poisson-Nernst-Planck framework is used to describe IPMC charge dynamics and perturbation methods are employed to establish an equivalent impedance model. The circuit consists of the series connection of a resistor associated to diffusion in the IPMC core and two complex elements pertaining to charge build up and mass transfer in the electrode regions. Each of these complex elements is composed of the parallel connection of a capacitor and a Warburg impedance that are, in turn, controlled by the DC bias. The framework is validated through comparison with experimental results on in-house fabricated IPMCs. Further insight on the accuracy of the circuit model is garnered through finite element analysis of the Poisson-Nernst-Planck system.

8687-54, Session 11

Design optimization of rod-shaped IPMC actuator

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Ionic polymer-metal composites (IPMCs) are some of the most well-known electro-active polymers. This is due to their large deformation provided a relatively low voltage source. IPMCs have been acknowledged as a potential candidate for biomedical applications such as cardiac catheters and surgical probes; however, there is still no existing mass manufacturing of IPMCs. This study intends to provide a theoretical framework which can be used to design practical purpose IPMCs depending on the end users interest. By explicitly coupling electrostatics, transport phenomenon, and solid mechanics, design optimization is conducted on a simulation in order to provide conceptual motivation for future designs. Utilizing a multi-physics analysis approach on a three dimensional cylinder and tube type IPMC provides physically accurate results for time dependent end effector displacement given a voltage source. Simulations are conducted with the finite element method and are also validated with empirical evidences. Having an in-depth understanding of the physical coupling provides optimal design parameters that cannot be obtained from a standard electro-mechanical coupling. These parameters are altered in order to determine optimal designs for end-effector displacement, maximum force, and improved mobility with limited voltage magnitude. Design alterations are conducted on the electrode patterns, electrode size and Nafion diameter in order to provide greater mobility, efficient bending, and improved force respectively. The results of this study will provide optimal design parameters of the IPMC for different applications.

8687-55, Session 11

Viscoelastic model of IPMC actuators

Veiko Vunder, Andres Punning, Alvo Aabloo, Univ. of Tartu (Estonia)

One of the constraining properties of the IPMC actuators is their back-relaxation. An excited IPMC actuator, instead of holding its bent state, relaxes back towards its initial initial shape even when the exciting signal is a DC voltage. This behavior is reported by many authors and is usually explained with diffusion of water back, or out of the electrodes.

The bending-relaxing behavior of IPMC actuators resembles viscoelasticity, but seems working partly conforming, partly contra to the electrical excitation. The classical schemes of viscoelasticity – the Maxwell model, Kelvin-Voigt model, and the various combinations of the two – cannot describe adequately this situation. Due to the constraint of the application of force, they are unable to describe simultaneously both – the actuation and relaxation – of the IPMC materials. The cause of this failure is the standard pattern of the viscoelastic models, where the load is external, and is applied to the whole system. The situation changes completely, when the impelling factor is applied between the spring and damper, resembling for instance charge making the elastic threads of the polymer molecules network expanding-contracting.

We show that a non-traditional approach to the well-known elements of the traditional viscoelastic schemes – spring and damper – results with a qualitatively new model of viscoelasticity. This mechanical analogy of viscoelastic behavior elucidates the naturalness of the back-relaxation behavior of the actuators. The PDE describing the system gives an intuitive and accurate charge-deflection correlation with back-relaxation included.

8687-56, Session 11

Deformation behavior of ionic polymer metal composite actuator in several pH solutions

Masaki Omiya, Wataru Aoyagi, Keio Univ. (Japan)

In this paper, the pH value of working solution of Ionic Polymer Metal Composite (IPMC) actuators was systematically changed and the effect of pH on the deformation behavior was experimentally investigated.

Ionic polymer metal composite (IPMC) actuators, which consist of a thin perfuorinated ionomer membrane and electrodes plated on both surfaces, can undergo a large bending motion when a small electric field is applied across its thickness direction. Because of its lightness, softness and usableness in wet conditions, IPMC actuators are promised to be used for artificial muscles, biomimetic actuators and medical applications. The deformation properties of IPMC actuators are influenced by working solutions. However, the basic understandings about the effect of pH value of working solution on the deformation

properties have not been clarified yet. Therefore, the pH characteristics of IPMC actuator were evaluated in this paper.

IPMC actuators with the palladium electrodes were used and the responses for step voltage in several pH solutions were investigated. The results showed that the deformation behavior is drastically changed between acid and alkali solutions. In acid solutions, IPMC actuator showed a relaxation motion, though IPMC actuator in alkali solutions kept its deformed shape during applying a voltage.

Cyclic voltammetry and alternating current impedance of IPMC were also measured. The results revealed that the maximum tip displacement and relaxation phenomenon of IPMC actuator were governed by the reduction of palladium electrode. The residual tip displacement is related to the charge transfer resistance and the double layer capacitance of IPMC actuator.

8687-57, Session 12

Electrorotation of novel electroactive polymers in uniform DC and AC electric field

Miklos Zrinyi, Semmelweis Univ. (Hungary); Masami Nakano, Tohoku Univ. (Japan)

We present experimental demonstration of the development of novel electroactive polymer composites which perform rotation in uniform DC and AC electric field. Small non-conducting objects dispersed in liquid dielectrics and subjected to homogeneous DC electric field exceeding some threshold value exhibit spontaneous rotation, called Quincke rotation. Polymer composites as well as pure polymers that fulfill these requirements have been developed and electro rotation of disk shaped polymer has been investigated. We have studied the angular motion of polymer disks around to an axis that perpendicular to the direction of applied electric field and have concluded that dynamics of the polymer rotor is very complex. It was found that angular deformation can also be induced by low frequency AC fields. Controllable rotation of small rotors is of relevance for a range of practical applications, for example in micro-motors or in microfluidics.

8687-58, Session 12

Artificial muscles emerging from lamina materials

Sina Sareh, Jonathan M. Rossiter, Univ. of Bristol (United Kingdom)

The soft actuation capabilities of electroactive polymers can be best exploited through formal design techniques. In this paper, the kirigami (literally 'cutting paper') design process is used to build monolithic mechanisms from lamina materials. These smart structures actuate out of the fabrication plane in response to a single electric stimulus. Kirimimetic patterns are cut into IPMC lamina materials in order to create complex transformable morphologies. This enables sub-mm scaling and monolithic batch fabrication to be used, thereby facilitating ready integration into commercial products. These technologies open up avenues for exploitation including ultra-small disposable mechanisms for a range of biomedical applications, smart deployable structures, and engineering applications where space is constrained. This paper reviews and classifies previous morphologies of EAP lamina materials and proposes novel kirimimetic actuation mechanisms. We also discuss the design and efficiency of novel flow control devices based on kirigami techniques and IPMC actuators.

8687-59, Session 12

Modeling and experimental study of bistable dielectric elastomer structures

Tiefeng Li, Zhannan Zou, Ke Li, Shaoxing Qu, Zhejiang Univ. (China)

Mechanical energy and electrical energy can be converted to each other by using a dielectric elastomer transducer. Energy dissipation caused by high voltage has been a major challenge in the practical applications of dielectric elastomer actuators. Properly designed dielectric elastomer bi-stable structures can actuate with a voltage pulse and remain the deformation without keeping high voltage. Critical actuation voltage, output force and displacement of the structure have been studied experimentally. We build up an analytical model for the dielectric elastomer bi-stable structure based on the frame work of thermodynamics and continuum mechanics. Various methods have been proposed to enhance the performance of the bi-stable structure and demonstrate the principles of operation in experiments.

8687-60, Session 12

On the development of planar actuators for variable stiffness devices

Markus Henke, Gerald Gerlach, Technische Univ. Dresden (Germany)

The contribution describes the development, the potential and the limitations of planar actuators for controlling bending devices with variable stiffness. Such structures are supposed to be components of new smart, self-sensing and -controlling composite materials for lightweight constructions. To realize a proper stiffness control, it is necessary to develop reliable actuators with high actuation capabilities based on smart materials. Several actuator designs driven by electroactive polymers (EAPs) and shape memory alloy wires (SMAs) are presented and discussed regarding to their applicability in such structures.

To investigate the actuators, a variable flexural stiffness device based on the control of its area moment of inertia was developed. The device consists of a multi-layer stack of thin, individual plates. Stiffness variation is caused by planar actuators with can control the sliding behavior between the layers by form closure structures. Previous investigations have shown that it is necessary to develop actuators with high actuation potential to ensure reliable connections between the layers.

To develop such planar actuators, several kinds of EAPs, including Danfoss PolyPower, VHB by 3M and a silicon elastomer actuators developed at the TU Dresden, have been studied as driving unit. These EAP driven actuators are compared to SMA driven ones. Comparison includes analytical models, finite element analysis and experimental data.

8687-61, Session 12

Electromechanical and electrooptical functions of plasticized PVC with colossal dielectric constant professor, president of fiber science and technology, Japan

Toshihiro Hirai, Shinshu Univ. (Japan)

Plasticized PVC shows very peculiar electrical deformation. The durability exceeds over 20 thousand times continuous operation with tacking force of 2 N/cm2 by applying dc electric field. The mechanism, however, remains unclear for long times. We recently found the PVC can show huge dielectric constant under the application of dc field. The colossal dielectric constant appears at certain plasticizer content at around 60% and reaches maximum at around 80%. The huge value of dielectric constant reaches over thousands at 1 Hz. The value is far higher than

those of each components. The colossal dielectric constant depends strongly on the chemical nature of the plasticizer. The phenomena can also explain the strong tacking force observed on the PVC. These nature was shown to be applicable for gripper, contractile actuator, etc. The colossal dielectric constant could also induce electrooptical function through changing refractive index. The mechanism proposed here can be suggested to be applicable to any conventional polymers if they meet some conditions required.

8687-62, Session 12

High-dielectric permittivity elastomers from well-dispersed expanded graphite in low concentrations

Malgorzata Kostrzewska, Anca G. Bejenariu, Anders Egede Daugaard, Anne L. Skov, Technical Univ. of Denmark (Denmark)

The development of high dielectric permittivity elastomer materials has attracted increased interest over the last years due to the direct relation to the overall performance of dielectric electroactive polymers. For this particular use both the electrically insulating properties as well as the mechanical properties have to be tightly controlled in order not to destroy the favorable elastic properties by the addition of e.g. particles or dipoles [1,2]. In the following expanded graphite in low concentrations (up to 5wt%) are investigated as a possible candidate as filler materials in very soft elastomers which by the addition of many traditional fillers requiring high concentrations, would either lose their stability or their softness. It is shown that the dielectric permittivity can be increased up to a factor of 4.5 compared to the pure silicone matrix. Furthermore the influence of several mixing procedures on the electrical and mechanical properties is investigated.

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8687-63, Session 12

Drop and dry film fabrication of Beta-phase Poly(vinylidene fluoride)

Go Murasawa, Ken Miyata, Akihiro Nishioka, Hidemitsu Furukawa, Yamagata Univ. (Japan)

We confirmed the presence of beta-phase poly(vinylidene fluoride) (PVDF) crystals when a PVDF solution drop was dropped on a substrate, then dried and formed as film (drop & dry fabrication). This study is conducted to investigate beta-phase PVDF formation mechanism in drop & dry fabrication technique. First, PVDF films are fabricated by drop & dry fabrication technique. Second, their PVDF crystalline structure is analyzed using x-ray diffraction. The presence of beta-phase PVDF crystals depends on the initial solution state and dry condition. Therefore, the effect of PVDF concentration in the solution, quantity of the solution drop, and dry speed on beta-phase PVDF crystal formation is investigated, and the formation mechanism is discussed with present experimental results.

8687-64, Session 13

Stable electroosmotically driven Nastic actuators *(Invited Paper)*

Elisabeth Smela, Deepa Sritharan, Univ. of Maryland, College Park (United States)

Nastic actuators use electroosmotic pumping to deform a compliant material. They are inspired by biological structures such as muscular hydrostats and bulliform plant cells, in which force transmission is provided by hydraulic pressure. The nastic actuators have embedded microchannels and reservoirs filled with a polar dielectric liquid; when an electric field is applied across the microchannels, liquid is pumped by electroosmosis between the reservoirs. Liquids are incompressible, so a change in volume of one reservoir results in compensatory changes in the other. We aim to create modular soft robots with arrays of nastic actuators.

Water has a high electroosmotic mobility, and therefore was used in initial prototypes. However, the electrolysis of water, which generates bubbles, limits the performance of the actuator. In the present work, we have replaced water with propylene carbonate and succeeded in the bubble-free operation of the actuator up to several kilovolts. The actuator deflects over 100 ?m within seconds, and operates continuously and stably for long times. High forces are achieved using large surface area porous polymer monoliths embedded between the reservoirs.

8687-65, Session 13

Adaptive lenses using transparent dielectric elastomer actuators

Samuel Shian, Harvard Univ. (United States); Roger M. Diebold, Harvard Univ. (United States) and Univ. of California, Santa Barbara (United States); David R. Clarke, Harvard Univ. (United States)

Variable focal lenses, used in a vast number of applications such as endoscopes, digital cameras, binoculars, information storage, communication, and machine vision, are traditionally constructed as a system consisting of solid lenses and separate actuating mechanisms. However, such lens systems are complex, bulky, inefficient, and costly. Each of these shortcomings can be addressed using an adaptive lens that performs as a lens system. In this presentation, we will push the boundary of adaptive lens technology through the use of a transparent dielectric elastomer actuator that is integral to the optics. Concept detail and lens construction will be described as well as electromechanical and optical performance. Preliminary data indicate that our adaptive lens prototype is capable of varying its focus by more than 37%, which is higher than that of human eyes. Furthermore, we will show how our approach can be used to achieve control over the lens characteristics which are difficult or impossible to achieve in other adaptive lens configurations.

8687-66, Session 13

Few layer graphene drive transparent dielectric elastomer actuator for variable focus lens application

Taeseon Hwang, Hyeok Yong Kwon, Joon-Suk Oh, Jung-Pyo Hong, Seung-Chul Hong, YoungKwan Lee, Hyouk Ryeol Choi, Sungkyunkwan Univ. (Korea, Republic of); Kwang Jin Kim, Univ. of Nevada, Las Vegas (United States); Jae-Do Nam, Sungkyunkwan Univ. (Korea, Republic of)

Transparent and stretchable dielectric elastomer actuator was fabricated for variable focus lens. Transparent few-layer-graphene (FLG) electrode

was prepared with simple chemical and mechanical exfoliation and transfer technique.

8687-67, Session 13

Design optimization of a linear actuator

Björn Rechenbach, Morten Willatzen, Univ. of Southern Denmark (Denmark); Kim P. Lorenzen, Danfoss PolyPower A/S (Denmark); Benny Lassen, Univ. of Southern Denmark (Denmark)

In this work the mechanical contacting of a linear dielectric elastomer actuator is investigated. The actuator is constructed by coiling the dielectric elastomer around two parallel metal rods, similar to a rubber band stretched by two index fingers. It has been developed at Danfoss PolyPower. The main challenge for this actuator design is to develop a durable solution for the mechanical connections between the soft elastomer material and the hard metal.

In this paper different connection types are investigated both experimentally and theoretically. It is shown theoretically that the design, where the elastomer can slip freely over the rod surfaces, shows the most uniform distribution of the mechanical stresses and the lowest values of the von Mises stress of the connection types considered. However, experiments under cyclic operation showed that wear of the elastomer material becomes a serious issue. The simplest way to overcome this issue is by gluing the elastomer onto half of the circumference of the metal rods. Unfortunately this leads to an uneven distribution of the mechanical stresses and high von Mises stresses around the points of contact, making the elastomer material there prone to failure.

The results of the theoretical investigations are used to design the geometry and the mechanical properties of a polymeric interlayer between the elastomer and the rods, gluing all materials together, so as to optimize the mechanical durability of the system. Finite element analysis is employed for the theoretical study which is linked up to experimental results performed by Danfoss PolyPower.

8687-68, Session 13

Tunable grating with active feedback

Samuel Rosset, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Benjamin M. O'Brien, Todd A. Gisby, Daniel Xu, The Univ. of Auckland (New Zealand); Herbert R. Shea, Ecole Polytechnique Fédérale de Lausanne (Switzerland); Iain A. Anderson, The Univ. of Auckland (New Zealand)

Dielectric Elastomer Actuators are interesting candidates for tunable optics. Through the fabrication of demonstrators such as tunable lenses, gratings or phase shifters, researchers have already demonstrated how DEAs' large deformations can be beneficial for optical applications. However, in addition to the tuning range, optical tunable devices must exhibit a very stable behavior under static actuation, showing little to no long-term drift. This requirement is problematic for DEAs, due to the viscoelastic nature of the elastomers used in the manufacturing of these actuators.

We report on the use of capacitive self-sensing to operate a DEA-based tunable grating in closed loop operation, which allows precise control of the grating period.

Additionally, we introduce a new actuation scheme for elastomeric tunable gratings based on two pairs of electrodes, each acting on an opposite side of the grating. The two sets of actuators are operated antagonistically in closed loop mode in order to keep the surface area of the grating constant during deformation: elongation along one side of the grating is compensated by compression on the perpendicular axis.

This configuration allows changing the grating period while keeping the amplitude of the periodic structure constant. The diffraction angle can therefore be tuned without simultaneous variation in the transmitted intensity, as observed for the traditional uniaxial stretching of a soft grating. We demonstrate that the use of active feedback allows to precisely control the strain of DEAs in quasi-static mode, even for VHB actuators which suffer from viscoelastic behavior in open loop mode.

8687-69, Session 13

Dielectric elastomer actuators for active microfluidic control

David McCoul, Coleman Murray, Dino Di Carlo, Qibing Pei, Univ. of California, Los Angeles (United States)

Dielectric elastomers with low modulus and large actuation strain have been investigated for applications in which they serve as “active” microfluidic channel walls. Anisotropically prestrained acrylic elastomer membranes are bonded to cover open trenches formed on a silicone elastomer substrate. Actuation of the elastomer membranes increases the cross-sectional area of the resulting channels, in turn controlling hydraulic flow rate and pressure. Bias voltage increases the active area of the membranes, allowing intrachannel pressure to alter channel geometry. The channels have also demonstrated the ability to actively clear a blockage. Applications may include adaptive microfilters, micro-peristaltic pumps, and reduced-complexity lab-on-a-chip devices.

8687-70, Session 13

All inkjet-printed electroactive polymer actuators for microfluidic lab-on-chip systems

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Piezoelectric electroactive polymers (EAP) are promising materials for applications in microfluidic lab-on-chip systems. In such systems, fluids can be analyzed by different chemical or physical methods. During the analysis the fluids need to be distributed through the channels of the chip, which makes a pumping function necessary. We present here all inkjet-printed EAP actuators that can be configured as a membrane-based micropump suitable for direct integration into lab-on-chip systems. Drop-on-demand inkjet printing is a versatile digital deposition technique that is capable of depositing various functional materials onto a wide variety of substrates in an additive way. Compared to conventional lithography-based processing it is cost-efficient and flexible, as no masking is required. The actuators consist of a polymer foil substrate with an inkjet-printed EAP layer sandwiched between a set of two electrodes. The actuators are printed using a commercially available EAP solution and silver nanoparticle inks. We have manufactured membrane-type as well as cantilever bending beam actuators. When a voltage is applied across the polymer layer, piezoelectric strain leads to a bending deflection of the beam or membrane. With lateral dimensions in the mm range and EAP thicknesses of 10 to 15µm the cantilever beams exhibit deflections of 190µm at driving voltages of 600V. Circular membrane actuators with 20mm diameter exhibit 70µm central deflection. A concept of a polymer-based micropump is presented. From the behavior of membrane actuators a pumping rate of several 100µL/min can be estimated, which is promising for applications in lab-on-chip devices.

8687-71, Session 14

Six-axis capacitive force/torque sensor based on dielectric elastomer

Hyouk Ryeol Choi, Ja Choon Koo, Hyungpil Moon, Dae Gyoeng Kim, Baek Chul Kim, Sungkyunkwan Univ. (Korea, Republic of)

The six axis F/T sensor is a primary component for the service robots, but its amazing cost (over $10,000) hampers the popularization of the service robots to the general users. In this paper, we present a six-axis force-torque capacitive sensor for robotic applications.

Dielectric elastomer is compressed or decompressed with external forces acting on it, resulting in variation of capacitance, which can be used as a kind of sensing scheme. The proposed sensor consists of plastic structure and dielectric elastomer capacitors. Since it takes a simple and easy structure, it is possible to fabricate by using a plastic molding process, which results in extremely lower cost than commercial products (100times less).

We present the basic structure and design of the sensor with explanation of the working principle. And a fabrication method dedicated to the sensor is explained. Finally, a prototype will be demonstrated with calibration procedures.

8687-72, Session 14

Study on the anti-slip using dielectric elastomer slip sensor

Cho Hanjoung, Baekchul Kim, Daegyeong Kim, Lee Youngkwan, Jae-Do Nam, Hyouk Ryeol Choi, Hyungpil Moon, Ja Choon Koo, Sungkyunkwan Univ. (Korea, Republic of)

There are some ongoing researches on contact information. It is very hard and also complex to define contact state between two confining objects. . It is even harder to find the contact state if the confining area continuously changes in time. Indirect assessment methods through existing force measurement is not easy to find out change of contact state clearly. But slip sensor was studied in this paper, that use dielectric elastomer that facilitate deformation. Since we can determine the detailed procedure of the state change of a direct contact with an object, we can apply anti-slip right before the slip occurs. We are designing dielectric elastomer slip sensor and we will determine and verify contact state various changes. To test the performance of the slip sensor, we set up equipment which induces slipping on the slip sensor. it is very important for grip stably between two objects. In order to make an object anti-slip, it is necessary to invastigation the current contact state of the object. So we can detect and prevent some slip status such as slipping for slip sensor made of dielectric elastomer. Therefore, In this paper wrote for an anti-slip technology.

8687-73, Session 14

Self sensing of multiple dielectric elastomer actuators

Daniel Xu, Todd A. Gisby, Sheng Quan Xie, Iain A. Anderson, The Univ. of Auckland (New Zealand)

There are over 600 skeletal muscles in the human body, many of which work together antagonistically, such as the muscles across the shoulder and knee joints. The coordination and control of groups of muscles is essential to achieve smooth coherent motion and precision positioning. This is made possible through muscle's ability to simultaneously provide actuation and sensing, a property known as self-sensing.

Actuation and self-sensing can now be mimicked on robotic devices using dielectric elastomer actuator (DEA) artificial muscles. DEAs, labelled artificial muscles owing to their comparable properties to real muscle, can be placed in antagonistic arrangements like the muscles across the joints. But the implementation of simultaneous actuation and self-sensing in groups of DEAs has remained a technical challenge. This is due to associated hardware costs and the computational workload required to accurately deduce sensory information in real time. As a result, only a small number of DEAs are able to be controlled economically. To address this, a portable self-sensing unit was developed that takes advantage of parallel processing, thus allowing multiple actuators to be sensed without any significant increase in computation time. This also dramatically increases the speed at which DEAs can be controlled. The self-sensing unit was designed with an easily scalable architecture thereby allowing a large network of DEAs to be controlled quickly and simultaneously.

8687-74, Session 14

Large displacement zipping DEAs for microfluidic large-scale integrated chips

Luc Maffli, Samuel Rosset, Herbert R. Shea, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

We report on a silicon microfabricated pump based on the zipping actuation principle, which consists in attracting a compliant electrode placed on a membrane against a rigid conductive body. In addition to the large strain common to DEA, zipping DEAs offer specific features like out-of-plane displacement, sealing of the rigid electrode and bistable operation. For particular configurations, the driving voltage is reduced using a high-quality rigid dielectric.

We have previously measured up to 300?m vertical deflection on 2mm-side zipping chambers with ion-implanted electrodes. Even if these electrodes have unique advantages compared to carbon-based ones (features down to 35?m, cleanroom compatibility and fast response), their stiffening impact is difficult to control accurately and limits the maximal deflection. In this work, we use silicone electrodes with dispersed carbon particles patterned by indirect stamping, taking benefit of a lower and better controllable stiffening on the membrane.

The performances of an actuator during a pumping cycle are directly related to the elastomer properties. We therefore investigate the use of different silicones by conducting electrical (permittivity, resistance under equibiaxial stretch) and mechanical (uniaxial stretch-stress curve) characterization. Inserting these data in the model, we further asses it by measuring the vertical deflection of mm-size zipping actuators.

Three zipping chambers with an embedded channel are integrated in-line, to build a peristaltic micropump. This demonstrates that it is possible to replace the pneumatic actuators of microfluidic large-scale integrated chips, making them portable. Zipping DEAs could also be first choice candidates for applications like braille displays or tunable optics.

8687-75, Session 14

Development of the dual-axis hybrid tactile sensor

Seonggi Kim, Hyungpil Moon, Ja Choon Koo, Hyouk Ryeol Choi, Sungkyunkwan Univ. (Korea, Republic of)

Recently, the tactile sensors using polymer have been studied in various robot fields which are required feedback on the contact force because the polymer is flexible and affordable.

In previous work, the dual-axis hybrid tactile sensor using PDMS (Polydimethylsiloxane) with a pair of electrode, that the metal was deposited directly on the PDMS surface, was proposed. The hybrid sensor can measure normal force and shear force with change of capacitance and resistance values. However, the metal is hard to be deposited on the surface of the PDMS because the PDMS is hydrophobic. The hydrophobic surface can be changed to hydrophilic using O2 Plasma treatment or UV treatment. When O2 plasma treatment or UV treatment is used, there is the problem that metal deposition and wiring should be going in limited time. Also, the deposited metal on the surface of the PDMS is easy to break because the deposited metal is exposed in the air.

In this paper, we propose the developed dual-axis hybrid tactile sensor that the PET (polyethylene terephthalate) film is inserted between the PDMS films. The deposited metal is not removed easily from the PET film because the adhesion is strong. Also, the PDMS surrounding the PET film plays the roles of dielectric elastomer and shielding the deposited metal from the external environment at same time.

Experimental results verify the effectiveness of the proposed developed dual-axis hybrid type force sensor.

8687-76, Session 15

Dielectric elastomers with novel highly-conducting electrodes

Holger Böse, Detlev Uhl, Fraunhofer-Institut für Silicatforschung (Germany)

Beside the characteristics of the elastomer material itself, the performance of dielectric elastomers in actuator, sensor as well as generator applications depends also on the properties of the electrode material. The most relevant requirements on the electrode material are a high electric conductivity, even under stretch, a low mechanical resistance against stretch and a high durability of the electrode coating. Various novel electrode materials based on metal particles in a silicone matrix were manufactured and their electrical and mechanical properties were investigated. For this purpose, electrode coatings with variation of the thickness and the metal particle concentration below and above the percolation threshold were prepared. Electric resistance measurements on the electrode materials were performed with the 4-point method. Furthermore, mechanical investigations of stress vs. strain on silicone films with and without electrode coatings were carried out in order to determine the mechanical resistance of the electrode coating. Finally, measurements of the actuation strain in the electric field on model actuators with the novel electrode materials were conducted. The specific conductivities of the electrode materials derived from the resistance measurements surmount those of reference materials based on graphite and carbon black in silicone by up to two orders of magnitude. A high conductivity of the new electrodes can be maintained even at uniaxial stretch deformations of 200 %. The results of the studies with the novel electrode materials are presented in detail in this contribution.

8687-77, Session 15

The effect of folds on highly compliant crumpled thin metal film electrodes used in dielectric elastomer actuators

Sze Hsien Low, Gih-Keong Lau, Nanyang Technological Univ. (Singapore)

Due to high electrical conductivity, metals have been the traditional material for electrodes. However, as metal films have low fracture strains, they are not commonly used as compliant electrodes in the field of dielectric elastomer actuators and generators. We have recently demonstrated that the use of metal films as electrodes can in fact allow dielectric elastomer actuators to have large actuated area strains of more than 100%. The metal film electrodes used have a network of crumples that unfolds as it is subjected to in-plane strains. This mechanism enables the metal electrodes to have a relatively low stiffening effect on the soft dielectric elastomer and to be able to retain its low resistance despite being bi-axially stretched to high strains. This is in contrast to corrugated metal electrodes that are stretchable only along one axis. When subjected to uni-axial strain, these crumpled electrodes had a sheet resistance of less than 100 Ω up to 200% and less than 1 GΩ up to 400%. This ability of metal electrodes to have a low sheet resistance would be particularly useful for dielectric elastomer generator applications as it facilitates in the reduction of parasitic losses. By metalizing a highly bi-axially pre-stretched dielectric elastomer that was subsequently partially relaxed, a bi-axial compressive force was introduced into the metal films, thereby causing a network of folds to form. In this paper, we study the change in the topography of the crumpled metal electrodes as the metal films are subjected to varying extents of bi-axial compression: from wrinkling to folding to hierarchical folding. It was found that this altered the electrodes' stretchability, as manifested in the performance of dielectric elastomer actuators using these crumpled metal films as electrodes.

8687-78, Session 15

Closed-loop control of a tube-type cylindrical IPMC

Benjamin Mead, Woosoon Yim, Siul A. Ruiz, Univ. of Nevada, Las Vegas (United States)

Ionic polymer metal composites (IPMCs) are one of the most widely used types of electro-active polymer actuator, due to their low electric driving potential and large deformation range. In this research a tube type IPMC was investigated. This IPMC has a circular cross section with four separate electrodes on its surface and a hole through the middle. The four separate electrodes allows for biaxial bending and accurate control of the tip location. One of the main advantages of using this type of IPMC is the ability to embed a specific tool and accurately control the tool tip location using the large deflection range of the IPMC. This ability has widespread applications including in the biomedical field for use in catheter procedures. In this report the results of the bending and force experiments were examined to determine the performance of this actuator alone. These experiments were then repeated using different embedded materials including plastic catheter lines, fiber optic cables, and electrical wiring. The results of these experiments were then compared against a theoretical three dimensional COMSOL Multipysics model. From here an electro-mechanical model of the IPMC was developed and integrated into a closed loop control system. To improve functionality and the user's experience the control system was designed to work on a laptop touchpad. This will provide a more familiar and intuitive interaction and cut down on operator training time.

8687-79, Session 16

P(VDF-TrFE) stacked actuators: design, fabrication, and performance

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Magnetostrictive alloys, shape memory alloys, piezo ceramics and some active polymers all generate strain due to a molecular structure change which can be stimulated in a variety of ways. An electrically derived stimulus is often a compact method of delivering the input power for conversion into mechanical work, and as such, contributes to an actuator's high power density compared to other stimulus sources. For a given volume or mass, a greater amount of mechanical power is often desirable. (Poly)vinylidene fluoride-trifluoroethylene or P(VDF-TrFE), a ferroelectric polymer, offers an alternative set of performance characteristics compared to other dielectric elastomer materials, exhibiting similar stroke and response times to more common dielectric elastomers, but approximately two orders of magnitude higher force, together with a stiffer bulk material. This makes P(VDF-TrFE) a complementary technology to occupy the gap between existing dielectric elastomers and active alloys and ceramics. The implications of design and fabrication of P(VDF-TrFE) at a prototype level are discussed, as currently there is very little information available reporting on the physical realisation of useful actuators in this respect. The key stages include thin film production (melting, stretching, annealing and irradiation), cutting, electroding, electrical connection and final assembly as encapsulated and insulated stacked actuators of 7 and 40 layers. A selection of experimental performance results is provided and areas for further work are suggested.

8687-80, Session 16

New DEA by organic modification of silicone and polyurethane networks

Bjoern Kussmaul, Michael Wegener, Martin Bluemke, Fraunhofer-Institut für Angewandte Polymerforschung (Germany); Jens Krause, Joachim Wagner, Torsten Feller, Karin Clauberg, Julia Hitzbleck, Bayer MaterialScience AG (Germany); Hartmut Krueger, Fraunhofer-Institut für Angewandte Polymerforschung (Germany)

Dielectric elastomer actuators (DEA´s) enable a wide range of interesting applications since they are soft, lightweight, low-cost and have direct voltage control. First industrial applications were implemented; a further increase of this DEA technology arises from the successful demonstration of energy harvesting by means of such transducer films.

However, one of the main obstacles is their high operating voltage, which tends to be several thousand volts. The operating voltage can be decreased by reducing elastomer film thickness, mechanical stiffness or increasing permittivity. Mostly, permittivity is increased by inorganic filler particles with high dielectric constant, which is disadvantageous due to material stiffening and sophisticated homogenization techniques.

Recently, we introduced a dipole grafting process as a simple and useful tool to enhance the permittivity of various silicones, which prevents agglomeration and gives homogeneous elastomer films even at molecular level. Additionally the Young's modulus is decreased due to a decrease in network density, so that the operating voltage is reduced by these synergetic effects. A similar approach can be achieved by using “smart fillers”, which are adapted macromolecular fillers with high permittivity and satisfying compatibility to the silicone.

Until now, these approaches were only tested with silicones and few organic dipole molecules were investigated.

At this point we can show that a new technique can be used with a wide spectrum of organic molecules that can be applied to polyurethanes, improving their actuation performance without reducing other material and electrical properties. The chemical, thermal, mechanical and electrical properties of films are discussed.

8687-81, Session 16

Effect of viscoelastic relaxation on the electromechanical coupling of dielectric elastomer

Bo Li, Hualing Chen, Junjie Sheng, Xi'an Jiaotong Univ. (China)

Dielectric elastomer is able to produce a large electromechanical deformation which is time-dependent and unstable due to the visco-hyper-elasticity. In the current study, we use a thermodynamic model to characterize the viscoelastic relaxation in the electromechanical deformation and instability of a viscoelastic dielectric. The parameters in the model were verified experimentally. We investigate the time-dependent mechanical deformation, electrical breakdown strength, polarization, and the electromechanical stability which are coupled by viscoelastic relaxation. The results show the electromechanical stability has strong time dependence, due to the stress relaxation when the pre-stretch is applied.

8687-82, Session 16

Synthesis and electromechanical characterization of a new acrylic dielectric elastomer

Wei Hu, Xiaofan Niu, Univ. of California, Los Angeles (United States); Xinguo Yang, Hunan Univ. (China); Qibing Pei, Univ. of California, Los Angeles (United States)

Dielectric Elastomers (DEs) are actuated under high electric field to produce large strains. Most high-performing DE materials such as the VHB membranes are commercial products designed for unrelated applications. The limited knowledge of the exact chemical structures of these commercial materials has made it difficult to understand the relationship between structures and electromechanical properties.
We report the synthesis of an acrylic copolymer elastomer based on n-butyl acrylate and acrylic acid by UV curing process. The crosslinked poly(n-butyl acrylate) moiety leads to low modulus or rubbery behavior in the resulting elastomer. Acrylic acid has the polarizable carboxylic group which results in an increase in dielectric constant. Silicone and ester oligomer diacrylate were also added to prevent crystallization and crosslink the polymer chains. Four acrylics formulations were developed with different amounts of acrylic acid. This gives a tunable stiffness and increases the dielectric constants from 4.3 to 7.1. The samples of best formulation demonstrated a 186 % area strain, a dielectric strength of 222 MV/m and an calculated energy density of 2.7 MJ/m3. To overcome electromechanical instability, different prestain ratios were investigated as well and an optimized point was determined. This material has a lifetime of thousands of cycle while showing an area strain more than 100%..

8687-83, Session 16

Effect of mechanical parameters on dielectric elastomer minimum energy structures

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Soft robotics is a field of robotics that potentially has many advantages compared to traditional approaches using rigid materials, such as, safe human-robot interaction, efficient/stable locomotion, etc. The objective of this study is to develop an artificial-muscle-based actuator for soft robotics using dielectric elastomer minimum energy structures (DEMES). We aim at a one-dimensional bending actuator with 90 degree stroke. DEMES consist of a pre-stretched dielectric elastomer actuator (DEA) laminated onto a flexible frame, which results in out-of-plane shape and large actuation stroke. Along with shape, actuation performance of DEMES depends on mechanical parameters such as thickness of the materials and pre-stretch ratio.

We report here the characterization results on the effect of mechanical parameters on actuation performance. The tested actuators have cm-size flexible-PCB (polyimide, 50 µm thickness) as frame-material. For the DEA, PDMS (DC186, ~50 µm thickness) and carbon black mixed silicone were used as membrane and electrode, respectively. The actuators were characterized by measuring the deformation and blocking force as a function of applied voltage. During the experiments, for the mechanical parameters, different pre-stretch methods (uniaxial, biaxial and its ratio), and frame geometries (rectangular with different width, triangular and circular) were used. In order to compare actuators with different geometries, same electrode area was used in all the devices. The results showed that the actuation stroke increased when biaxial pre-stretch was used. Also, the stroke changed with the ratio of biaxial pre-stretch. The triangular and circular frame required no reinforcing parts to realize the desired deformation unlike rectangular frame.

8687-84, Session 17

GEM Printer: 3D gel printer for free shaping of functional gel engineering materials

Hidemitsu Furukawa, Muroi Hisato, Kouki Yamamoto, Ryo Serizawa, Jin Gong, Yamagata Univ. (Japan)

In the past decade, several high-strength gels have been developed. These gels are expected to use as a kind of new engineering materials in the fields of industry and medical as substitutes to polyester fibers, which are materials of artificial blood vessels. However it is difficult for

gels to mold into forked structure or cavity structure by using cutting or mold. Consequently, it is necessary to develop the device to synthesize and mode freely gels at the same time. In this study, we try to develop an optical 3D gel printer that enables gels to mold precisely and freely. In the gel printer, the UV laser is focused by the objective lens to put out the optical fiber efficiently. For the free forming of double network gels, the 1st gels are ground to particles and mixed with 2nd pregel solution, and the mixed solution is gelled by the irradiation of UV laser beam through an optical fiber. The use of the optical fiber makes one-point UV irradiation possible. In addition, because the optical fiber is controlled by 3D-CAD, the precise and free molding in XYZ directions can be realized. Proceedings of the molding are divided into two main steps. Gelation in a plane performs by moving optical fiber in X-Y directions. Then moving the optical fiber in Z direction, gelation in a plane carries on in the same way. We succeeded in synthesizing and molding gels at the same time using the gel printer. The dimensions of gel samples prepared by the gel printer are almost the same as the designed.

8687-85, Session 17

Polyelectrolyte gels as bending actuators: modeling and numerical simulation

Thomas Wallmersperger, Technische Univ. Dresden (Germany); Karsten Keller, Univ. Stuttgart (Germany); Abdolhamid Attaran, Technische Univ. Dresden (Germany)

Polyelectrolyte gels are ionic electroactive materials. They have the ability to react as both, sensors and actuators. As actuators they can be used e.g. as artificial muscles or drug delivery control; as sensors they may be used for measuring e.g. pressure, pH or other ion concentrations in the solution.

In this research polyelectrolyte gels placed in aqueous solution with mobile anions and cations are investigated. Due to external stimuli the polyelectrolyte gels can swell or shrink enormously by the uptake or delivery of solvent.

In the present research a coupled multi-field problem within a continuum mechanics framework is proposed.

The modeling approach introduces a set of equations governing multiple fields of the problem, including the chemical field of the ionic species, the electrical field and the mechanical field.

The constitutive law will be carried out by extending the Gibbs free energy to include the contributions from the different fields in the system. In the presentation it is demonstrated that the proposed constitutive law is thermodynamically consistent.

The numerical simulation is performed by using the Finite Element Method. Within the study some test cases will be carried out to validate our model against published experimental results.

In the works by Gülch et al., the application of combined anionic-cationic gels as grippers was shown. In the present research for an applied electric field, the change of the concentrations in the complete polymer is simulated by the given formulation. These changes lead to variations in the osmotic pressure resulting in a bending of the polymer gripper. The obtained numerical results match quite well with the experimental results.

8687-86, Session 17

The effects of bilayer geometry on the detachment process and operation efficiency of polypyrrole/gold bilayer actuators

Vinh Ho, Lawrence Kulinsky, Marc J. Madou, Univ. of California, Irvine (United States)

Polypyrrole/gold (PPy/Au) bilayer actuators are used in a wide variety of applications, from micro-robotics to drug delivery. PPy is biocompatible and it requires only a small voltage for actuation, typically less than 2 V. It has good electrical and mechanical properties, and it can be actuated in different electrolytes including those similar to biological fluids. For optimal utilization of PPy/Au bilayer actuators, ongoing research efforts have focused on theoretical development and experimental validation of predictive bilayer bending models. Although these models provide an adequate prediction for free-standing or detached actuators, these studies do not discuss actuators that are initially attached to a substrate, which are relevant for many applications including drug delivery and biosensing platform.

In this work, the influence of geometry, corners and edge effects on the PPy/Au bilayer actuator release process was examined. Initial detachment was observed to begin along the corners and edges due to higher interfacial stresses there. Narrow rectangular actuators detached most effectively among the tested actuators due to their high perimeter to area ratio and presence of corners. In contrast, circular actuators with smaller perimeter to area ratio were last to detach. While the results and discussion in this paper are specific for PPy/Au bilayer actuators, the insights gained from this study can be applicable for other actuators that are initially attached to the substrate, but are designed to detach or peel off in the process of normal operation. The actuator's operation efficiency can be controlled by the selection of actuators' geometry.

8687-87, Session 17

Study of hybrid actuators based on conducting polymer sandwich complex

Rudolf Kiefer, Univ. of Tartu (Estonia); Jadranka Trava-Sejdic, Paul A. Kilmartin, The Univ. of Auckland (New Zealand); Rauno Temmer, Tarmo Tamm, Alvo Aabloo, Univ. of Tartu (Estonia)

Novel bending hybrid conducting polymer actuators were made from pure electrochemically polymerized conducting polymer materials. The working principle for these free-standing conducting polymer (CP) films is based on their selective anion and cation-driven actuation. If one CP layer shows during certain potential (0V to 0.8V) minor actuation of anions, (PPy/DBS) the second layer can be chosen for anion-driven actuation such as PPy/TFSI. Polymerization of both CP layers together can result in sandwich complex with bilayer functionality in certain potential range depending from solvent and electrolytes. The results of a comparative study of various combination of sandwich CP films in terms of actuation properties are presented in this study.

In case of PEDOT/TBACF3SO3, it was recently discovered that the anion or cation-driven actuation depends from the polymerization conditions. Intensive electro-chemomechanical deformation measurements studies of free-standing PEDOT/TBACF3SO3 films have revealed that careful selection of polymerization potentials can be used to form PEDOT/TBACF3SO3 films with mainly cation or anion driven actuation.

Free-standing films of PEDOT actuators electrodeposited in same electrolyte at different polymerization potentials in bilayer functionality are investigated in this work in view of their bending properties at different solvent and electrolyte. Linear actuation at certain applied voltage ranges can be achieved, if three carefully chosen different conducting polymer layers (Trilayer) are piled together.

Conference 8688: Active and Passive Smart Structures and Integrated Systems VII

Sunday - Thursday 10–14 March 2013

Part of Proceedings of SPIE Vol. 8688 Active and Passive Smart Structures and Integrated Systems 2013

8688-1, Session 1

Frequency-tunable vibratory energy harvester for powering consumer electronics

Xiyuan Liu, Mohammed F. Daqaq, Clemson Univ. (United States)

Energy harvesting from human locomotion has been highlighted in current technologies for self-powering electronic devices. In this report, we introduced an electromagnetic vibratory energy harvester to generate electricity from the strides taken during walking or jogging. In this design, the electricity was generated from a time-varying magnetic field in the flux path induced by the oscillation of a magnetic pendulum between two fixed magnets. A nonlinear electromechanical model, which mimicked the behavior of a damped Duffing oscillator, was presented to describe the interaction between the mechanical and electrical subsystems, and then solved analytically using the method of multiple scales. Our design offered unique tunable characteristics on its peak frequency, in which the frequency can be adjusted to specific values that match user requirements, thereby increasing the power generated. Under optimal loading conditions, the device is capable of generating 1.6 mW of output power at a frequency of 5.2 Hz and a base acceleration of 2 m/sec^2. The performance of the device in charging a small battery while jogging is investigated. The motion of a typical swinging arm in terms of frequency and acceleration is reproduced on an electrodynamic shaker and used to charge a 100 µAh battery yielding an estimated charging time of 12 minutes.

8688-2, Session 1

Steady-state dynamics of a two degree-of-freedom bistable oscillator for energy harvesting

Ryan L. Harne, Manoj Thota, Kon-Well Wang, Univ. of Michigan (United States)

Recent interest in bistable devices for vibration energy harvesting has given evidence of their beneficial performance in realistic stochastic or low frequency excitation environments since the snap through effect (high displacement switching from one stable state to another) is a non-resonant dynamic. It has yet to be rigorously determined how coupling to other degrees of freedom may play a role in enhancing bistable energy harvesting performance since the nonlinearities do not allow for a direct analogy from linear examples. This paper assesses the potential for improving energy harvesting performance by coupling a bistable oscillator to a conventional linear oscillator. A theoretical investigation is presented to evaluate the influences of coupling using the metrics of mass ratio and tuning ratio. Advantageous design regimes are classified and physical explanations for the results are provided.

8688-3, Session 1

Design and performance enhancement of hydraulic-pressure energy harvesting systems

Ellen A. Skow, Kenneth A. Cunefare, Alper Erturk, Georgia Institute of Technology (United States)

Hydraulic pressure rippled energy harvesters generate low-power electricity from off-resonance dynamic pressure excitation of piezoelectric elements. Improvements were made to a hydraulic pressure ripple energy harvester prototype design and performance. Hydraulic systems inherently have a high energy intensity associated with the mean pressure and flow. Accompanying the mean pressure is dynamic pressure ripple, which is caused by the action of pumps and actuators. Pressure ripple is generally a deterministic source with a periodic time-domain behavior conducive to energy harvesting. An energy harvester prototype was designed for generating low-power electricity from pressure ripples. These devices generate low-power electricity from off-resonance dynamic pressure excitation. The power produced per volume of device was increased through decreasing the device size and adding an inductor to the system circuit. Fluid-mechanical interface modifications that increase the force applied to the piezoelectric element allow for more compact devices. The prototype device utilizes a piezoelectric stack with high overall capacitance allowing for inductance matching without using a switching circuit. Initial testing with addition of an inductor produced over 2.1 mW, an increase of 78% as compared to the device without the inductor. Power output model simulations assume a resistive-inductive circuit.

8688-4, Session 1

Piezoelectric PVDF film energy harvester for powering a wireless sensor system

Enrico Bischur, Norbert Schwesinger, Technische Univ. München (Germany)

Floorings are dynamically stressed if masses move on it. Energy harvesters with piezoelectric PVDF film were built that generated electric energy out of this dynamic stress. These harvester modules were used to power a wireless sensor system.

Two layers of PVDF film and two aluminum foils are stacked alternating and rolled on a winding mandrel. The rolled laminate was flattened afterwards. The last fabrication step was the polarization of the PVDF film.

The piezoelectric properties depend strongly on the remanent polarization of the PVDF material. The value of the remanent polarization of the PVDF film is influenced by the electric field strength across the film and the polarization temperature. The main problem preventing a sufficient polarization of the modules is the dielectric breakdown of the film. Thus different setups of temperature and electric field strength were tested. In the end the modules were polarized with field strength of 100 – 120 MV/m at a temperature of 90°C.

Modules with a dimension of 160mm x 90mm and 20 layers of active PVDF material were used to power the EnOcean 'EDK 300 development kit for Energy Harvesting Wireless systems'. Each module was connected by a full bridge rectifier with the energy management system. It was possible to charge the storage capacitors of the system to the desired voltage level. The system was able to check its sensors and to send the values to the systems receiver station. The configuration could be used also to check if a person steps on one desired module.

8688-5, Session 2

Piezoelectric array of oscillators with respective electrical rectification

I-Ching Lien, Yi-Chung Shu, National Taiwan Univ. (Taiwan)

This talk reports both modeling and experimental observations of the case of parallel connection of multiple piezoelectric oscillators with respective electrical rectification. Such an array structure offers advantages of boosting power output and exhibiting broadband energy harvesting. Indeed, the array problem based on an overall electrical rectification has been recently investigated by the present authors who showed its electrical behavior is determined by the matrix formulation of generalized Ohm's law (Lien and Shu, Smart Materials and Structures, Vol. 21: 082001, 2012). In contrast, here we show that the electrical response for an array structure with respective electrical rectification is

governed by simultaneous nonlinear equations with constraints indicating blocking by rectifiers. The theoretical estimates are proposed and validated numerically by circuit simulations. In addition, experimental validation is carried out by developing an array structure consisting of three piezoelectric bimorphs. Harvested power against frequency for various electrical loads are measured and compared to analytic estimates. The results show that both are in good agreement. Finally, the comparisons between the case based on an overall electrical rectification and that based on respective rectification are made and discussed.

8688-6, Session 2

Investigating synchronized switching in aeroelastic flutter energy harvesting

Matthew J. Bryant, Alexander D. Schlichting, Ephrahim Garcia, Cornell Univ. (United States)

This paper investigates 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 then transduce these vibrations to electrical current via cyclically straining piezoelectric patches. The aeroelastic energy harvester device consists of a cantilevered piezoelectric beam with a small plate attached to the tip of the beam by a flexible joint. Above a critical flow speed, a flutter instability occurs causing the plate to oscillate with coupled pitching and heaving vibrations in a stable limit cycle, cyclically straining the piezoelectric beam and generating an alternating electric current.

We investigate the effects of the energy harvesting circuit design on the performance of the aeroelastic harvester, and the effects of the circuit on the flutter dynamics and limit cycle behavior. Techniques like synchronized switching have been shown to significantly enhance energy extraction performance in base excitation systems, but have been largely ignored in fluid-driven vibration energy harvesting. The fluid-structure interaction limit cycles that drive aeroelastic energy harvesters are affected by the electromechanical coupling and therefore by circuit topology. Meanwhile, the available kinetic energy for any flow energy harvester is proportional to the device swept area, which is determined by the limit cycle behavior. Thus the circuit design can have significant effects on not only the power output of the device, but also its energy capture efficiency, and operating flow requirements.

8688-7, Session 2

Influence of the topology for a networked SSHI piezoelectric harvesting configuration

Yang Li, Daniel Guyomar, Claude Richard, Institut National des Sciences Appliquées de Lyon (France)

This paper focuses on the influence of the topology of a networked SSHI (Synchronized Switch Harvesting on Inductor) piezoelectric harvesting configuration. Generally, an energy harvester is used as a localized and standalone system. In the case of large structure and for large harvested energies, it is usually not easy to increase the size of the piezoelectric patches. In order to harvest energy in the regions of maximum strain of the structure, the networked piezos harvester including many separated piezoelectric patches must be set up with only one output. The main concern is how to connect the different piezoelectric elements together and how to implement accurately the SSHI strategy for maximizing the total output power.

This paper presents 5 different circuit topologies with/without SSHI strategy. This work is based on simulations made in the Matlab/Simulink environment and using the Simscape library. The simulations are done for pulse excitation and harvesting is thus considered in pulse mode. For each circuit topology, the total output energy is dependent on the output capacitance. The experiments results show: a) the SSHI in series and the SSHI in parallel could get much higher output energy. b) the feasibility of grouping various harvesters within a network connected on only one load without losing performance. The parasitic capacitance due to the bonding is also investigated. This capacitance corresponds to the isolation layer between the structure and the bottom electrode of the piezoelectric patches. Results demonstrate a sufficiently large capacitance (a few microns bonding layer) allow sufficient isolating of the network without any risk of affecting the harvester coupling coefficients.

8688-8, Session 2

Review of power electronics for energy harvesting systems

Peng Li, Lei Zuo, Stony Brook Univ. (United States)

Energy harvesting devices are designed to capture the ambient energy in various forms surrounding the energy harvester, such as thermal energy, solar energy, biological energy and kinetic energy, etc., and convert it into the form of usable electrical energy. The output electrical energy from energy harvesters is typically unstable, both in current, voltage and power. Thus, voltage regulation is needed to make the harvested energy suitable to either directly power electronic devices or be stored in energy storage elements. Also, power management would be necessary to make the energy harvesting system work in desired condition to maximize the energy extraction and promote the conversion efficiency of the energy harvesting systems, which can be achieved by applying appropriate control schemes on the power electronic circuits.

Power electronic circuit forms the bridge between the energy transducer (harvester) and the energy storage element. The electronic interface circuits have critical effects on the energy harvesting scale, robustness and energy harvesting efficiency. Abundant work on interface power electronic circuits with functions of voltage regulation, power conditioning, resonance tuning and control for energy harvesting systems has been conducted and reported. This paper will review recent reported concepts for power electronic circuits in energy harvesting systems. Reported interface electronic circuit concepts are compared in the view of energy conversion efficiency, start-up behavior, and complexity. The focus of this paper is on circuit concepts used in large scale applications that can achieve power transfer in both directions.

8688-9, Session 2

Practical implementation of piezoelectric energy harvesting synchronized switching schemes

Alexander D. Schlichting, Ephrahim Garcia, Cornell Univ. (United States)

Many closed-loop control methods for increasing the power output from piezoelectric energy harvesters have been investigated over the past decade. Initial work started with the application of Maximum Power Point Tracking techniques (MPPT) developed for solar energy harvesting. More recent schemes have focused on taking advantage of the capacitive AC nature of piezoelectric harvesters to manipulate the transfer of energy from the piezoelectric to the storage element. There have been three main techniques investigated in the literature: Synchronized Charge Extraction (SCE), Synchronized Switching and Discharging to a Capacitor through an Inductor (SSDCI), and Synchronized Switch Harvesting on an Inductor (SSHI). While significant increases in harvested power are seen both theoretically and experimentally using powerful external control systems, the applicability of these methods depends highly on the performance and efficiency of the control method which implements the synchronized switching. This work focuses on the practical questions which dictate the applicability of SSDCI. Many piezoelectric energy harvesting systems are used to power devices controlled by a microcontroller (MCU). However its availability for the implementation of the switching control depends on the duty cycle of MCU. This is because putting the MCU to sleep is a common method for significantly reducing system energy requirements. To remedy this issue, this work investigates analog methods for implementing the switching control for SSDCI. The

practicability of these methods is measured by investigating the overall system and component level efficiency, mass, and power production.

8688-10, Session 3

Broadband energy harvesting using nonlinear 2-DOF configuration

Hao Wu, Lihua Tang, Panduranga Vittal Avvari, Yaowen Yang, Chee Kiong Soh, Nanyang Technological Univ. (Singapore)

Vibration energy harvesting using piezoelectric material has received great research interest in the recent years. To enhance the performance of piezoelectric energy harvesters, one important concern is to increase their operating bandwidth. Various techniques have been proposed for broadband energy harvesting, such as the resonance tuning approach, the frequency up-conversion technique, the multi-modal harvesting and the nonlinear technique. Usually, a nonlinear piezoelectric energy harvester can be easily developed by introducing a magnetic field. Either mono-stable or bi-stable response can be achieved using different magnetic configurations. However, most of the research work for nonlinear piezoelectric energy harvesting has focused on the SDOF cantilever beam configuration. A recently reported linear 2-DOF harvester can achieve two close resonant frequencies with significant power outputs. However, for this linear configuration, although a broader bandwidth can be achieved, there exists a deep valley in-between the two response peaks. The presence of the valley will greatly deteriorate the performance of the energy harvester. To overcome this limitation, a nonlinear 2-DOF piezoelectric energy harvester is proposed in this article. This nonlinear harvester is developed from its linear counterpart by incorporating a magnetic field using a pair of magnets. Experimental parametric study is carried out to investigate the behaviour of such harvester. With different configurations, both mono-stable and bi-stable behaviours are observed and analysed. An optimal configuration of the nonlinear harvester is thus obtained, which can achieve significantly wider bandwidth than the linear 2-DOF harvester and at the same time overcome its limitation.

8688-11, Session 3

Modeling of wide-band frequency-adjustable piezoelectric bimorph rnergy harvester

Haifeng Zhang, Univ. of North Texas (United States)

Piezoelectric energy harvesters are ideal for capturing energy from mechanical vibrations in the ambient environment. Numerous studies have been made of this application of piezoelectric energy conversion. However, in order for the energy harvester to produce a substantial amount of energy, the mechanical vibration frequency must match the operational frequency of the energy harvester. The traditional piezoelectric harvester only operates on a single frequency. Therefore, it can only be used in a very narrow frequency range. In this presentation, we discuss the modeling and the experiment for a new, broadband piezoelectric energy harvester. The energy harvester is implemented as a series of connected vibrating piezoelectric bimorph beams capable of operating over a wide range of frequencies. The results show that the operating frequency can be adjusted by changing the stiffness of a connecting spring and/or a small mass mounted on the bimorph. The results provide a foundation for the design of a frequency-self-tuning piezoelectric energy harvester capable of maximizing power efficiency.

8688-12, Session 3

Fundamental power limits of piezoelectric energy harvesters based on material strength

Michael W. Shafer, Ephrahim Garcia, Cornell Univ. (United States)

Piezoelectric energy harvesting has been plagued by the narrow frequency response in typical designs. Despite the fact that many vibration sources are broadband in nature, these tuned cantilever beams only produce significant power when operated very near their tuned frequency. While others have proposed using multiple beams or frequency up conversion to improve broadband response, we have developed a device capable of responding to any input frequency.

In this paper, we propose a new method of energy harvesting that uses free-slewing and hard stops to allow for excitation over a wide frequency range. The device consists of a typical piezoelectric beam with new boundary conditions. The root of the beam is pinned to the host structure, rather than being clamped. This pinned condition allows for excitation of the beam at all frequencies. Opposing hard stops are placed along the beam to limit the angular deflection of the beam. We present experimental results for such a system, and show that given the proper spacing of these stops relative to the input vibrations, we are able to harvest power over a much wider range than is possible using existing cantilevered designs.

8688-13, Session 3

A piezoelectric power harvester based on stainless steel substrate with dual oscillators

Ya Shan Shih, Sun Chiu Lin, Wen Jong Wu, National Taiwan Univ. (Taiwan)

The powering source of the wireless sensor nodes (WSN) has been a critical subject throughout recent years. Considering the inconvenience of battery replacement by man, power harvesting has been profoundly investigated by researchers so as to provide a constant power source for every single node. This work proposes a MEMS-fabricated-micro-piezoelectric power harvester based on a stainless steel substrate, which is consisted of dual oscillators. The stainless steel substrate not only fortifies the robustness of the device but also lowers the resonance frequency comparing to the conventional device with silicon substrate. The lowered resonance frequency of the harvester of the device is 27 Hz and 66.4 Hz for different thicknesses of substrate, 30 and 50 micrometers. The overall optimal output voltages of the two thicknesses were 1.1 V and 1.05 V, for the 30 and 50 micrometers devices, respectively. With the second oscillator located in the middle of the structure, the second resonance frequency was also lowered to 115 Hz. The device was also found to possess an up-conversion effect, which can enable the device to work at multiple frequencies. Under the harmonic frequencies, peak values of the output voltage were also found to be close to the output voltage of resonance frequency. For example, under 13.6 Hz, which is one-fifth of the device's resonance frequency, the output voltage is approximately equal to that of the resonance frequency. Moreover, from the up-rising trend of the voltage respond, it is predicted that the device may have a broad band effect under vibrating frequencies lower than 10 Hz.

8688-14, Session 3

A multiaxial piezoelectric energy harvester

Hadj daoud Mousselmal, Pierre-Jean Cottinet, Institut National des Sciences Appliquées de Lyon (France); Boudjemaa Remaki, Institut des Nanotechnologies de Lyon (France); Lionel Petit, Institut National des Sciences Appliquées de Lyon (France)

An important limitation in the classical energy harvesters based on cantilever beam structure is its monodirectional sensibility. The external excitation must generate an orthogonal acceleration from the beam plane to induced flexural deformation. If the direction of the excitation deviates from this privileged direction, the harvester output power is drastically reduced. This point is obviously very restrictive in the case of an arbitrary excitation direction induced for example by human body movements or vehicles vibrations.

In order to overcome this issue of the conventional resonant cantilever configuration with seismic mass, a multidirectional harvester is

introduced here by the authors. The multidirectional ability relies on the exploitation of 3 degenerate structural vibration modes where each of them is induced by the corresponding component of the acceleration vector. This specific structure has been already used for 3 axis accelerometers but the approach is here totally revisited because the final functional goal is different.

This paper presents the principle and the design considerations of such multidirectional piezoelectric energy harvester.

A finite element model has been used for the harvester optimisation. It has been shown that the seismic mass is a relevant parameter for the modes tuning because the resonant frequency of the 1st exploited flexural mode directly depends on the mass whereas the resonance frequency of the 2nd flexural mode depends on its moment of inertia.

A centimetric prototype derived from a commercial piezoelectric buzzer has permitted to valid the theoretical approach.

Finally, the feasibility of such harvester in MEMS form is shown with the help of a finite element model.

8688-15, Session 4

Synthesizing fluidic flexible matrix composite based cellular structures

Suyi Li, Kon-Well Wang, Univ. of Michigan (United States)

Fluidic flexible matrix composite (F2MC) cell is investigated as a building block for multi-cellular, multi-functional adaptive structures. When different F2MC cells are connected through internal fluidic circuit to form a cellular structure, it will exhibit dynamic behavior with distinct poles and zeros, which can be tailored by varying the F2MC cellular parameters. This paper will discuss a synthesis procedure for such F2MC multi-cellular structures. The procedure is essentially a hybrid numerical method combining the Jacobi Inverse Eigenvalue problem solver and Genetic Algorithm. It is capable of precisely placing the system poles and zeros at desired locations by choosing F2MC parameters; it is also capable of providing several feasible solutions in one run. In this research, as an example, a three-cell string is investigated to illustrate the system physics and synthesis procedure. It is found that, for a given set of feasible poles and zeros, the corresponding feasible cellular design is not unique. All of these feasible cellular designs will form a design space, and the dimension of this space depends on the number of F2MC cells. The extra degrees of freedom of the design space, combined with the physical insights revealed by a dimensionless dynamic model, makes it possible to add and achieve more design objectives.

8688-16, Session 4

Piezoelectric bimorph optimization for a dual-actuated flapping-wing micro air vehicle

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Piezoelectric bimorph actuators, as opposed to rotary electric motors, have been suggested as an actuation mechanism for flapping wing micro air vehicles (FWMAVs) because they exhibit favorable characteristics such as low weight, adaptable frequencies, and variable amplitudes. Research at the Air Force Institute of Technology has shown that by using one actuator per wing, up to five degrees of freedom are possible. However, due to the weight constraints on a FWMAV, the piezoelectric bimorph actuators need to be fully optimized to allow controlled and un-tethered flight to occur.

This study focuses on three areas of investigation in order to optimize the piezoelectric actuators: validating and modifying analytical models that have been previously suggested for the performance of piezoelectric bimorph actuators; identifying the repeatability and reliability of current custom manufacturing techniques; and determining the failure criteria for piezoelectric actuators so that they can be driven at the highest maximum voltage, yielding the best performance characteristics. Through the optimization, manufacturing, and fracture strength testing of piezoelectric bimorphs, analytical and empirical models have been created to yield minimum mass and minimum power consumption actuators to meet the force and displacement required in a dual actuated FWMAV.

8688-17, Session 4

Nonlinear experimental study of the vibration energy harvester for cardiac pacemakers

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In vitro experiments show that a novel piezoelectric energy harvester can generate sufficient energy to power cardiac pacemakers. Cardiac pacemakers are used to artificially regulate heartbeats. Currently pacemakers are powered by batteries, which consist 60 percent of their size. Although the power consumption of a pacemaker is less than a microwatt, the battery is depleted in 5 to 7 years. When the battery is run out, the pacemakers is surgically replaced. We have developed a vibration energy harvester to generate electrical energy from heartbeat-induced vibrations. Successful implementation of the technology means that the patients do not have to endure frequent operations required to regularly change the pacemakers.

To obtain realistic estimates of the heartbeat induced vibrations, we use the data collected during animal surgeries. After the chest area was opened and the heart was exposed, a laser Doppler vibrometer was used to measure the vibrations inside the chest area. The vibration data is used for experimental investigation of the developed piezoelectric energy harvester. The harvester was designed based on the previously developed models for nonlinear energy harvesters. The fabricated harvester is connected to a closed loop shaker. The electromagnetic shaker is controlled to precisely replicate the measured chest area vibrations. We have measured the vibrations at several points in the chest area including points on the heart surface as well as points on the connective tissue, lungs, and the diaphragm. It is demonstrated that sufficient energy can be generated if the energy harvester is positioned at any of the measurement points. The heart rate insensitivity of the device was confirmed by comparing the energy generation from different heart rates.

8688-18, Session 5

Vibration shape effects on the power output in piezoelectric vibro-impact engergy haverters

Jens Twiefel, Leibniz Univ. Hannover (Germany)

Vibro-Impcact harvesting devices are one concept to increase the bandwidth of resonant operated piezoelectric vibration generators. The fundamental setup is a piezoelectric bending element, where the deflection is limited by two stoppers. After starting the system in resonance operation the bandwidth increases towards higher frequencies as soon the deflection reach the stopper. If the stoppers are rigid, the frequency response gives constant amplitude for increasing frequencies, as long the system is treated as ideal 1-DOF system with symmetric stoppers. In consequence, the bandwidth is theoretically unlimited large. However, such a system also has two major drawbacks, firstly the complicated startup mechanism and secondly the tendency to "drop" from the high constant branch in the frequency response on the much smaller linear branch. Nevertheless, the system has its application wherever the startup problem can be solved. Most modeling approaches utilize modal 1-DOF models to describe the systems behavior and do not tread the higher harmonics of the beam element.

This work investigates the effects of the stoppers on the vibration shape of the piezoelectric beam, wherefore a finite element model is used. The used elements are one-dimensional two node elements based on the Timoshenko-beam theory. The finite element code is implemented in MatLab. The model is calculated utilizing time step integration for simulation, to reduce the computation time an auto-resonant calculation method is implemented. A control loop including positive feedback and saturation is used to create a self-excited system. Therefore, the system is always operated in resonance (on the backbone curve) and the frequency is a direct result of the computation. In this case tip velocity is used as feedback.

This technique allows effective parametric studies. Investigated parameters include gap, excitation amplitude, tip mass as well as the stiffness of the stopper. The stress and strain distribution as well as the generated electrical power is analyzed with respect to the proper operation range. Further an experimental setup is introduced for validation of the model. Preliminary measurements show the plausibility of the presented results.

8688-19, Session 5

Analysis and optimization of standing wave thermoacoustic-piezoelectric energy harvester: An electrical circuit analogy approach

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The performance of a standing wave thermoacoustic-piezoelectric (TAP) energy harvester is developed using an electrical circuit analogy approach. The harvester converts thermal energy, such as solar or waste heat energy, directly into electrical energy without the need for any moving components. The input thermal energy generates a steep temperature gradient along a porous stack. At a critical threshold of the temperature gradient, self-sustained acoustic waves are developed inside an acoustic resonator. The associated pressure fluctuations impinge on a piezoelectric diaphragm, placed at the end of the resonator. The resulting interaction is accompanied by a direct conversion of the acoustic energy into electrical energy. The behavior of this class of harvesters is modeled using an electrical circuit analogy approach. The developed model is a multi-field model which combines the descriptions of the acoustic resonator and the stack with the characteristics of the piezoelectric diaphragm. The onset of self-sustained oscillations of the harvester is predicted using the root locus method and SPICE software (Simulation Program with Integrated Circuit Emphasis). The predictions are validated against published results. The developed electrical analog and the associated analysis approach present invaluable tools for the design and the optimization of efficient thermoacoustic-piezoelectric (TAP) energy harvesters.

8688-20, Session 5

A magnetic/piezoelectric-based thermal energy harvester

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In this paper, we demonstrate a magnetic/piezoelectric-based thermal energy harvester utilizing an optimized thermal-convection mechanism to enhance the heat transfer in the energy harvesting/converting process in order to maximize the power output. The harvester consists of a serpentine CuBe spring, Gd soft and NdFeB hard magnets, mechanical frame, and piezoelectric PZT cantilever beams. Soft and hard magnet is fixed on the spring and frame, respectively. Piezoelectric beams are sandwiched between the spring and frame. Based on the harvester's configuration, the energy harvesting/converting process is divided to two steps. For the first step, the soft magnet is close to the cold side so that the soft magnet's temperature is lower than its curie temperature. Thus, the soft magnet exhibits a ferromagnetic property. Due to the magnetic-attraction force between the soft and hard magnet, the soft magnet (fixed on the spring) moves toward the hard magnet (on the hot side). When the soft magnet approaches to the hard magnet (hot side), the soft magnet's temperature is increased. When the soft magnet's temperature is higher than its curie temperature (i.e., the second step), the soft magnet loses ferromagnetic property resulting in eliminating the magnetic-attraction force. Thus, the soft magnet fixed on the spring bounces back to its initial location/state due to the spring-back force. Through the cyclic process, the spring/piezoelectric-beams continuously oscillates and subsequently produces voltage output due to the piezoelectric effect. The voltage response of the harvester under a temperature-difference of 25°C is 16.6 mV with an oscillating frequency of 0.58 Hz. (Note: For more details, please refer to the two-pages abstract we upload).

8688-21, Session 5

A vibration energy harvester using diamagnetic levitation

Sri Vikram Palagummi, North Carolina State Univ. (United States)

This paper will introduce a novel electromagnetic energy harvesting device which uses a diamagnetic levitation system for powering wireless sensors or other low power electronics by extracting energy from ambient vibrations. The harvester uses two diamagnetic plates made of pyrolytic graphite between which a cylindrical magnet levitates passively. The weight of the floating magnet is balanced by the force of the field of a big lifting magnet and the two pyrolytic graphite plates. Two archimedean spiral coils are placed in circular grooves which are engraved in the pyrolytic graphite plates, for converting the mechanical energy into electrical energy efficiently.

The diamagnetic plates serve dual purpose of providing vertical stability and restoring force to the floating magnet. As the restoring force is solely due to the repulsion of the magnetic field, there is no significant mechanical damping which is generally unavoidable in mechanical suspension like systems, commonly designed in conventional energy harvesting devices. A thin coil model is used to approximate the magnet and a thorough theoretical analysis of the energy harvester is done.

A few parametric studies are conducted on the geometric configurations of the coils along with the dimensions of the floating magnet to enhance the efficiency of the harvester. Both theoretical and experimental results show that this energy harvesting system is efficient and can capture low frequency broadband spectra. This low working frequency range (0.1Hz-10Hz) is especially suited for civil structures which have very low natural frequencies.

8688-22, Session 6

Identification of flexible structures by frequency-domain observability range context

Mark A. Hopkins, Rochester Institute of Technology (United States)

This paper presents the mathematical and algorithmic details of a system-identification method for very high-order, very broad-bandwidth models of flexible structures. The method uses the well-known frequency-domain observability range space extraction (FORSE) algorithm to individually identify a large number of parallel second-order resonant-mode submodels. FORSE is used to create narrowband "context models" in a lightly damped system, from which the models of specific individual resonant modes can be extracted. The paper goes on to show how to combine the extracted models of many individual resonant modes at different frequencies into one larger, broadband state-

space model. Using this method on a variety of large flexible structures, we have created very high-order state-space models that accurately match measured FRD over very broad ranges of frequency, i.e., FRD having resonant peaks spread across five orders-of-magnitude (or more) of frequency bandwidth. An interesting flexible-structure example is included in the paper.

8688-23, Session 6

Modeling and control of a jellyfish-like bio-inspired AUV

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Current autonomous underwater vehicle (AUV) designs have a serious deficiency in autonomy time due to its ballistic type of construction: a cylindrical body propelled by a rear engine. This type of design does not take advantage of the fluid that has to be displaced to move the vehicle forward, drastically reducing the overall system efficiency and consequently its operation time. In order to improve this aspect many engineers have been looking to nature for inspiration. Jellyfish provide a promising candidate to look for new ideas since jellyfish have a unique propulsion mechanism. Several researches have pointed out that their propulsion mechanism is indeed efficient allowing the animal to have great autonomy. The use of such novel bio-inspired vehicle design demands an evaluation of the current mathematical modeling in order to adequately describe the behavior of such a vehicle. This paper develops a time-varying rigid body model for the kinematics and dynamics of a AUV based on jellyfish propulsion concept. A nonlinear sliding mode controller is also proposed to drive the system to its origin.

8688-24, Session 6

Computation of 2D vibroacoustic wave's dispersion for optimizing acoustic power flow in interaction with adaptive metacomposites

Manuel Collet, Morvan Ouisse, Univ. de Franche-Comte (France); Mohamed N. Ichchou, Ecole Centrale de Lyon (France); Roger Ohayon, Conservatoire National des Arts et Métiers (France)

Research activities in smart materials and structures are very important today and represent a significant potential for technological innovation in mechanics and aerospace. In order to implement new active functionalities inside the considered system, modern processing methods are now available which allow integration of dense and distributed set of smart materials, electronics, chip sets and power supply systems. It is also possible to develop the next generation of smart "composite" structures also called adaptive metacomposite. By using such an integrated distributed set of electromechanical transducers, one can imagine to attain new desired dynamical behavior that can allow the control of mechanical or acoustic flow in a large frequency band.

In this paper, we present an integrated methodology for optimizing vibroacoustic energy flow in interaction between an adaptive metacomposite made of periodically distributed shunted piezoelectric material glued onto passive plate and open acoustic domain. Extension of shifted cell operator methodology to fluid-structure interaction is presented. The computation of interacting Floquet-Block propagators is also used to optimize vibroacoustic indicators as noise absorption and emission. The main purpose of this work is first to propose the numerical methodology to compute the fluid-structure multi-modal wave dispersions. In a second step optimization of electric circuit is used to control the acoustic power flow. 3D standard computation is also use to confirm the efficiency of the designed metacomposite in term of acoustic emissivity and absorption.

8688-25, Session 6

Increasing overall wind-farm power efficiency by optimal cooperative control

Jinkyoo Park, Stanford Univ. (United States)

The objective of this research is to improve the cost-effectiveness and production efficiency of wind farms using cooperative wind-farm control. Nacelle yaw and blade pitch angles are the key factors determining power production and loading for a wind turbine. At the same time, these factors can adjust the wake direction and intensity in a way that adversely affects the performance of other wind turbines in the wind farm. Conventional wind-turbine control methods maximize single turbine power production, but can lower overall wind-farm power efficiency due to wake interference. By introducing a cooperative game concept from game theory, a new equilibrium point for wind-turbine power production can be derived such as to increase total wind-farm power efficiency. To this end, a convex optimization problem with the objective of maximizing the sum of power production of wind turbines in a wind farm was formulated and simulated. The derived control policy leads to sets of coordinated optimum control inputs (the nacelle yaw and blade pitch angles) for various wind conditions in a wind farm. The results of this research can lead to increased power efficiency and prolonged wind-farm operation periods.

8688-26, Session 6

Design of smart composite platforms for adaptive trust vector control and adaptive laser telescope for satellite applications

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

This paper presents design of smart composite platforms for adaptive trust vector control (TVC) and adaptive laser telescope for satellite applications. To eliminate disturbances, the proposed adaptive TVC and telescope systems will be mounted on two analogous smart composite platform with simultaneous precision positioning (pointing) and vibration suppression (stabilizing), SPPVS, with micro-radian pointing resolution, and then mounted on a satellite in two different locations. The adaptive TVC system provides SPPVS with large tip-tilt to potentially eliminate the gimbals systems. The smart composite telescope will be mounted on a smart composite platform with 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.

8688-27, Session 7

Vibration damping of a cantilever beam utilizing fluidic flexible matrix composites

Bin Zhu, Chris D. Rahn, Charles E. Bakis, The Pennsylvania State Univ. (United States)

This paper presents a novel approach for damping the vibration of a cantilever beam by bonding a fluidic flexible matrix composite (F2MC) tube to the beam and using the strain induced fluid pumping. The transverse beam vibration couples with the F2MC tube strain to generate flow into an external accumulator through an orifice that dissipates energy. The energy dissipation is especially significant at the resonances of the cantilever beam, where the beam vibrates with greatest amplitude and induces the most fluid flow from the F2MC tube. As a result, the resonant peaks can be greatly reduced due to the damping introduced by the flow through the orifice. An analytical model is developed based on Euler-Bernoulli beam theory and Lekhnitskii's solution for anisotropic layered tubes. In order to maximize the vibration reduction, a parametric study of the F2MC tube is performed. The analysis results show that the resonant peaks can be provided with a damping ratio of up to 13.7% by tailoring the fiber angle of the F2MC tube, the bonding locations of the tube, and the orifice flow coefficient.

8688-28, Session 7

Analytical solutions to H_2and H_∞ optimization of resonant shunt electromagnetic tuned mass damper and vibration energy harvester

Lei Zuo, Wen Cui, Xiudong Tang, Stony Brook Univ. (United States)

The classic tuned mass damper (TMD) is a passive vibration control device composed of an auxiliary mass connected to a vibrating object with a spring and an energy-dissipative element. When its parameters are optimized, it can reduce the vibration effectively. Inspired by the piezoelectric shunting damping treatment, this paper proposed a concept of electromagnetic TMD, where an electromagnetic transducer shunt with a resonant RLC circuit is placed between the primary structure and the base, realizing the function TMD without additional mass. The resonance created by the RLC circuit has the similar effect as the one induced by the auxiliary mass-spring system. The parameters of the RLC circuits are optimized in this paper for both vibration mitigation performance and energy harvesting with closed-form solutions. Both H_2and H_∞optimization criterions, which is to minimize the root-mean-square vibration under random excitation, and to minimize the peak magnitude in the frequency domain are investigated. The main contribution of this paper is to derive the exact closed-form solutions for H_2 optimization and approximate closed-form solutions for H_∞ optimization of the electromagnetic TMD system. The results are then compared with the numerical solutions in order to verify the accuracy. Furthermore, for implementation purpose, we also investigate the sensitivity of system performances to parameter change of the electromagnetic TMD system.

8688-29, Session 7

A new global approach using a network of piezoelectric elements and energy redistribution for enhanced vibration damping of smart structure

Dan Wu, Daniel Guyomar, Claude Richard, Institut National des Sciences Appliquées de Lyon (France)

A new global approach for improved vibration damping of smart structure, based on global energy redistribution by means of a network of piezoelectric elements is proposed. It is basically using semi-active Synchronized Switch Damping technique. SSD technique relies on a cumulative build-up of the voltage resulting from the continuous switching and it was shown that the performance is strongly related to this voltage. The increase of the piezoelectric voltage results in improvement of the damping performance. External voltage sources or improved switching sequences were previously designed to increase this voltage in the case of single piezoelectric element structure configurations. This paper deals with extended structure with many embedded piezoelectric elements. The proposed strategy consist of using an electric network made with non-linear component and switches in order to set up and control a low-loss energy transfer from source piezoelements extracting the vibrational energy of the structure and oriented toward a given piezoelement in order to increase its operative energy for improving a given mode damping.

This paper presents simulation of a clamped plate with four piezoelectric elements implemented in the Matlab/SimulinkTM environment. The various simulation cases show the relationship between the damping performance on a given targeted mode and the established power flow. SSDD and SSDT are two proposed original networks. Performances are compared to the SSDI baseline. A damping increase of 18dB can be obtained even with a weakly coupled piezoelectric element in the multi-sine excitation case. This result proves the importance of new global non-linear multi-actuator strategies for improved vibration damping of extended smart structure.

8688-30, Session 7

Experimental investigation of dynamic performance of a prototype hybrid-tuned mass damper under human excitation

Nima Noormohammadi, Paul Reynolds, The Univ. of Sheffield (United Kingdom)

Current sport stadia designs focus mainly on maximising audience capacity and providing a clear view for all spectators. Hence, incorporation of one or more cantilevered tiers is typical in these designs. However, employing cantilevered tiers, usually with relatively low damping and natural frequencies, can make grandstands more susceptible to excitation by human activities. This is caused by the coincidence between the activity frequencies (and their lowest three harmonics) and the structural natural frequencies hence raising the possibility of resonant vibration. This can be both a vibration serviceability or safety issue.

Past solutions to deal with observed or anticipated vibration serviceability problems have been mainly passive methods, such as tuned mass dampers (TMDs). These techniques have exhibited problems such as lack of performance and off-tuning caused by human-structure interaction. To address this issue, research is currently underway to investigate the possible application of hybrid TMDs (HTMDs), which are a combination of active and passive control, to improve the vibration serviceability of such structures under human excitation.

The work presented here shows a comparative experimental investigation of a passive TMD and a prototype HTMD applied on a slab strip structure. The most effective control algorithm to enhance the performance of the HTMD and also deal with the off-tuning problem is investigated. The laboratory structure used here is an in-situ cast simply-supported post-tensioned slab strip excited by forces from a range of human activities.

8688-31, Session 7

Simultaneous supply of infinite and infinitesimal stiffness of active isolation systems that are exposed to multiple vibration sources

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A common aim of vibration isolation systems is to reduce the transmissibility from seismic base level disturbances to sensitive structures. To obtain a desirable low isolation frequency, vibration isolation systems are typically equipped with low stiffness interfaces between the involved structures. Strongly detrimental influences to the possible vibration reduction performance are caused by the effects of additional disturbances that act on the isolated object.

This paper introduces theoretically and examines experimentally the solution on how the conflict of simultaneous vibration isolation and energy reflection can be solved at a single component. The described technique enables vibration reduction at a sensitive object while seismic base and direct force disturbances are concurrently present. This paper shows that even soft, adaptively altered isolation interfaces can reach these contrary goals, because they can simultaneously generate high stiffness as well as a high flexibility of the isolation interface. These interfaces are equipped with piezoelectric patch actuators to enable active control. The used active control mechanism and the very promising experimental results are highlighted in this paper.

Because of the chosen mechanical setup of such isolation systems, the used controller can be updated very quickly when system parameters change. This is possible without any further excitations and without further sensors.

8688-78, Session PTues

Damping properties of stay cable-passive damper system with effects of cable sag and damper stiffness

Min Liu, Harbin Institute of Technology (China)

At present and to reduce or eliminate the large amplitude vibration of the stay cables, passive dampers, such as viscous oil dampers have been successfully implemented to stay cables vibration control and achieved effective control efficacy. Without the influence of cable sag, bending stiffness and damper stiffness, several surveys have shown that the maximum amount of damping added to the cable with a transverse passive damper is approximately proportional to the distance, relative to the cable length, between the damper and the cable/deck anchorage. The present paper derivate the asymptotic solution of modal damping of one taut stay cable attached with one passive damper including damper stiffness and viscous damping. The effect of the damper stiffness on the modal damping of the stay cable-passive system was analytical investigated. On the basis of the asymptotic solution of modal damping of one stay cable attached with one passive damper with the effect of cable stiffness and by using the decay factor of damper stiffness and the decay factor of cable sag, maximum modal damping ratio and corresponding optimal damping coefficient, which indicates the relationships of the characteristics of the damper and the cable sag was theoretically analyzed. Numerical analysis of parameters on the effect of dynamic performance of the controlled stay cable was conducted. The numerical and analytical results show that the maximum modal damping ratio decrease with the increasing of sag and damper stiffness, and the corresponding optimal damper coefficient increase. The influence on modal damping ratio of the sag and damper stiffness for different symmetric vibration mode is same trend. The presented investigations would be used for the passive damper design of the stay cable vibration mitigation

8688-79, Session PTues

Dynamic design of laminated piezocomposites structures (LAPS) using topology optimization method

Ruben A. Salas, Emilio C. N. Silva, Univ. de São Paulo (Brazil)

Laminated piezocomposite materials are composed by layers of piezoelectric, metal and composite material (epoxy matrix with carbon or glass fiber), which have advantages over conventional piezoelectric materials, because of their superior characteristics, which cannot be achieved by any of its components isolated, for example, more flexibility and strength and less weight. Under this approach, this work aims at the development of Laminated Piezocomposite Structures (LAPS) what primarily consist of multi-layer structures, through the vibration modes and resonance frequencies design aiming at dynamic applications. Among the potential applications of these structures it can be cited piezomotors, sonar devices and energy harvester, being of great interest the improvement of its dynamic characteristics and performance. The dynamic design of a LAPS is complex, however, it can be systematized by using the Topology Optimization Method (TOM). The TOM is a method based on the distribution of material in a fixed design domain with the aim of extremizing a cost function subject to constraints inherent to the problem by means of combining the optimization algorithms and the finite element method (FEM). The TOM formulation for the LAPS dynamic project aims to determine together the optimal topology of the materials for different layers, the polarization sign of the piezoelectric material and the fiber angle of the composite layer, in order to design a particular vibration mode by means of maximizing the vibration amplitude at certain points for a specified resonance frequency, or the energy conversion. Results are presented to illustrate the method.

8688-80, Session PTues

A bio-inspired test system for bionic above-knee prosthetic knees

Daihua Wang, Lei Xu, Qiang Fu, Gang Yuan, Chongqing Univ. (China)

Recently, prosthetic knees in the developing stage are usually tested by installing them on amputees' stumps directly or on test platforms. Although amputees can fully provide the actual motion state of the thigh, immature prosthetic knees may hurt the amputees. For the test platform, it just can partly simulate the actual motion state of the thigh with the limitation of the motion model of the thigh, the merits or demerits of newly developed bionic above-knee prosthetic knees cannot be accessed thoroughly. Aiming at the defects of two testing methods, this paper presents a bio-inspired test system for bionic above-knee prosthetic knees. The proposed bio-inspired test system is composed of a test platform and a bio-inspired control system, as shown in figure 1. The test platform includes a vertical ball screw and a horizontal ball screw, which are used to control the movement of the thigh. The vertical ball screw is used to simulate the up-and-down movement of the hip joint, and the horizontal ball screw is used to simulate the swing movement of the thigh. The bio-inspired control system comprises the signal acquisition and processing system, which is wore by the healthy tester, and the motor control system. The bio-inspired control system uses the acquired motion signal of the thigh of the healthy tester, rather than the motion model of the thigh, to control the thigh of the test platform to track the motion of the thigh of the healthy testers. The bio-inspired test system is developed and experimentally tested with a newly developed magnetorheological prosthetic knee in our lab. The research results show that the bio-inspired test system can not only ensure the safety of the testers, but also track all kinds of the actual motion state of the thigh of the testers in real time.

8688-81, Session PTues

Theory and experiment research of two-dimension acoustic metamaterial

Hongwei Sun, Jiangsu Automation Research Institute (China); Ying Li, Nanjing Univ. of Science and Technology (China); Perngjin F. Pai, Univ. of Missouri-Columbia (United States); Zhiming Li, Jiangsu Automation Research Institute (China)

This paper presents modeling and analysis methods for design of a acoustic metamaterial panel consisting of two isotropic plates and small membrane-mass subsystems for absorption of low frequencies transverse elastic waves. Two models of a unit cell are derived and used to demonstrate the existence of negative effective material properties. Moreover, the design of experiment sample confirms that the model and analysis methods are valid. (1) The frequency of the membrane-mass subsystems are uniform distribution in whole acoustic metamaterial panel have two vibration models. (2) The different distributions of membrane-mass subsystems and their resonance frequencies result in different vibration isolation characteristics.(3) PSV is used to test and the result show that a low frequency wave absorber does not require nano-manufacturing techniques .(4) if we design the frequency of the membrane-mass subsystems different it can change the character of the metamaterial panel.

8688-82, Session PTues

Analysis and modeling of a piezoelectric energy harvester for powering a wireless sensor

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The present study deals with the modeling of a piezoelectric energy harvester whose task is to power a transducer. The purpose of the overall project is the realization of a sensor (an accelerometer) which measures the same vibrations to which it is subjected.

A bimorph with two PZT layers in a cantilever configuration is dynamically bent due to vibrations; the resulting deformation ensures enough output current for powering an electronic circuit.

Careful attention is paid to the transduction of mechanical energy into electrical, taking concepts from models available in the literature. An analytical model is presented, that describes the dynamics of mechanical part using the electrical duality; in particular the coupling of the variables is represented by an equivalent transformer.

This model is validated by means of experimental tests carried out on two types of bimorph, assuming different kinds of real scenarios (various input and frequency of vibrations).

Voltage and power output obtainable are investigated, considering different load conditions and acceleration amplitudes. Focus is also given to the determination of the natural frequency of the system as a whole: in fact, the piezo generator is very sensitive to the electrical load and the usable bandwidth is very narrow. For this reason, in addition, a finite element model is provided, which simulates the dynamic response of the electromechanical system.

Another objective is to define the optimal electrical quantities for the power management circuit, since the bimorph is connected to a circuit for the energy storage; this has the task of powering the sensor and the wireless transmitter.

8688-83, Session PTues

Modeling and comparison of cantilevered piezoelectric energy harvester with segmented and continuous electrode configurations

Hongyan Wang, Harbin Institute of Technology (China) and Qiqihar Univ. (China); Lihua Tang, Nanyang Technological Univ. (Singapore); Xiaobiao Shan, Tao Xie, Harbin Institute of Technology (China); Yaowen Yang, Nanyang Technological Univ. (Singapore)

Conventional cantilevered piezoelectric energy harvesters (PEHs) have usually been designed as continuous electrode configuration (CEC). The energy harvester with CEC can only work around the first resonance efficiently due to the cancellation effect of the electrical output around higher modes. Some studies show the use of segmented electrode configuration (SEC) can improve the electrical output from higher modes. However, the output from each electrode pair on the opposite sides of the strain node needs to be rectified separately to avoid the cancellation effect. Thus, theoretical formulation for power estimation becomes challenging because of some nonlinear electrical components included. In this paper, a method based on combining the equivalent circuit model (ECM) and the circuit simulation is proposed to estimate the power outputs of the cantilevered PEH with the SEC. First, the parameters in the ECM considering multiple modes of the PEH with the SEC are identified from the finite element analysis. The ECM is then established and simulated in the SPICE software. The validity of the ECM is validated using system-level finite element analysis. Finally, the optimal power outputs from the PEH with the SEC are compared with those from the PEH with the CEC. The results illustrate the feasibility of the SEC as a simple and effective means for enhancing the power outputs of a PEH at higher vibration frequencies.

8688-84, Session PTues

MR tactile device for minimally invasive surgery (MIS): experimental investigation

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Recently, it is very popular in modern medical industry to adopt robotic technology for minimally invasive surgery (MIS). Compared with open surgery, the MIS needs the robot to perform surgery through the usage of long surgical instruments that are inserted through incision points. This causes the surgeon not to feel viscosity and stiffness of the tissue or organ. So, for the tactile recognition of human organ in MIS, this paper proposes a novel tactile device that incorporates with magnetorheological (MR) fluid. The MR fluid is fully contained by diaphragm and several pins. By applying different magnetic field, the operator can feel different force from the proposed tactile device. In order to generate required force from the device, the repulsive force of human body is firstly measured as reference data and an appropriate size of tactile device is designed. Pins attached with diaphragm are controlled by shape memory alloy (SMA). Thus, the proposed tactile device can realize repulsive force and shape of organ. Also, for real application, slave robot with force sensor is utilized to obtain information of organ or tissue. It has been demonstrated via experiment that the measured force can be achieved by applying proper control input current. In addition, psychophysical experiments are conducted to evaluate performance on the tactile rendering of the proposed device. From these results, the practical feasibility of the tactile device is investigated.

8688-85, Session PTues

The assessment of chevron knee bracing frames seismic behavior

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This study is intended to assess the behavior of a structural lateral bracing system, called Chevron Knee Bracing (CKB). In this type of bracing, the knee elements help the system to dissipate energy through the formation of plastic flexural and/or shear hinges. The approach proposed by FEMA P695 based on an acceptable low probability of structural collapse is used in the following study. Nonlinear static and dynamic analyses are also carried out on the models of representative archetypes. Collapse Margin Ratios (CMRs) of the defined models are achieved throughout the conducting Incremental Dynamic Analyses (IDA). Then, in the next step, these ratios are modified to obtain an Adjusted Collapse Margin Ratio, ACMR for each archetype. To investigate the behavior of the mentioned lateral bracing frames, the values of calculated ACMRs are compared with the accepted values proposed by FEMA P695. The total system collapse uncertainty is also considered in this procedure.

1. The main focus of this study is on the seismic behavior of Chevron-Knee Bracing (CKB) frames. Knee elements can be utilized besides the bracing members. In this case these elements help the total structural system dissipates more energy while the bracing elements provide enough stiffness to limit structural drifts due to the seismic loading [1-3]. To assess the performance of CKB frames, under the severe earthquakes, the following steps are taken:

• Several archetypes with different characteristics are considered and designed;

• An appropriate Pushover analysis, for the archetypes under consideration, is accordingly performed;

• The roof drifts, which are relevant to the yielding of knee elements in shear and flexural mode as well as the ones relevant to the buckling of compression braces, are obtained. The maximum base shear capacity (Vmax) corresponding to the ultimate roof displacement can also be obtained from these analyses [4,5];

• In the next step, the set of selected records, to conduct nonlinear dynamic analyses, consists of 22 pairs of earthquake records, which is proposed by FEMA P695 [6], is considered;

• Then, Incremental Dynamic Analysis (IDA) is performed, in order to establish the Median Collapse Capacity (MCC) and Collapse Margin Ratio, CMR, for each index archetype model [7];

• Then, the Collapse Margin Ratio is evaluated after conducting nonlinear IDA for each archetype, [6];

• Considering the values calculated for CMRs, ACMRfor each model, can successfully be evaluated throughout considering the spectral shape effects of the record set by a simple computation [6];

• Furthermore, the collapse fragility curve of each model can be derived and then revised by considering all of uncertainty sources.

2. To approve the seismic behavior of the Chevron-Knee-Bracing system which is under consideration, it is necessary for the ACMR values of each index archetypes and the average of these values in each performance group to be more than the acceptable values proposed by FEMA P695. These acceptable values of Adjusted Collapse Margin Ratios are based on total system collapse uncertainty and the values of acceptable probability of collapse.

Collapse Margin Ratios and adjusted values of these ratios for selected individual archetypes are presented in this investigation. According to this study, it is evident that an acceptable performance has been achieved by all of index archetypes and performance groups, which are investigated in this paper.

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8688-86, Session PTues

Multichannel active vibration control using MicroBlaze soft processor on Xilinx Virtex-4 FPGA

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The Design & Development of a Xilinx Virtex-4 FPGA based Embedded System Active Vibration Controller is presented in this paper. This is achieved by implementing the MicroBlaze Soft-core Processor on the FPGA fabric. The active adaptive controller is based on FxLMS algorithm implemented in C++ on the MicroBlaze™ soft processor of the high speed high Performance Compact Xilinx Virtex-4 FPGA (Field Programmable Gate Array). Xilinx's EDK (Embedded Development Kit) is the development package for building MicroBlaze embedded processor system on Xilinx FPGAs. XPS (Xilinx Platform Studio) of EDK is used to configure and build the hardware specification of the embedded system & SDK enables programmers to write, compile, and debug C/C++ applications for their embedded system. The GPIOs of the MicroBlaze™ soft core processor has been linked to the ADCs/DACs of the indigenously designed FPGA board for completing the control loop. The control code is in C++ & loopback codes are in VHDL. The two have been successfully linked & four channel real time control tests have been performed successfully on a composite research wing model. The results of the study are brought out in the present paper.

8688-87, Session PTues

Electrically-controlled release of tannic acid from calcium-alginate hydrogel in transdermal drug delivery application

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This work focuses the release behavior of tannic acid from calcium-alginate hydrogels, (Ca-Alg), under applied the electric field towards transdermal drug delivery application. Ca-Alg hydrogels are prepared by solution-casting, using alginate and $CaCl_2$ as the matrix and the crosslinking agent, respectively. The Ca-Alg hydrogels properties are determined in terms of the molecular weight between crosslinks, the crosslinking density, and the mesh size via the Equilibrium Swelling Theory as modified by Bray and Merril. The release behavior is investigated using a modified Franz-Diffusion cell in the MES buffer solution at pH of 5.5 and the temperature of 37 ºC during 48 hours based on the effect of crosslinking ratio, (mole of crosslinking agent : mole of alginate monomer) and under applied the electric field. The amount of drug release, reported in the aspect of the diffusion coefficient, is determined through the Higuchi equation. The diffusion coefficient of

tannic acid decreases with increasing crosslinking ratio because of the smaller pore size of the Ca-Alg hydrogel. The diffusion coefficient of tannic acid increases under applied the electric field due to the electro-repulsive force between the tannic acid anion and negative charge of electrode.

8688-88, Session PTues

Optical limiting by nonlinear scattering in 2,2'-dipyridylamine hydrofluoride nanoparticles in chloroform and diethyl ether suspensions

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This paper reviews the optical limiting properties of 2,2?-dipyridylamine hydrofluoride nanoparticles suspended in chloroform and diethyl ether. Nonlinear transmittance measurements were carried out for different sample concentrations and reveal that 2,2?-dipyridylamine hydrofluoride nanoparticles can serve as good candidates for effective optical limiting over broad laser energy ranges. A modified Z-scan technique was employed to recognize the performance and basis of optical limiting in the sample. As corroborated by the results of the Z-scan experiment, higher the concentration of the sample, better is the performance of the optical limiter.

8688-89, Session PTues

Testing of CLEMR damper and its application to structures using fuzzy logic

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In recent years, some large tonnage Magnetorheological (MR) dampers have been used for reduction of structural vibration. In order to produce a large damping force, the coil number of these dampers needs to be increased, it will lead to greater complexity in controller and external power supply, once power fails, the damper will fail too. Additionally, MR damper has intrinsically time-delay phenomena and nonlinear characteristic. Therefore, it is an interesting and challenging task to determine the control current. This study will introduce a new kind of combined lead extrusion magnetorheological (CLEMR) damper, which can produce a large damping force even when power fails. The relationship between the current and the damping force of the CLEMR damper is experimental studied. A formula relating the damping force and the current of CLEMR damper is put forwarded that matches the experimental data. Then a real-time control strategy based on fuzzy control for the structures with CLEMR dampers is proposed and a fuzzy controller is then designed to determine control currents of the CLEMR dampers. This method can resolve the damper time-delay problem and does not need exact mathematical models. Finally, the time-history analysis on a reinforced concrete structure with CLEMR dampers using the fuzzy control strategy is calculated through the programming by MATLAB. Simulation results show that CLEMR dampers can reduce the seismic responses of structures effectively. Simulation results of the fuzzy control system are then compared with those of the LQR control system, the passive-on control system, the passive-off control system, and the uncontrolled system. Comparison results show that the fuzzy control strategy can determine control currents of CLEMR dampers accurately and quickly and the fuzzy control strategy can reduces seismic responses of the structures more effectively than the passive-on control strategy, the passive-off control strategy.

8688-90, Session PTues

Enhancement of piezoelectric energy harvesting with multi-stable nonlinear vibrations

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In the quest for long-term service of various low-power sensor systems, there has been prominent research in the field of energy harvesting. Vibration based piezoelectric energy harvesting (PEH) gained popularity owing to the fact that the piezoelectric materials provide a high power density. Due to several drawbacks of linear PEH devices, a gradual shift towards the nonlinear PEH has been observed lately. In this article, emphasis has been laid on investigating the performance enhancement of a PEH device due to the nonlinearity introduced by a magnetic field at the tip of the cantilever. The magnetic field is introduced with a few permanent magnets. The experimental setup consists of a piezoelectric cantilever beam with a tip mass containing an encased magnet. Additional magnets around the tip mass are tuned to induce multi-stable nonlinear vibrations of the cantilever beam. The whole arrangement is mounted on a supporting frame which vibrates on a shaker. The present work investigates the feasibility of multi-stable nonlinear configurations to enhance the efficiency of PEH. As little work has been reported on the multi-stable nonlinear PEH device, a basic parametric study is conducted to obtain an optimal configuration for performance enhancement of the harvester. The study reveals that the multi-stable configuration is able to provide a widened bandwidth with an increased voltage output as compared to conventional linear PEH devices.

8688-91, Session PTues

Zero-crossing velocity detector design for self-powered piezoelectric energy harvesting devices

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In this study, the design of a self-powered switching based interfacing circuit for piezoelectric energy harvesting devices using a zero-crossing velocity detector is proposed. One of the most important applications is to combine the energy harvesting devices with wireless sensor networks (WSN) because the major problem of the WSN sensors is the battery life time which will arise higher maintained requirements and limit the application areas. In order to increase the efficiency of the piezoelectric energy harvesting device, the synchronized switching harvesting techniques are already proven to boost power output of energy harvesters significantly . However, the synchronized switching technique needs the external power to be realized and limited the application of energy harvesting applications. To make the synchronized switching technique be used in real applications, a self-powered technique based on a zero-crossing velocity detector is proposed. The zero-crossing velocity detector substitutes the function generator to make the switches can turn on at the optimal time and can remove the time lag drawback of the traditional peak detector. The design of the piezoelectric patch for zero-crossing velocity detector will be presented in this study and the theoretical analysis and experimental results will also be examined.

8688-92, Session PTues

An adaptive non-model-based control strategy for smart structures vibration suppression

Francesco Ripamonti, Matteo Morlacchi, Ferruccio Resta, Politecnico di Milano (Italy)

The vibration reduction in mechanical systems can be performed by means of active control strategies. For nonlinear and time-varying systems, an attractive solution is represented by the use of an adaptive feedback control, in which the system identification plays a fundamental role.

In this work, an innovative non model-based identification system is proposed. It works splitting the measured signal into its principal components through a real time Subspace Tracking (ST) algorithm. Each component is then identified by a low order ARMA/ARMAX model, returning the system natural frequencies and damping ratios. These are used to set the gain of the Direct Velocity Feedback (DVF) control law. More precisely the gain of the control law varies according to the difference between estimated and desired damping ratio of a given signal component (e.g. the first modal contribution).

The possibility to feedback the reconstructed velocity (with only the first principal components) instead of the measured one, with a consequent reduction of the required control force, is investigated too.

The proposed adaptive control algorithm has been tested both numerically and experimentally on a smart structure test rig. In particular a carbon fiber plate, clamped on three sides and forced by piezoelectric patches, has been analyzed.

8688-93, Session PTues

Experiment and analysis of morphing skin based on shape-memory composite tube

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As a typical smart material, shape memory polymer (SMP) has the capability of variable stiffness to external stimuli, such as heat, magnetic, electricity and solvent, et al. In this study, a kind of morphing skin is designed based on shape memory polymer composite (SMPC) tube. The SMPC tube is made of SMP and carbon fiber. The SMP material used in this study is styrene-based shape memory resin with glass transition of 62?, which belongs to thermosetting resins. And the skin is composed of silicon rubber and SMPC tube. The morphing skin possesses the flexibility under high temperature condition and the rigidity under low temperature condition. Significant changes in effective engineering modulus can be achieved through regulating the environment temperature. In order to investigate the basic performances of deployment for morphing skin, several experimental and simulation methods are used as follows: by using finite element analysis, we can get the temperature distribution of SMPC tube in ventilation with hot water. In order to examine the heating mode, a unique heating system is designed. The heating system can meet the uniform heating of SMPC tube. The deflection can be gotten via the stress-bearing capability test. From the fatigue test we can investigate the recovery capability of morphing skin. Infrared test is done to show the temperature distribution of the skin. At last we can get the outcome of theoretical calculations and experimental results compared.

8688-94, Session PTues

Implementation of a modal disturbance estimator for vibration suppression

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Fiber Bragg Gratings (FBG) sensors have a great potential in active vibration control of smart structures thanks to their small transversal size and the possibility to make an array of many sensors. They can be embedded in carbon fiber structures and their effect is nearly negligible.

This paper presents a control strategy for the suppression of vibration due to unknown disturbance forces in large, nonlinear flexible structures. The control action proposed, based on the modal approach, consists of two contributions. The first is the well-known Independent Modal-Space Control, which increases system damping and improves its behavior close to the resonance frequencies. The second is a disturbance estimator, which calculates the modal components of the external forces acting on the system and compensates for them using actuator forces. The system modal coordinates, required by both logics, are estimated through a modal state observer.

The work shows how the use of FBG sensors allows improving the performance of the control to suppress vibration. The advantage mainly consists on the opportunity to have a large number of measurements regarding the state of deformation of the whole structure.

The proposed control logic is tested on a carbon fiber smart structure composed of a thin cantilever beam with 14 longitudinal FBG sensors and 3 piezoelectric actuators (PZT).

8688-95, Session PTues

Influence of thermal strain and pyroelectric effects on active vibration control of a smart piezo structure

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Augmented piezoelectric constitutive equations with temperature dependent piezoelectric and permittivity coefficients are used to derive a finite element model of two dimensional ‘smart piezo plate’. Equations of motion are derived using Hamilton’s variational principal. Variation of thermal strain effect, pyroelectric effect and static sensor voltage with temperature is shown non-linear. This is contrary to linear one as reported in the literature. Influence of these thermal effects on active vibration control performance of a ‘smart piezo structure’ is also investigated.

8688-96, Session PTues

Electroaeroelastic modeling and analysis of a hybrid piezoelectric-inductive flow energy harvester

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The exploitation of aeroelastic vibrations (coupled with a proper transduction mechanism) for converting wind energy into low-power electricity has received growing attention in the energy harvesting literature. The use of an aeroelastic typical section is a convenient approach to create instabilities and persistent oscillations for energy harvesting. The potential applications of flow energy harvesting range from aircraft structures to several engineering problems involving wireless electronic components located in high wind areas. Most of the existing research on wind energy harvesting has focused on transforming flow-induced vibrations into electricity by employing electromagnetic or piezoelectric transduction mechanisms separately. In this work, a hybrid airfoil-based aeroelastic energy harvester that simultaneously exploits piezoelectric transduction and electromagnetic induction is analyzed based on fully coupled electroaeroelastic modeling. Both forms of electromechanical coupling are introduced to the plunge degree of freedom. The interaction between total power generation (from piezoelectric transduction and electromagnetic induction) and the linear electroaeroelastic behavior of the typical section is investigated in the presence of two separate electrical loads. The effects of systems

parameters, such as internal coil resistance, on the total power output and linear flutter speed are also discussed.

8688-97, Session PTues

Application of a passive/active autoparametric cantilever beam absorber with PZT actuator for duffing systems

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An experimental investigation is carried out on a cantilever-type passive/active autoparametric vibration absorber, with a small PZT patch actuator, to be used in a primary damped Duffing system. The primary system consists of a mass, viscous damping and a cubic stiffness provided by a soft helical spring, over which is mounted a cantilever beam with a PZT patch actuator actively controlled through an acquisition card installed on a PC running on a Matlab/Simulink platform to attenuate harmonic and resonant excitation forces. With the addition of a PZT actuator to the cantilever beam absorber, cemented to the base of the beam, the autoparametric vibration absorber is made active, thus enabling the possibility to control the effective stiffness and damping associated to the passive absorber and, as a consequence, the implementation of an active vibration control scheme able to preserve, as possible, the autoparametric interaction as well as to compensate varying excitation frequencies and parametric uncertainty. This active vibration absorber employs feedback information from a high resolution optical encoder on the primary Duffing system and an accelerometer on the tip beam absorber, a strain gage on the base of the beam, feedforward information from the excitation force and on-line computations from the nonlinear approximate frequency response, parameterized in terms of a proportional gain provided by a voltage input to the PZT actuator, thus modifying the closed-loop dynamic stiffness and providing a mechanism to asymptotically track an optimal, robust and stable attenuation solution on the primary Duffing system. Some simulation and experimental results are included to describe the dynamic and robust performance of the overall closed-loop system.

8688-98, Session PTues

A fuzzy-logic based dual-purpose adaptive circuit for vibration control and energy harvesting using piezoelectric transducer

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Due to their two-way electromechanical coupling effect, piezoelectric transducers can be used to synthesize passive vibration control schemes, e.g., RLC circuit with the integration of inductance and resistance elements that is conceptually similar to damped vibration absorber. Meanwhile, the wide usage of wireless sensors has led to the recent enthusiasm of developing piezoelectric-based energy harvesting devices that can convert ambient vibratory energy into useful electrical energy. It can be shown that the integration of circuitry elements such as inductance can benefit the energy harvesting capability. Here we explore a dual-purpose circuit that can facilitate simultaneously vibration suppression and energy harvesting. It is worth noting that the goal of vibration suppression and the goal of energy harvesting may not always complement each other. That is, the maximization of vibration suppression doesn't necessarily lead to the maximization of energy harvesting, and vice versa. In this research, we develop a fuzzy-logic based algorithm to decide the proper selection of circuitry elements to balance between the two goals. As the circuitry elements can be online tuned, this research yields an adaptive circuitry concept for the effective manipulation of system energy. Comprehensive analyses are carried out to demonstrate the concept and the performance improvement.

8688-99, Session PTues

Smart integrated energy monitoring and management system for standalone photovoltaic systems

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In the present work, an integrated smart real-time energy monitoring and management system for standalone photovoltaic system is designed and implemented. The energy consumption form the PV module is controlled based on accurate determination of the periods of times at which the loads are required to be operated and the performance of the system is continuously monitored by calculating and recording the consumed and generated power from the PV system. These requirements are fully fulfilled using an accurate and efficient programming environment. Initially, the program is fed with the details load usage time table and with the signals from different sensors. The program automatically reads the date and time from the controlling computer internal clock and the controlling signals from the different sensors are also considered to operate the required loads based on users' requirements. The controlling signals are generated and send to the load driving circuits through the data acquisition card. Based on the knowledge of the switched on loads and the time periods at which these loads are operated, the total energy consumed by the loads is continuously monitored and compared with the energy generated from the PV modules at the same time. The energy level in the storage units is determined and further decisions and/or actions, like reduction of loads, are taken. It has to be mentioned that the usage of the standard plate forms and programming environment in our present work make the system flexible to be upgraded to fulfill additional users' requirements.

8688-100, Session PTues

A cantilevered piezoelectric bi-stable composite concept for broadband energy harvesting

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Vibration based energy harvesting has received extensive attention within the smart structures community during the last decade [1, 2]. Recently, the idea to exploit nonlinearity to achieve broadband energy harvesting has been introduced [3]. Nonlinear systems have been shown to operate over a wide band of frequencies delivering high power. In particular, systems exhibiting bi-stability have been shown to achieve the objective of broadband high energy conversion. Amongst these bi-stable composite plates show several advantages, including design flexibility for multiple resonance tuning owing to their two-dimensional nature, and reduced complexity as no external magnets are required to achieve bi-stability [4].

In this paper, a novel cantilevered bi-stable composite plate concept is presented for broadband nonlinear energy harvesting. The cantilevered configuration offers enhanced response characteristics over previously proposed unconstrained bi-stable plates as larger strains close to the clamp end increase the effectiveness of the piezoelectric transducers. Furthermore, the current investigation couples the advantages of broadband conversion of bi-stable composites with a broadband shunting circuit to enhance the harvesting capabilities of the employed piezoelectric transducers. An analytical model for the cantilevered bi-stable harvester is developed allowing for calculation of important dynamic characteristics, including modal frequencies and mode shapes. The separation between the first bending modes of each stable configuration is studied as it has been shown to control the range for which cross-well broadband oscillations are obtained. An experimental investigation is carried out for the proposed design showing wideband frequency conversion maintaining large power output.

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8688-32, Session 8

Principle, design, and testing of an inner bypass magnetorheological damper for shock and vibration mitigation

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Aiming at fundamentally improving the performance of the MR dampers, including maximizing dynamic range and minimizing field-off damping force, this study presents the principle of an inner bypass magnetorheological damper (IBMRD). The IBMRD mainly consists of twin tubes, i.e., the inner tube and outer concentric tube, piston, and annular MR fluid flow gap sandwiched between the inner and outer tubes. In the IBMRD, the inner tube is simultaneously used as the guide for the movable piston and the bobbin for the electromagnetic coil windings, and five active rings on the inner tube, annular MR fluid flow gap, and outer tube forms five closed magnetic circuits. Based on the structural principle of the IBMRD, the IBMRD is configured and its finite element analysis (FEA) is implemented. After theoretically constructing the hydro-mechanical model for the IBMRD, its mathematical model is established using a Bingham-plastic nonlinear fluid model. The characteristics of the IBMRD are theoretically evaluated and compared with those of a conventional piston-bobbin MR damper with an identical active length. In order to validate the theoretical results predicted by the mathematical model, the prototype of the IBMRD is designed, fabricated, and tested. The servo-hydraulic testing machine (MTS 810) and rail-guided drop tower are used to provide sinusoidal displacement excitation and shock excitation to the IBMRD, respectively.

8688-33, Session 8

A new magnetorheological elastomer-base isolator for structural control

Majid Behrooz, Xiaojie Wang, Faramarz Gordaninejad, Univ. of Nevada, Reno (United States)

This paper presents a new MagntoRheological Elastomer (MRE) base isolator for civil structures' vibration control. The elastomeric element of the traditional steel-rubber base isolator is upgraded with a composite layer of passive elastomer and MRE which makes the isolator controllable in terms of stiffness and damping. The variable stiffness and damping isolator (VSDI) is designed based on optimization of magnetic field passing through MREs to achieve maximum changes in mechanical properties. The controllability of the prototype VSDI is investigated experimentally under shear tests and vibration experiments include swiping sinusoidal single degree of freedom (SDOF) tests on a single VSDI, integrated system of four VSDIs and a mass in on and off states. Integrated systems are used to observe the effect of combination of multiple VSDIs in the system. Double lap shear experiments in on and off states are performed to find the force-deformation curve of the devices. Then the single VSDI's behavior in on and off states is modeled using Bouc-Wen hysteresis model. The natural frequency of VSDIs is compared to simulation results. The results show that both the single VSDI and integrated systems of VSDIs can increase the stiffness and damping due to activation. The simulation results also demonstrate the accurate modeling of VSDIs using the proposed model.

8688-34, Session 8

Continuous variable transmission and regenerative braking devices in bicycles utilizing magnetorheological fluids

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The use of magnetorheological (MR) fluids in vehicles has been gaining popular recently due to its controllable nature, which gives automotive designers more dimensions of freedom in functional designs. However, not much attention has been paid to apply it to bicycles. This paper is aimed to study the feasibility of applying MR fluids in different dynamic parts of a bicycle such as the transmission and braking systems. MR continuous variable transmission (CVT) and power generator assisted in braking systems were designed and analyzed. Both prototypes were fabricated and tested to evaluate their performances. Experimental results showed that the proposed designs are promising to be used in the bicycle application.

8688-35, Session 9

Position control of SMA having Seebeck voltage as feedback

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Shape Memory Alloys (SMA), as a branch of smart material actuators, are widely researched in the areas of control applications. These actuators exhibit considerable hysteresis between the supply voltage (conventionally used in resistive heating) and position characteristics of the SMA. Unless a model matches the actuator's nonlinearities, the control of a SMA would result in an error between the desired and actual strain. An Adaptive Neuro Fuzzy Inference System (or ANFIS) model is proposed to model the hysteresis of the system. The hysteresis of SMA is path dependent, thus controlling the SMA in real time requires a time series forecasting a nonlinear model. The input parameters for such ANFIS model would be a physical variable at time t and at a time t-n, where n is a time delay. The present work studies the effect of time delay on the actuator nonlinearities for two ANFIS models. One of the models studies the relationship between the desired displacement of SMA and the supply voltage across the SMA. A SMA – Constantan thermocouple measures the temperature of this SMA and feeds back the state of the SMA to the controller. Other ANFIS model predicts the actual displacement of SMA from the feedback temperature. A PID controller is developed having Seebeck Voltage of an SMA – Constantan thermocouple as feedback.

8688-36, Session 9

Simultaneous measurement of longitudinal and lateral piezoelectric strain coefficients using digital-image correlation

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Digital image correlation (DIC) will be demonstrated to be an accurate tool for the noncontact, non-destructive and rapid characterization of the converse piezoelectric effect in bulk and thin films. The out-of-plane (d33) and in-plane (d31) piezoelectric strain coupling coefficients of PZT-5H wafers will be measured simultaneously by imaging the

wafer's cross section under free mechanical boundary conditions. The large piezoresponse at switching domains and nonlinear behavior of PZT-5H will be visualized in strain-electric field butterfly loops. The results will show DIC as a simple advantageous technique to use for the characterization of piezoelectric materials under the influence of any field and physical constraints.

8688-37, Session 9

Design of direct-drive servo-valve operated by the piezostack actuator

Juncheol Jeon, Quoc Hung Nguyen, Seung-Bok Choi, Inha Univ. (Korea, Republic of)

Electro-hydraulic servo-valves have been widely used in various automatic systems which need high precision of flow rate or pressure control to provide excellent static and dynamic control performance. The servo-valves are generally classified into single-stage valve and two-stage valve. Direct drive servo-valve (DDV) is a kind of single-stage valve in which the actuator is directly connected to the spool of the valve. In the conventional DDVs, the spool is generally actuated by electro-magnetic actuator. Therefore, performance characteristics such as the accuracy and bandwidth of the DDVs are limited. In this paper, a new type of the DDV operated by piezostack actuator is proposed and the goal of the proposed DDV is to achieve an accurate control of the flow rate at high frequency. The proposed DDV consists of a piezostack actuator, a displacement amplifier to amplify displacement from the piezostack actuator and a spool valve mechanism. In this study, firstly the mathematical model of the displacement amplifier actuated with the piezostack actuator is derived and validated by experimental result. Then, significant geometric dimensions of the spool are determined considering required performance characteristics of the valve and practical applications. Analytical model of the proposed DDV is then derived and performance characteristics the valve are analyzed.

8688-38, Session 9

Effect of misalignment between ultrasound piezoelectric transducers on transcutaneous energy transfer

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This paper investigates ultrasound-based piezoelectric recharging system for implantable medical devices. Application of the ultrasound power delivery to actual implantable devices is relatively new while biological application of the ultrasound was initiated about a century ago.

Overall charging efficiency of the piezoelectric ultrasonic transcutaneous energy transfer system depends on frequency matching of the transmitter and receiver, electrical, mechanical and acoustical impedance characteristics, distance between the transducers, and misalignment. However, through a number of experiments, it was realized that the angular misalignment between transmitter and receiver was one of key factors to have effect on the power transmission efficiency.

Analytical modeling of piezoelectric ultrasound recharging system was first built and computer simulation was conducted to examine the sensitivity of non-parallel incident wave between the piezoelectric transducers.

The results indicate that the range of misalignment angle can be found in terms of the wavelength and diameter of the transducers, and distance between the transducers providing design flexibility without significant degradation of the efficiency.

8688-39, Session 10

Experimental testing of spanwise morphing trailing edge concept

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Aircraft wings with smooth, hinge-less morphing ailerons exhibit increased chord-wise aerodynamic efficiency over conventional hinged ailerons. Ideally, the wing would also use these morphing ailerons to smoothly vary its airfoil shape between spanwise stations to optimize the lift distribution and further increase aerodynamic efficiency. However, the mechanical complexity or added weight of achieving such a design has traditionally exceeded the potential aerodynamic gains. By expanding upon the previously developed cascading bimorph concept, this work uses embedded Macro-Fiber Composites and a flexing box mechanism to achieve a spanwise-varying morphing trailing edge. The morphing actuators are spaced spanwise along the wing with an elastomer spanning the gaps between them, which allows for optimization of the spanwise lift distribution while maintaining the continuity and efficiency of the morphing trailing edge. The concept is implemented in a representative UAV wing with a 12 inch chord. The actuation capabilities of the concept are evaluated with and without spanning material on a test stand, free of aerodynamic loads. In addition, the actuation restrictions of the spanning elastomer, necessary in adapting the morphing concept from 2D to 3D, are characterized. The wing is then tested in the University of Michigan 5'x7' wind-tunnel to evaluate the capability of the concept to maximize aerodynamic performance at various angles of attack. The results are compared with a wing with conventional ailerons. The results show an increase in the lift to drag ratio at each angle of attack, with a marginal weight increase.

8688-40, Session 10

Power requirements for bi-harmonic amplitude and bias modulation control of a flapping-wing micro air vehicle

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Flapping wing micro air vehicles (FWMAVs) have been a growing field in the research of micro air vehicles, but little emphasis has been placed on control theory. Research is ongoing on how to best power FWMAVs in hover given limited mass and volume. This paper focuses on the power requirement as a function of control authority to manipulate the wings of a FWMAV. Bi-harmonic Amplitude and Bias Modulation (BABM) is a novel control theory that allows two actuators to produce forces and moments in 5 DOF. A baseline power requirement will be established to achieve and simulate hover in order to evaluate the additional power requirements and resulting maneuverability using BABM. Several FWMAV prototypes will be constructed and tested on a 6-component balance. Force and moment data will be collected as each control parameter is varied. The results will map control parameters to forces/moments/power for each degree of freedom. Forces and moments required to generate desirable motion will be shown plotted against power required to generate the forces. These results will be used to generate a feasible design. The results will show how much power over the hovering baseline BABM control requires in order to achieve forces and moments in 5 DOF. This work will provide the designer with the expected maneuverability for a given maximum available power for a FWMAV using BABM control.

8688-41, Session 10

Active damping for General Electric 41% subscale GEnx composite fan blade with embedded piezoelectric patches

Benjamin B. Choi, NASA Glenn Research Ctr. (United States); Kirsten P. Duffy, The Univ. of Toledo (United States)

NASA Glenn Research Center (GRC), in collaboration with GE Aviation, began the development of a smart adaptive structure system with piezoelectric transducers to improve composite fan blade damping at resonances for future aircraft. The flexible macro-fiber-composite patches were embedded within a 41% subscale GEnx composite fan blade in a location of high resonant strain for the target 1B mode, protecting the brittle piezoceramic material from the airflow and from debris. Because the blade is too large for GRC's Dynamic Spin Rig, a stack of surface-mounted flexible patches was used to excite the blade at the target frequency. One thin and small sensor patch was also embedded next to the actuator patch for a displacement feedback controller. The optimal locations for sensors, actuators and exciters for the test were investigated. Since the limited space in which the blades reside in the engine, we developed a novel digital shunt scheme to replace the conventional electric passive shunt circuits. The digital shunt dissipates strain energy through the load resistor on a power amplifier. Results show that with a single actuator patch, active vibration control causes the damping ratio to increase from a baseline of 0.3% critical damping to about 1.0% damping.

8688-42, Session 10

Characterization of multifunctional skin-material for morphing leading-edge applications

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Former research on morphing droop nose applications revealed great economical advantages due to gapless surfaces which support longer areas of laminar flow along the aircraft. Various kinematics are already published but the major challenge is still open: the qualification of a solid material or material-mix which meets the compromise of needed stiffness and flexibility. Moreover a list of additional functions are listed by the flight worthiness requirements which are set by the aircraft-manufacturer.

As a result of several national and European projects the DLR developed a gapless smart droop nose concept, which was successfully tested via 3 dimensional demonstrators under flight-similar conditions to prove the functionality during operation. The main structure is made of commercial available glass-fibre reinforced plastics (GFRP, Hexcel Hexply 913).

This paper presents elementary tests for characterising hybrid lay-ups and their integrity by applying loads. On the one hand the presented work is focussed on the integrity of material-interfaces and on the other hand the efficiency and feasibility of embedded anti-icing- and deicing-systems. The anti-icing and deicing methods are compared under extreme thermal conditions due to their efficiency. In addition the systems are also mechanically tested to simulate and study their long-term stability for service.

It can be concluded that different preparation-steps as well as different adhesives have their significant influence to the interface-stability. The efficiency of anti-icing and deicing is mainly influenced by the electrical contact and the feasibility to be incorporated into the lay-up of the tested hybrids.

8688-44, Session 11

A magneto-rheological fluid-based torque sensor for smart torque wrench application

Farzad Ahmadkhanlou, Gregory N. Washington, Univ. of California, Irvine (United States)

Magneto-Rheological fluid has been widely used in semi-active based-dampers, actuators, brakes, and clutches. In this paper, the authors have developed a new application where MR fluid is being used as a sensor. A novel MR-fluid based torque wrench has been developed with a rotary MR fluid-based damper. The desired set torque ranges from 0.1 to 5 N.m. Having continuously controllable yield strength, the MR fluid-based torque wrench presents a great advantage over the regular available torque wrenches in the market. This novel design is capable of providing continuous set toque from the lower limit to the upper limit while regular torque wrenches provide discrete set torques only at some limited points. This feature will be especially important in high fidelity systems where tightening torque is very critical and the tolerances are low.

8688-45, Session 11

Simulation of adaptive semi-active magnetorheological seat damper for vehicle occupant blast protection

JinHyeong Yoo, Muthuvel Murugan, U.S. Army Research Lab. (United States)

Mines, specifically Anti-Vehicular (AV) Improvised Explosive Devices (IED), are a significant threat for military vehicles and their occupants. This study investigates a lumped-parameter human body including lower leg in seated posture with a quarter-car model for blast injury assessment simulation. To simulate the shock acceleration of the vehicle, mine blast analysis was conducted on a generic land vehicle crew compartment (sand box) structure. For the purpose of simulating human body dynamics with non-linear parameters, a physical model of lumped-parameter human body with a quarter car model was implemented in a multi-body dynamic simulation software. For implementing control scheme, a control algorithm was made to work with the multi-body dynamic model by running co-simulation with the control scheme software plug-in. The injury criteria and tolerance levels for the biomechanical effects are discussed for each of the identified vulnerable body regions, such as the lower leg, the spine, and the neck. The desired objective of this analytical model development is to study the performance of adaptive semi-active magnetorheological damper that can be used for vehicle-occupant protection technology enhancements to the seat design in a mine-resistant military vehicle.

8688-46, Session 11

Control of 4-DOF MR haptic master: slave robot for minimally invasive surgery

Chang-Ho Uhm, Phoung-Bac Nguyen, Seung-Bok Choi, Inha Univ. (Korea, Republic of)

In this paper, the MR haptic master and slave robot for minimally invasive surgery (MIS) have been designed and tested. The proposed haptic master consists of three actuators; two MR brakes featuring gimbal structure for 3-DoF rotation motion(X, Y and Z axes) and one MR clutch for 1-DoF translational motion. The proposed slave robot which is remotely connected with the haptic master has vertically multi joints, and it consists of four DC servomotors; three for positioning endoscope and one for spinning motion. Using force sensors and rotary encoders that installed on the master and slave, the force and position information sensed by the slave robot is transmitted to the master and vice versa. In that way, the surgeon can feel the repulsive force from the slave when he/she manipulates the master. This master-slave system runs

as if a teleoperation system through TCP/IP connection, programmed by C#. In order to achieve the desired force and position trajectories, a sliding mode controller (SMC) is designed and implemented. The sliding mode controller known to be robust to uncertainties can compensate the adverse effect of the hysteretic behaviors of MR fluid. It has been demonstrated that the effective tracking control performances for the desired motion are well presented in time domain and their tracking errors are evaluated.

8688-47, Session 11

An improved polynomial dynamic model of a magnetorheological fluid damper under impact loadings

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With fast response time and adjustable damping properties, magnetorheological (MR) dampers have shown their capabilities in reducing vibration of structures when subjected to impact loadings. In order to achieve the best performance of MR dampers for vibration control, a suitable semi-active control method is needed. Understanding and modeling of the dynamic behavior of MR dampers is crucial in development of such control strategies.

Comparing with several commonly used models for MR dampers, such as Bingham, Herschel-Bulkey or related models, this paper presented both theoretical and experimental studies on modeling MR dampers under impact loadings. An improved polynomial model with simple form, which is easy to be solved inversely and suitable for implement in real time control, is proposed. A series of experimental tests are performed to evaluate the accuracy of the proposed model. The results show that the proposed model can well describe the relationship of damper velocity and its output force during buffering motion. And under the action of MR damper, buffering process of the whole mechanical system becomes smoother.

8688-48, Session 11

Energy-efficient MRF brakes and clutches avoiding no-load losses

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A challenge opposing a commercial use of actuators like brakes and clutches based on magnetorheological fluids (MRF), are durable no-load losses. A complete torque-free separation of these actuators is inherently not yet possible due to the permanent liquid intervention for the fluid engaging parts. Especially for applications with high rotational speeds up to some thousand RPM, this drawback of MRF actuators is not acceptable.

In this paper, approaches will be presented that that allows a controlled movement of the MRF from an active shear gap into an inactive shear gap, enabling a complete separation of the fluid engaging surfaces. This behavior is modeled for a novel actuator design by the use of the ferrohydrodynamics and therefore simulations are performed for investigating the transitions between braking resp. coupling and idle mode. Measurements performed with a realized MRF actuator show that the viscous induced drag torque can be reduced significantly.

8688-49, Session 11

Design of the magnetorheological mount with high-damping force for the marine diesel-generator set

Ok-Hyun Kang, Won-Hyun Kim, Won H. Joo, Hyundai Heavy Industries Co., Ltd. (Korea, Republic of); Joon-Hee Park, Inha Univ. (Korea, Republic of)

This paper investigates controllable magnetorheological (MR) mounts for the marine diesel generators. Sometimes, significant vibrations over allowable limits are observed on the diesel generators. The vibration should be reduced to satisfy the requirements. Although passive mounting with rubber isolators on the engine has been usually used, the vibratin reduction is not always sufficient. Expecting that the requirement to vibration reduction will get stronger, semi-active vibration isolation system using MR fluid is required. To the aim, tow MR mount configurations of flow mode type were considered. The mounts was developed considering the necessary damping forces. The peak force is primariliy attributed to the mount stroke, but the stroke is very small, compared to MR dampers. To solve the problem andenhance the damping force, configurations of increasing the flow passage of MR fluids within restricted shapes were designed. To identify whether the required damping force is generated, excitation test was conducted. Since damping property of the MR fluid is changed by variation of the applied magnetic field strength and frequency, responses of the mounts were compared by chaning the applied current and frequency. Subsequently, the vibration control performance for 1 DOF system was evaluated. From the experimental results, it was verified that the developed MR mount can be applicable to D/G set for vibration control

8688-50, Session 12

Vibration energy harvesting using Galfenol-based transducer

Viktor Berbyuk, Chalmers Univ. of Technology (Sweden)

Traditionally the development of vibration energy harvesters was based on the use of piezoelectric materials. A great attention, however, is paid now to magnetostrictive alternative. The promise of magnetostriction was greatly increased since the development of an Iron-Gallium alloys (Galfenol). In this paper the novel design of Galfenol based vibration energy harvester is presented. The device uses Galfenol rod diameter 6.35 mm and length 50mm, polycrystalline, production grade, manufactured by FSZM process by ETREMA Product Inc. Collecting coil consists of 4000 turns of Cu wire. Magnetic bias is created by magnets with diameter 6mm, length 10mm and flex density 1,17-1,27T. For experimental study of the harvester, the test rig was also developed. It was found by experiment that for given frequency of external excitation there exist optimal values of bias and mechanical prestress which maximize generated voltage and harvested power. Under optimized operational conditions and external excitations with frequency 50Hz the designed transducer generates about 10 V and harvests about 0,45 W power. Within the running conditions, the Galfenol rod power density was estimated to 340mW/cm3. The obtained results show high practical potential of vibration-to-electrical energy conversion by using magnetostrictive material Galfenol.

8688-51, Session 12

Durability of a d33-mode piezo-composite electricity-generating element

Nam-Seo Goo, Van-Lai Pham, Jun Zhao, Jisoo Park, Konkuk Univ. (Korea, Republic of)

Numerous studies have demonstrated the possibility of using piezoelectric generators to harvest energy from various ambient sources.

A piezo-composite generating element (PCGE) has been proposed recently. The PCGE is composed of layers of carbon/epoxy, piezoelectric lead zirconate titanate ceramic (PZT), and glass/epoxy cured at an elevated temperature. Through the curing process, the PCGE stores residual stress in the PZT layer from the mismatch in the coefficients of thermal expansion among the constituent layers. There are two common modes used for energy harvesting: d33-mode and d31-mode. In this work, a d33 mode PCGE was tested concerning its mechanical and heated behavior. The main focuses are the durability and reliability of PCGEs in different conditions. A motor level system has been designed for this experimental purpose. To investigate the durability of PCGEs, the output voltage of the PCGEs will be observed every time the impact force is applied, which can be controlled by the motor level system until several million times. The reliability of PCGEs is examined by testing their output voltage, owing to the impact force from the motor level system after they are picked up from a chamber with an elevated temperature.

8688-52, Session 12

Enhanced piezoelectric energy harvesting utilizing magnetic effect

Jiong Tang, Jiawen Xu, Univ. of Connecticut (United States)

Piezoelectric transducers are widely employed in vibration-based energy harvesting schemes. Fundamentally, the efficiency of energy harvesting using piezoelectric transducers hinges upon the electromechanical coupling effect. While at the material level such coupling is a given material property, at the device level it is possible to vary and improve the energy conversion capability between the electrical and mechanical regimes by a variety of means, e.g., structural tailoring and incorporating additional components. In this research, we explore changing the effective flexibility of the energy harvester by using the magnetic effect. It is shown that a properly configured and positioned magnet can induce force that can effectively improve the electromechanical coupling of the energy harvester. Comprehensive analytical and experimental studies are carried out to demonstrate the concept and validate the performance improvement.

8688-53, Session 12

A hybrid electromagnetic energy harvesting device for low-frequency vibration

Hyung-Jo Jung, Jeongsu Park, In-Ho Kim, KAIST (Korea, Republic of)

An electromagnetic energy harvesting device, which converts a translational base motion into a rotational motion by using a rigid bar having a moving mass pivoted on a hinged point with a power spring, has been recently developed for use of civil engineering structures having low natural frequencies. The device utilizes the relative motion between moving permanent magnets and fixed solenoid coil in order to harvest electrical power. In this study, the performance of the device is enhanced by introducing a rotational-type generator at a hinged point. In addition, a frequency up-conversion technique, which makes use of an auxiliary energy harvesting system of high natural frequencies to further improve the efficiency, is incorporated into the device. The effectiveness of the proposed hybrid energy harvesting device based on electromagnetic mechanism is verified through a series of laboratory tests and preliminary field tests.

8688-54, Session 12

Design of laminated piezocomposite energy harvesting devices using topology optimization methods

Cesar Y. Kiyono, Emilio C. N. Silva, Univ. de São Paulo (Brazil)

Energy harvesting devices are smart structures capable of converting the mechanical energy (generally vibrations) that would be wasted in the environment into usable electrical energy. Laminated piezocomposite shell structures have been largely used in the design of these devices because of their large generation areas and their possibility of changing the displacement field by properly orienting the composite fibers. The design of energy harvesting devices are complex and they can be efficiently designed using topology optimization methods (TOM), which combines optimization algorithms and finite element methods (FEM). In this work, the energy conversion can be improved by maximizing the electric power generated by the piezoelectric material in a damped harmonic analysis. The effective electric power is measured at a coupled electric circuit, which is also modeled in the FEM. The electric power is maximized by optimally distributing piezoelectric material and choosing its polarization sign, and properly choosing the fiber angles of composite materials. The material model used to distribute piezoelectric material and to choose its polarization sign is the PEMAP-P model, and to optimize the composite fiber orientation, the discrete material optimization(DMO) method is used. Numerical examples are presented to illustrate the proposed methodology.

8688-55, Session 12

Development of a piezoelectric polymer wind energy harvesting flag

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In recent years, wind energy harvesting systems using piezoelectric materials have been studied by a lot of researchers. However, energy harvesting methods using flexible thin piezoelectric films had not been well developed due to the extremely small power generation. In this study, a piezoelectric wind energy harvesting method using high-polymer films was investigated experimentally. At first, the feasibility of the systems was shown in laboratory experiment by using various sizes and boundary conditions of piezoelectric films subjected to the airflow direct and inverse piezoelectric effects of distributed piezoelectric films simultaneously, active flexible structures which posess vibration damping ability can be able to construct. However, conventional studies are limited to the control of relatively small (micron-order) displacements of thin flexible structures as well as numerical studies by handling controller design of software aspects. In this paper, several fundamental active vibration control principles, which will be valid in actual implementation, of smart flexible structures using piezoelectric films as distributed sensor/actuator have been developed. By applying each of these methods, it was verified that the enough vibration control effects were actually obtained and the theory agrees well with the experiment.

8688-56, Session 12

Highly-integrated energy harvesting device for rotational applications utilizing quasi-static piezoelectric and electromagnetic generators

Jens Twiefel, Marc C. Wurz, Leibniz Univ. Hannover (Germany)

This work addresses the design of an integrated energy harvesting system under production viewpoints. The system is developed to harvest energy form rotational movements. Therefore, a piezoelectric bending element – connected to the rotational part - is actuated by magnetic force introduced by a hard magnet installed in the fixed frame. A similar setup is already introduced in literature; this work concentrates on a high integration, the energy harvesting circuit, including rectifier, power management and storage is integrated in the structure of the bending harvester. Further on the soft magnetic tip mass is combined with a coil for electro-magnetic energy harvesting; the necessary electronic is also integrated in the structure. The paper addresses the special systems demands for large scale production. The production technology for a mall series of prototypes is explained in detail. Performance tests of the device conclude this study.

8688-57, Session 13

Study of a piezoelectric energy harvester with a dynamic magnifier

Dejan Vasic, François Costa, Ecole Normale Supérieure de Cachan (France)

A piezoelectric energy harvester with a multi-mode dynamic magnifier is proposed and modeled in this paper. An analytical model in the form of matrix relations connecting the mechanical quantities of one end to the other in the case of a dynamic magnifier energy harvester is presented. These relations enable us to determine the behavior of magnifier by considering the mechanical boundary conditions of assembly of the three sections of the dynamic magnifier. A typical harvester is composed of a cantilever beam with tip mass at the end and a PZT film on the beam surface, which operate mainly around the first natural frequency. The vibration energy harvester study in this paper with multi-mode dynamic magnifier is composed of a tuned mass, where an intermediate mass is inserted between the vibration structure and the energy harvester beam to amplify the vibration of the harvester.

The usual model of a magnifier, is “distributed parameters model”, it presents the electromechanical solution of a piezoelectric cantilever for transverse vibrations with Euler-Bernoulli beam assumption. In the present paper, the analytical model is inspired by the 4x4 chain matrix formalism. In addition to the benefits of a “distributed parameters model”, the present model combines several other advantages: it is suited for the dynamic magnifier design because the model can take into account various electrical and mechanical boundary conditions.

The results show that output power of the harvesting beam is amplified for efficient energy harvesting over a broader frequency range.

8688-58, Session 13

Investigation of bistable piezo-composite plates for broadband energy harvesting

David N. Betts, Christopher R. Bowen, Hyunsun A. Kim, Nicholas Gathercole, Christopher T. Clarke, Univ. of Bath (United Kingdom); Daniel J. Inman, Univ. of Michigan (United States)

This paper reports the static and dynamic behavior of nonlinear [0/90] bistable composite plates with bonded piezoelectric layers, excited by mechanical vibrations across a broadband range of frequencies. This approach exploits the large amplitude oscillations inherent in a structure with two stable configurations. These nonlinear devices have improved power generation compared to conventional resonant systems and can be designed to occupy smaller volumes than bistable magnetic cantilever systems. A Digital Image Correlation system is used to map the surface deflections of the devices and thus characterize the differing modes of oscillation observed for a range of vibrational inputs. Low amplitude oscillations, intermittent snap-through between stable configurations, nonuniform responses and large amplitude oscillations are observed for differing inputs, highlighting the dependency of the power output on the vibrational input. We develop a dynamics model for this system, extending existing static modeling and using the findings of the presented experimental studies. Finite element analysis is used to better understand the complex phenomena including the effects of geometric imperfections and manufacturing asymmetry. This work will draw the three areas of experimental data, analytical modeling and finite element modeling together to form a comprehensive investigation of the piezoelectric bistable composite plates as a means of converting waste vibration energy into harvested electrical energy.

8688-59, Session 13

Mechanical and thermal energy harvesting utilizing phase transformations in 32-mode relaxor-ferroelectric single crystals

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This work presents experimental evidence of giant electro-mechanical energy conversion under ferroelectric/ferroelectric rhombohedral-orthorhombic phase transformation. Combinations of stress, electric field and temperature drive a phase transformation from rhombohedral to orthorhombic in [011] cut ferroelectric single crystals. This phase transformation is accompanied by a large jump in electric displacement and strain. The results indicate that the ferroelectric crystals produce significantly increased electrical energy density per cycle that that of the linear piezoelectric effect. Electrical energy is harvested from a mechanical and thermal excitations applied to a ternary Pb(In1/2Nb1/2)O3-Pb(Mg1/3Nb2/3)O3-PbTiO3 (PIN-PMN-PT) single crystal of composition just at the rhombohedral side of a morphotropic phase boundary. An overview of 32 mode phase transformation energy harvesting is discussed.

8688-61, Session 14

Energy harvesting from harmonic and noise excitation of multilayer piezoelectric stacks: modeling and experiment

Sihong Zhao, Alper Erturk, Georgia Institute of Technology (United States)

This article theoretically and experimentally studies deterministic and stochastic piezoelectric energy harvesting using a multilayer stack configuration for civil infrastructure system applications that involve large compressive loads, such as vehicular and foot loads acting upon pavements. Simplified electromechanical modeling efforts of stack-based vibrational energy harvesters have been mostly focused on deterministic forms of mechanical excitation as in the typical case of harmonic excitation. In this paper, we present analytical and numerical modeling of piezoelectric energy harvesting from harmonic and random vibrations of multilayer piezoelectric stacks under axial compressive loading. The analytical electromechanical solution is based on the power spectral density of random excitation and the voltage – to – pressure input frequency response function of the harvester. The first one of the two numerical solution methods employs the Fourier series representation of the vibrational excitation history to solve the resulting ordinary differential equation, while the second method uses an Euler-Maruyama scheme to directly solve the governing electromechanical stochastic differential equation. The electromechanical model is validated through several experiments for a multilayer PZT-5H stack under harmonic and random excitations. The analytical predictions and numerical simulations exhibit very good agreement with the experimental measurements for a range of resistive loads and input excitation levels.

8688-62, Session 14

Shear-mode energy harvesting of piezoelectric sandwich beam

Mohammad H. Malakooti, Henry A. Sodano, Univ. of Florida (United States)

Piezoelectric materials with high electromechanical coupling are good candidates for energy harvesting applications by transforming mechanical energy to useful electrical power. Since the d15

electromechanical coupling coefficient is the highest coupling coefficient in piezoelectric materials, the maximum electrical power output will be obtained by exciting the shear mode of piezoelectric structure. Using the Timoshenko beam theory, a model is proposed to simulate the energy harvesting performance of piezoelectric sandwich beam. The significance of geometry and material properties of layers will be studied and the final results will be validated with numerical solutions.

8688-63, Session 14

Power-generation prediction for piezoelectric composite plates by modal analysis

Yuan-Fang Chou, Chen-Hsiang Cheng, National Taiwan Univ. (Taiwan)

When the thickness of a plane structure is much smaller than its other characteristic lengths, a plate model is more realistic than a beam model. For a thin piezoelectric layer fully coated with metal electrodes on its top and bottom surfaces, the internal electric field is simple and easy to model. Therefore, it is advantageous to derive a piezoelectric composite plate model based on E-form constitutive equations. This approach is adopted to develop a mathematical model of Kirchhoff–Love type for a plate composed of a piezoelectric layer and a metal layer.

To develop a method for calculating the loaded-circuit voltage between the top and bottom electrodes is one of the major tasks of this paper. The electric power generated from piezoelectric layer is found by modal analysis. Top and bottom electrodes of the piezoelectric layer are shorted for calculating the resonant frequencies and mode shapes. Once these two electrodes are connected to an external circuit load, the boundary conditions of top and bottom surfaces become nonhomogeneous. Superposition of short-circuit modes and one particular field constitutes the nonhomogeneous solution.

A composite plate composed of a 0.3mm thick copper layer and a 0.2mm thick PZT-5A layer is investigated. The cantilever plate of 25mm in length is base-excited near the first resonant frequency. When connected to a circuit with certain load impedance, more than 80% efficiency of power generation can be achieved.

8688-69, Session 14

Electromechanical and statistical modeling of turbulence-induced vibration for energy harvesting

Jared D. Hobeck, Daniel J. Inman, Univ. of Michigan (United States)

Extensive research has been done on the topics of both turbulence-induced vibration and vibration based energy harvesting; however, little effort has been put into bringing these two topics together. Preliminary experimental studies have shown that piezoelectric structures excited by turbulent flow can produce significant amounts of useful power. This research could serve to benefit applications such as powering remote, self-sustained sensors in small rivers or air ventilation systems where turbulent fluid flow is a primary source of ambient energy. A novel solution for harvesting energy in these turbulent fluid flow environments was explored by the authors in previous work, and a harvester prototype was developed. This prototype, called piezoelectric grass, has been the focus of many experimental studies. In this paper the authors present a theoretical analysis of the piezoelectric grass harvester modeled as a single unimorph cantilever beam exposed to turbulent cross-flow. This distributed parameter model is developed using a combination of both analytical and statistical techniques. The analytical portion uses a Rayleigh-Ritz approximation method to describe the beam dynamics, and utilizes piezoelectric constitutive relationships to define the electromechanical coupling effects. The statistical portion of the model defines the turbulence-induced forcing function distributed across the beam surface. The model presented in this paper will be validated using the results of several experimental case studies. Preliminary results have shown that the model agrees quite well with experimental data. A parameter optimization study will be performed with the proposed model. This study will demonstrate how a new harvester could be designed such that maximum power output can be achieved in a given turbulent fluid flow environment.

8688-64, Session 15

Effect of loading rate on the superelastic behavior of SMAs under multi-axial loading condition: analytical modeling and experiment

Masood Taheri Andani, Mohammad H. Elahinia, The Univ. of Toledo (United States)

Multi-axial behavior of shape memory alloy (SMA) bars with circular cross section is studied by considering the effect of temperature gradient in the cross section as a result of latent heat generation and absorption during forward and reverse phase transformations. The local form of energy balance for SMAs by taking into account the heat flux effect is coupled to a closed-form solution of SMA bars subjected to multi-axial loading. The resulting coupled thermo-mechanical equations are solved for SMA bars with circular cross sections. A number of experiments were conducted with different loading conditions and at various loading rates. The experimental results were then successfully compared with the model. Several numerical case studies are presented and the necessity of considering the coupled thermo-mechanical formulation is demonstrated by comparing the results of the proposed model with those obtained by assuming an isothermal process during loading–unloading. It is shown that the isothermal solution is valid only for specific combinations of ambient conditions and loading rates. The present approach is a beneficial platform in modeling and analysis of applications with high loading rates.

8688-65, Session 15

Adaptive, energy steering three-dimensional lattice substructures

James Ayers, Kuang C. Liu, Anindya Ghoshal, U.S. Army Research Lab. (United States)

This work pursues the ability to steer energy under repeated impact loads by an adaptive periodic 3D lattice system with modular unit cells. Traditional beam forming relies on the structural anisotropy of the lattice to redirect energy, however fracturing of the lattice provides a secondary energy absorbing phenomenon. After impact and the subsequent fracture of a modular unit cell, its beam forming and energy absorbing capabilities have been compromised and can no longer fulfill the design requirements. An adaptive lattice system, which will reconfigure and thereby restoring a portion of its original capabilities, will decrease the vulnerability of the residual structure. The proposed system contains three sequential, repeated phases:

1) passive redirection of perpendicular impact loads,

2) in-situ self-diagnosis of compromised unit cells, and

3) planar restructuring of lattice configuration.

The redirection of energy is achieved through the periodic arrangement of stacked through-thickness unit cells that enable anisotropic beam forming. The design of the unit cell reduces to an optimization function, with particular attention given to pyramidal, cubic, and hexahedral based geometries.

Ligament-wise resistance measurements, or another suitable indicator, will be used to diagnosis the residual structural integrity of each modular lattice. An active path of least resistance circuit, whereby a parallel resistor circuit with a ratio R2>>R1 (R1 being the ligament resistance) is current monitored across R2. Once the ligament fractures, R1 will become much greater than R2 and the current monitor will indicate failure. This can also be used to trigger actuation mechanisms. By measuring the total resistance of the unit cell, the number of damage ligaments can be extrapolated and its residual strength correlated. The planar restructuring of the lattice is inspired by the simple children's game called the sliding puzzle. The location of each modular unit cell is controlled via magnetic actuators, which in the future can be driven by autonomous circuits. Mechanical interference due to fractured components is the primary obstructions to motion. Elastic bands are used for fragment capturing and unit cell collapsing post fracturing to reduce the mechanical interference.

A two phased validation and verification technique is employed. First, numerical studies are used to simulate the energy steering of the impact and validate the optimal lattice design. Secondly, experimental techniques are used to determine the energy steering efficiency after repeated impacts.

8688-66, Session 15

An active control logic to improve the fatigue strength of smart flexible structures

Francesco Ripamonti, Pasquale Ambrosio, Ferruccio Resta, Francesco Braghin, Politecnico di Milano (Italy)

It's general opinion that a vibration control would intrinsically imply a fatigue damage reduction. Anyway this assumption could not be such obvious. For example, consider a bad actuator positioning in which the control force could be higher than disturbances, with consequent local damage effects, or high frequency, low displacements and high deformation conditions or even situation with strong spillover problems. These considerations give the opportunity to deeper investigate the fatigue phenomena on smart structures and their reduction from a control theory point of view.

In this paper, a simplified interpretation of the fatigue damage is given using the frequency analysis framework for a generic linear structure. It gives an overview of the most relevant parameters, which affect the phenomenon. As a consequence, a control logic is defined by an optimization problem with a quadratic functional. Moreover, since the fatigue phenomenon is non-linear with the structure displacement amplitude, an adaptive control logic is applied. The control gains are real time computed monitoring the modal coordinates amplitude.

Finally, the control logic was tested on a multilayer carbon fiber plate (1100 x 1000 x 1.4 mm) fixed at three sides, sensed with five extensometers and actuated by five piezoelectric patches. The results with adaptive control show a sensible improvement in terms of the fatigue damage with respect to the uncontrolled case and the "classical" LQG control solution.

8688-67, Session 15

On ultrasonic squeeze film levitation: Modeling and feedback control of ultrasonic bearing systems

Sebastian Mojrzisch, Joerg Wallaschek, Leibniz Univ. Hannover (Germany)

In this paper the modeling and feedback control of non-contact ultrasonic squeeze film levitation bearings are presented. Starting from linearization of the governing nonlinear differential equations, simplified models are given in order to make it accessible to a wide range of applications. Besides of detailed derivation of the equations to calculate the steady state load carrying force, the transient behavior of the overall system is investigated. It is shown that the ultrasonic transducer as well as the buildup of the load supporting squeeze film have a transient behavior of first order lag type. Whereas the time constants are significantly influenced by the operating point of the system. The influence of the squeeze number and the vibration amplitude are presented. Moreover the steady state open loop stability of the system is examined. In this context the influence of lateral movement and forced vibration of the levitating member on the stability of the system are shown. Finally the design of a state feedback position control is shown. This is applied to a linear and a journal squeeze film levitation bearing. For both systems the theoretical models are validated experimentally. It turns out that the theoretical models are in good agreement with the obtained experimental results. The paper is closed by an outlook of future applications of ultrasonic squeeze film levitation bearings.

8688-68, Session 15

Power fluctuation reduction methodology for the grid-connected renewable power systems

Fadhil T. Aula, Samuel C. Lee, The Univ. of Oklahoma (United States)

This paper presents a methodology for eliminating the influence of the power fluctuations of the renewable power systems. The renewable energies which are to be considered uncertain and uncontrollable resources can provide only irregular electrical power to the power grid. This irregularity could cause the instability of the power system and impacts the operation of conventional power plants, and the power system is vulnerable to collapse if necessary actions are not taken to reduce the impact of these fluctuations. This methodology aims at minimizing this fluctuation and makes the generated power close to a constant level and maintaining it. This requires a prediction tool for estimating the generated power in advance to provide the range and the time of occurrence of the fluctuation. Since the most of the renewable energies are weather based, as a result a weather forecasting technique will be used for predicting the generated power. The elimination of the fluctuation also requires stabilizing facilities to maintain a consistent level. The characteristics of these stabilizing facilities depend on the type of the renewable energies. In this study, we use a wind farm and a photovoltaic array as renewable power systems, therefore a pumped-storage and batteries bank are used as stabilizing facilities. The methodology for balancing the power predictions and power stabilizations to eliminate the influence of the power fluctuations of this grid-connected renewable power system is presented. For illustrative purpose, a model of wind and photovoltaic systems is included and its power fluctuation reduction is verified through simulation.

8688-69, Session 16

Experimental characterization of a bi-dimensional array of negative capacitance piezo-patches for vibroacoustic control

Flaviano Tateo, Manuel Collet, Morvan Ouisse, FEMTO-ST (France)

A recent technological revolution in the fields of integrated MEMS has finally rendered possible the mechanical integration of active smart materials, electronics and power supply systems for the next generation of smart composite structures.

Using a bi-dimensional array of electromechanical transducers, composed by piezo-patches connected to a synthetic negative capacitance, it is possible to modify the dynamics of the underlying structure.

In this study, we present an application of the Floquet-Bloch theorem for vibroacoustic power flow optimization, by means of distributed shunted piezoelectric material. In the context of periodically distributed damped 2D mechanical systems, this numerical approach allows one to compute the multi-modal waves dispersion curves into the entire first Brillouin zone. This approach also permits optimization of the piezoelectric shunting electrical impedance, which controls energy diffusion into the proposed semi-active distributed set of cells.

Furthermore, we present experimental evidence that proves the effectiveness of the proposed control method. The experiment requires a rectangular metallic plate equipped with seventy-five piezo-patches, controlled independently by an electronic circuit composed of a number

of passive elements (i.e. resistances and capacitance), and an operational amplifier able to reproduce the negative capacitance effect. More specifically, the out-of-plane displacements and the averaged kinetic energy of the controlled plate under an harmonic excitation are compared in three different cases (open-circuit, short-circuit and controlled circuit). The resulting data will clearly show how this proposed technique is able to damp and selectively reflect incident waves.

8688-70, Session 16

Performance-based design of buildings with superelastic-friction base isolators

Osman E. Ozbulut, Univ. of Virginia (United States)

The seismic performance of a three-story building isolated with superelastic-friction base isolator (S-FBI) systems is investigated through a performance-based evaluation approach. The S-FBI system consists of a flat steel-PTFE sliding bearing and a superelastic NiTi shape memory alloy (SMA) device. Sliding bearings limit the maximum seismic forces transmitted to the superstructure to a certain value that is a function of friction coefficient of sliding interface. Superelastic SMA device provides restoring capability to the isolation system together with additional damping characteristics. A probabilistic performance-based assessment of the isolated building with S-FBI system is conducted using the methodology developed by Pacific Earthquake Engineering Research Center (PEER).

First, a probabilistic seismic hazard analysis (PSHA) is performed for a selected site at the western United States. The peak ground acceleration (PGA) is selected as the intensity measure. An analytical model of the isolated building with the S-FBI system is developed to determine the response of the structure under a ground motion input. Incremental dynamic analyses are conducted at different intensity levels. A suite of 20 ground motion records is employed in nonlinear response time history analysis. Peak interstory drift, peak floor acceleration, and peak and residual isolator drift are selected as the primary demand parameters. Damage states for the superstructure and isolation system are defined to relate the demand parameters to damage. Fragility functions of non-isolated and isolated building are derived to study the effectiveness of the S-FBI system. A parametric study is conducted to evaluate the effect of mechanical properties of the S-FBI system on the performance of the isolated buildings.

8688-71, Session 16

Tunable bandgaps in one-dimensional granular crystals composed of cylindrical particles

Jinkyu Yang, Mehrashk Meidani, Taegyu Kang, Feng Li, Univ. of South Carolina (United States); Duc Ngo, Eastern International Univ. (Viet Nam)

Granular crystals have shown to be able to filter out a wide range of vibrational excitations by leveraging acoustic bandgaps, in which mechanical waves in certain frequencies are not allowed to transmit. In this study we examine the variations of the filtering properties of granular crystals composed of short cylindrical particles. According to the Hertzian contact theory, the lateral interactions of two slanted cylindrical bodies form an elliptic contact that is strongly affected by the relative alignment angle and the applied static forces. We investigate the filtering behavior of these granular crystals as we gradually change the axial force, eccentricity, and contact angle between the particles. For experiments, we apply broadband, white acoustic noise to one end of the granular crystal and measure the transmitted mechanical waves from the other end to obtain its frequency responses. As a result, we find that the position and number of bandgaps in frequency space can be tuned by changing eccentricity and axial force between the particles. Particularly, we can successfully create multiple bandgaps either by imposing unbalanced eccentricity, or by strategically varying alignment angles between the particles. To verify the experimental results, we simulate the propagation and dispersion of mechanical waves with a discrete element model. Closed-form analytical solutions are also obtained based on the nonlinear wave dynamics and classical contact theory. We find that the discrete element simulations and analytical results are in good agreement with the experimental results. This study shows that granular chains with the aforementioned setup can be used as a tunable filtering structure to shield noise and vibration for different applications.

8688-72, Session 16

Approximate pole-placement controller using inverse plant dynamics for floor vibration control

Donald S. Nyawako, Paul Reynolds, Malcolm J. Hudson, The Univ. of Sheffield (United Kingdom)

Past researches and field trials have demonstrated the viability of active vibration control technologies for the mitigation of human induced vibrations in problematic floors. They make use of smaller units than some of their passive counterparts, provide quicker and more efficient control, can tackle multiple modes of vibration simultaneously and adaptability can be introduced to enhance their robustness. Predominantly SISO and multi-SISO collocated sensor and actuator pairs have been utilised in direct output feedback schemes that make use of the direct velocity feedback (DVF) control law. On-going studies have extended such past works to include model-based control approaches, for example, pole-placement, which demonstrate increased flexibility in achieving desired vibration mitigation performances but for which stability issues must be adequately addressed.

The work presented here is an extension to the pole-placement controller design using an algebraic approach that has been investigated in past studies. An 'approximate' pole-placement controller formulated via the inversion of the floor dynamics, considered as minimum phase, is designed to achieve target closed-loop performances of the closed-loop system. This design approach has been found to avoid the numerical problems that are associated with the algebraic pole-placement approach for higher order plant models. Analytical studies and experimental tests are based on a laboratory structure and comparisons are made with the DVF control scheme. It is shown that with minimal compensation, the approximate pole-placement controller scheme is easily formulated and implemented and offers good vibration mitigation performances.

8688-73, Session 16

Passive and hybrid piezoelectric circuits to reduce induced-atmospheric turbulence vibration of a plate-like wing

Tarcisio M. P. Silva, Carlos De Marqui, Univ. de São Paulo (Brazil)

The effects of atmospheric turbulence on Unmanned Aerial Vehicles (UAVs) are an important design parameter for both structural and performance aspects. In this work, a method to damp random (turbulence induced) vibrations of a plate like wing by using hybrid (active-passive) piezoelectric circuits, in addition to passive piezoelectric circuits, is presented. The performance of the different vibration control strategies is verified at several flight conditions, ranging from low airflow speeds to the proximity of the flutter condition. An electromechanically coupled finite element model (that accounts different external circuits) is combined with unsteady aerodynamic models (the doublet-lattice method and Roger's model) and an atmospheric turbulence model (Karman spectrum) to develop a piezoaeroelastic model of cantilevered plates representing wing-like structures. The behavior of the piezoaeroelastic system is investigated in time and frequency domains. In the first case study, load resistances (one for each mode to be controlled) are connected to a bimorph piezoceramics and the shunt damping effect is investigated. Later, resistive-inductive circuits (in series connection)

are considered in the electrical domain of the problem (one for each mode). Each inductor is calculated for a target frequency (resonance) as well the optimal resistor obtained for maximum damping. In the last case study, a voltage source is combined to the circuits of the previous passive cases and a Linear Quadratic Gaussian controller designed. The performance of the hybrid controller (which uses the direct and inverse piezoelectriceffects simultaneously) is investigated and compared to the previous passive cases.

8688-74, Session 17

Simulation study of semi-active control of stay cable using MR damper under wind excitations

Jiangyun Liu, Hongwei Huang, Limin Sun, Tongji Univ. (China)

Mechanical dampers have been proved to be one of the most effective countermeasures for vibration mitigation of stay cables in various cable-stayed bridges over the world. However, for long stay cables, as the installation height of the damper is restricted due to the aesthetic concern, using passive dampers alone may not satisfy the control requirement of the stay cables. Therefore, semi-active MR dampers have been proposed for the vibration mitigation of long stay cables. However, the highly nonlinear feature of the MR damper lead to a relatively complex representation of its mathematical model, and makes it difficult to be applied to suppress cable vibration with an efficient control algorithm. This paper aims to evaluate the effectiveness of MR damper for vibration mitigation of stay cable under complex wind excitations. A semi-active control algorithm based on the universal design curve of dampers was developed using a bilinear mechanical model of the MR damper. Simulation study was carried out for the cable-MR damper system. Firstly, fluctuating wind field was generated using the method of weighted amplitude wave superposition (WAWS) and Kaimal spectrum and the time-history sample curve of turbulent wind speed of stay cable was obtained. Then the dynamic response of the cable-MR damper system was computed using the proposed semi-active control algorithm. Finally, the effectiveness of the MR damper for control of cable vibration was assessed through computing the root mean square value of acceleration at each measuring point.

8688-75, Session 17

A comparison between the IMSC and the DMSC for vibration suppression of smart flexible structures

Francesco Ripamonti, Mattia Serra, Ferruccio Resta, Politecnico di Milano (Italy)

The proposed paper deals with a new control technique for the vibration reduction of flexible smart structures based on modal approach and named Dependent Modal Space Control (DMSC). The well-known Independent Modal Space Control (IMSC), devised in the ‘80 s, allows changing the frequency and the damping of the controlled modes leaving the mode shapes unaltered by using diagonal control gain matrices. The DMSC, instead, besides frequency and damping, can also impose the controlled mode shapes through full control gain matrices. In this way the DMSC can be applied allowing the creation of virtual nodes in desired point of the structure with consequent advantages in many applications. Anyway in the most of control problems, due to the limited number of sensors-actuators available and the worsening spillover effects, the generic eigenvector imposition is not possible and the same method is applied in a different way. Imposed the desired controlled poles, the optimal eigenstructure assignment can be suitably computed through a Genetic Algorithm in order to reduce the structure vibration by minimizing an Input-Output performance index in a desired frequency range, depending on the physics of the problem. Constraining the optimization the stability of a determined number of modes in closed loop can be ensured too.

In order to prove the advantages of this new method, a comparison between the IMSC and DMSC using numerical simulations and experimental tests on a cantilevered beam are carried out.

8688-76, Session 17

Numerical assessment of seismic performance of steel building with recentering damper under near-fault ground motions

Hui Qian, Zhengzhou Univ. (China); Hongnan Li, Dalian Univ. of Techonolgy (China); Gangbing Song, Univ. of Houston (United States)

The seismic performance of steel building with recentering damper-based energy dissipation system under near-fault ground motions are numerically investigated in this paper. Innovative hybrid shape memory alloys friction damper, possessing both large energy dissipation and re-centering capabilities, was developed and tested. The goal of the paper is to assess the effectiveness of the recentering damper in mitigating the seismic response of steel structure exited by strong near-fault ground motions. A simulation program was presented, and nonlinear analysis of a three-story steel frame with and without the dampers subjected to representative near-fault ground motions was performed. The results show the damper has both the stable energy dissipating capacity and re-centering feature under reverse loading and is effective in reducing the seismic response of steel building exited by strong near-fault ground motions.

8688-77, Session 17

Novel vibration-assisted cell injector based on shearing piezoactuator

Zenan Wang, Su Zhao, Wei Tech Ang, Nanyang Technological Univ. (Singapore)

Various designs of piezo-assisted Intracytoplasmic sperm injection (ICSI) has been developed, which achieved higher success rate than conventional ICSI. A common issue is that lateral oscillation of the injection pipette tip is always excited by the intended axial actuation. Researchers hold different opinions on which oscillation, axial or lateral, has more dominate effect on the piercing process. In this paper, different functionality of the axial and lateral oscillations during cell injection is investigated. A novel vibration-assisted injector is developed which uses a piezoelectric shear actuator with free stroke of 10?m in two axes. Different from the previous designs, axial and lateral oscillations are generated separately. For axial experiment, a short pipette (450 ?m in length, 30 ?m in diameter) with high first bending and longitudinal natural frequencies (137.6 kHz and 1.08 MHz) is fabricated. While driven in axial direction at frequency below 40 kHz, the pipette can be considered as rigid body. In lateral case, a 51 mm long micropipette is driven in a transverse direction at the thick end to excite bending modes. Experimental results obtained using zebrafish embryos reveal that lateral oscillations reduces the cell deformation rate during penetration dramatically, while axial oscillations show little effect. As less deformation on the cell wall leads to less pressure change inside the cell, thus lateral oscillation is more beneficial than axial oscillation in piezo-assisted ICSI. These findings help to understand the underlying physics of vibration-assisted injector. Future design vibration-assisted injector should focus on generating lateral oscillations instead of axial ones.

Conference 8689: Behavior and Mechanics of Multifunctional Materials and Composites VII

Sunday - Thursday 10–14 March 2013

Part of Proceedings of SPIE Vol. 8689 Behavior and Mechanics of Multifunctional Materials and Composites 2013

8689-1, Session 1

Ultrahigh-energy density and fast discharge nanocomposite capacitors *(Invited Paper)*

Haixiong Tang, Henry A. Sodano, Univ. of Florida (United States)

Recently, nanocomposites combining a high breakdown strength polymer and high dielectric permittivity ceramic filler have shown great potential for pulsed power applications. However, while current nanocomposites improve the dielectric permittivity of the capacitor, the gains come at the expense of the breakdown strength, which limits the ultimate performance of the capacitor. Here, we develop a new synthesis method for the growth of barium strontium titanate nanowires and demonstrate there use in ultra high energy density nanocomposites. This new synthesis process provides a facile approach to the growth of high aspect ratio nanowires with high yield and control over the stoichiometry of the solid solution. The nanowires are grown in the cubic phase with a Ba0.2Sr0.8TiO3 composition. The poly(vinylidene fluoride) nanocomposites resulting from this approach have high breakdown strength and high dielectric permittivity which results from the use of high aspect ratio fillers rather than equiaxial particles. The nanocomposites are shown to have an ultra high energy density of 14.86 J/cc at 450 MV/m, and provide microsecond discharge time comparable to commercial biaxial oriented polypropylene capacitors. The energy density of our nanocomposites exceeds those reported in the literature for ceramic/polymer composites, and is 1138% greater than the reported commercial capacitor with energy density of 1.2 J/cc at 640 MV/m for the current state of the art biaxial oriented polypropylene.

8689-2, Session 1

Non-uniform electric field and nonlinear piezoelectric behavior in active fiber composites

Hassene Ben Atitallah, Zoubeida Ounaies, Pennsylvania State Univ. (United States); Anastasia Muliana, Texas A&M Univ. (United States)

Active fiber composites (AFCs) are comprised of long circular fibers in a polymer (usually a polyimide and epoxy). The fibers are made of a piezoelectric ceramic, lead zirconate titanate (PZT). The AFCs use interdigitated electrodes, which produce electric field lines parallel to the fiber direction instead of through-the-thickness as in the more common d31-piezoelectric configuration. As a result, the AFC takes advantage of the PZT's d33 constant, which is approximately twice as high as the d31 constant. It is noted that, the d33 of the AFC is almost a third of the PZT's, mainly because of the mismatch in the dielectric properties between the polymer matrix and the ceramic fiber. Nonetheless, the AFCs are still of great interest because they have the potential to combine the flexibility and light weight of the polymer to the high piezoelectric performance of PZT. Most of the available modeling work on AFCs consider the piezoelectric behavior of the fibers to be linear, or to take full advantage of the actuation capabilities of AFCs, high electric fields needs to be applied which causes non linear behavior as we have seen in the experiments we did on AFCs. So the model will evaluate the AFC properties taking into consideration the non linear piezoelectric behavior of the fibers and releasing the assumption of a uniform electric field inside the fibers.

8689-3, Session 1

Analysis of the impedance resonance of piezoelectric multi-fiber composites

Stewart Sherrit, Samuel C. Bradford, Jet Propulsion Lab. (United States); Ashot Djrbashian, Glendale Community College (United States)

Multi-Fiber Composites (MFC's) produced by Smart Materials Corp behave essentially like thin planar stacks where each piezoelectric layer is composed of a multitude of fibers. We investigate the suitability of using previously published inversion techniques by Sherrit et al[1]. for the impedance resonances of monolithic co-fired piezoelectric stacks to the MFC to determine the complex material constants from the impedance data. The impedance equations examined in this paper are those based on the derivation by Martin[2] . The utility of resonance techniques to invert the impedance data to determine the small signal complex material constants are presented for a series of MFC's. The technique was applied to actuators with different geometries and the real coefficients were determined to be similar within changes of the boundary conditions due to change of geometry. The scatter in the imaginary coefficient was found to be larger. The technique was also applied to the same actuator type but manufactured in different batches with some design changes in the non active portion of the actuator and differences in the dielectric and the electromechanical coupling between the two batches were easily measureable. Since the model is based on material properties rather than circuit constants, it allows for the direct evaluation of specific aging or degradation mechanisms in the actuator. A simplified impedance equation in the limit of a large number of layers is also presented and standard methods of determining the material coefficients that does not require non-linear regression are presented.

[1] S. Sherrit, S.P. Leary, B.P. Dolgin, Y. Bar-Cohen, R. Tasker, "The Impedance Resonance for Piezoelectric Stacks", Proceedings of the IEEE Ultrasonics Symposium, pp. 1037- 1040, San Juan, Puerto Rico, Oct 22-25, 2000

[2] G.E. Martin, JASA, 36, pp. 1496-1506, 1964

8689-4, Session 2

A quantum informed continuum model for ferroelectric and flexoelectric materials *(Invited Paper)*

William S. Oates, The Florida State Univ. (United States)

Connections between quantum mechanics and continuum mechanics are explored by utilizing relations based on electron density within a lattice, strain, and strain gradients. Theoretically, it is shown that anisotropic stress is proportional to quadrupolarization and can be directly determined if the nuclear charge and electron density is known. The result is an extension of the Hellmann-Feynman theory which illustrates how electrostatic stresses can be used to model stress in solid materials. Further, flexoelectricity is found to be proportional to the next two higher order poles. These relations are obtained by correlating a nucleus-nucleus potential and nucleus-electron potential with a deformation gradient. An example is given for barium titanate by solving the electron density using density function theory (DFT) and open source Abinit software. Stresses under different lattice geometric constraints are modeled and compared to nonlinear continuum mechanics to understand differences in formulating stresses directly from DFT versus a Landau-deGennes free energy function that includes rotationally invariant polarization and quadrupolarization order parameters.

8689-5, Session 2

Effect of stress loading on large field dielectric loss in lanthanum-doped lad zirconate titanate

John A. Gallagher, Hwan Ryul Jo, Christopher S. Lynch, Univ. of California, Los Angeles (United States)

Ferroelectric material losses in devices ranging from acoustic transducers to energy harvesters result in the conversion of energy to heat. Under small amplitude sinusoidal drive, either electrical or mechanical, the losses can be expressed in terms of a loss tangent. The largest source of loss is associated with domain wall motion. This paper focuses on large field dielectric loss in the presence of stress in lanthanum-doped lead zirconate titanate ($Pb_{0.92}La_{0.08}(Zr_{0.65}Ti_{0.35})_{0.98}O_3$, or PLZT 8/65/35). Dielectric loss was experimentally measured using a technique that matches the area within a unipolar electric displacement – electric field hysteresis loop to an equivalent area ellipse-shaped hysteresis loop. The results indicate that the dielectric loss initially increases with electric field amplitude, but then decreases as the field amplitude is further increased. This is consistent with the material nearing polarization saturation levels.

8689-6, Session 2

Experimental characterization of interdigitated electrode designs

David M. Pisani, Christopher Lynch, Univ. of California, Los Angeles (United States)

Interdigitated Electrodes (IDEs) on thin ferroelectric plates or fibers enable the use of the d_{33} piezoelectric coefficient in the plane of the plate or along the fiber. Several geometric parameters affect the poling process and the resulting piezoelectric coupling of the device. These include the electrode width, electrode spacing, and plate thickness. This work uses experimental techniques to compare the effect of IDE geometry to computational models. The comparison focuses on two phenomena that can reduce the net polarization achieved in the material if not properly addressed: The volume of material beneath the electrodes shielded from electric field, and electrode width to fiber thickness ratios causing polarization to saturate underneath the electrode and not in the plate cross section. Through experimental and computational means, the mechanisms of IDE geometry to device performance have been found and can be used to tailor device design accordingly.

8689-7, Session 2

Electric-field induced antiferroelectric to ferroelectric phase transformation in the modified PZT system and the effects of compositional modifications

Hwan Ryul Jo, Christopher S. Lynch, Univ. of California, Los Angeles (United States)

Electric field induced antiferroelectric to ferroelectric phase transformation is observed in the modified PZT systems. The advantage of this phase transformation is the large polarization and strain that are attractive for various electromechanical devices. The effects of compositional modifications on both A- and B- site were investigated to obtain the proper dielectric and piezoelectric properties required for device functionality. The compositions of interest are near to or on the morphotropic phase boundary between antiferroelectric and ferroelectric phases at which the dielectric and piezoelectric properties are the highest. The main effort of this compositional study was focused on finding the composition with large polarization and strain, low hysteresis and coercive field, and high dielectric and piezoelectric coefficients. The B-site modification was carried first by doping Sn^{4+} to the system and changing the ratio of Zr^{4+}, Sn^{4+}, and Ti^{4+}. The A-site can be modified by adding either La^{3+} or Ba^{2+} and usually decreases hysteresis. The La^{3+} or Ba^{2+} is selected to increase or decrease coercive field, respectively. Both AFEt-FEr and AFEo-FEr phase transformations are evaluated to compare two different types of AFE-FE phase transformation. Each composition was fabricated with the conventional mixed oxide method and grain size of samples is examined by the scanning electron microscopy. X-ray diffraction method was used to confirm the crystal structure of each composition.

8689-8, Session 3

Bayesian techniques to quantify parameter and model uncertainty in nonlinear distributed smart material systems

Ralph C. Smith, Nathan Burch, North Carolina State Univ. (United States)

Piezoelectric, magnetic and shape memory alloy (SMA) materials offer unique capabilities for energy harvesting and reduced energy requirements in aerospace, aeronautic, automotive, industrial and biomedical applications. However, all of these materials exhibit creep, rate-dependent hysteresis, and constitutive nonlinearities that must be incorporated in models and model-based control designs to achieve their full potential. Furthermore, models and control designs must be constructed in a manner that incorporates parameter and model uncertainties and permits predictions with quantified uncertainties. In this presentation, we will discuss Bayesian techniques to quantify uncertainty in nonlinear distributed models arising in the context of smart systems. We will also discuss the role of these techniques for subsequent robust control design.

8689-9, Session 3

Lamb-wave dispersion under finite plastic deformation

Kuang Liu, Anindya Ghoshal, U.S. Army Research Lab. (United States)

The effect of elasto-plastic material behavior on Lamb wave speeds is investigated. This research is motivated by potential applications to nondestructive evaluation and structural health monitoring, particularly crack tip plasticity. The finite deformation of a semi-infinite plate due to plasticity is used to accommodate the changes in density and plate thickness. This is achieved by superimposing small strain waves upon a finitely deformed volume. The characteristic Lamb wave equations are modified such that the thickness and density become functions of plastic deformation. This in turn alters the shear and longitudinal wave speeds. Results illustrating the change in group velocities of the fundamental Lamb wave modes are shown for the load cases of uniaxial tension, uniaxial compression, and biaxial tension/compression. The results show that the S0 exhibits significant variations in group velocity in the highly dispersive regions, up to 20% variations in wave speed. By exploiting this result, it may be possible to utilize wave speed measurements to determine plastic zones through Lamb-like waves. The nondispersive regions show insignificant changes, likely on the level of experimental noise. Further analysis of the results illustrate that isolating changes in velocities into thickness and density effects is not straightforward as the mechanisms both behave nonlinearly. A geometrically nonlinear finite element of a notched plate was performed to quantify the finite deformation near the crack tip. The results confirmed that in applications, both thickness changes and density changes can be expected and are driving mechanisms for wave speed variations.

8689-10, Session 3

Micromechanics and finite element analysis of piezoelectric structural fiber composites

Qingli Dai, Kenny Ng, Michigan Technological Univ. (United States)

This paper presents the combined micromechanics analysis and finite element modeling of the electromechanical properties of piezoelectric structural fiber (PSF) composites. The active piezoelectric materials are widely used due to their high stiffness, voltage-dependent actuation capability, and broadband electro-mechanical interactions. However, the fragile nature of piezoceramics limits their sensing and actuating applications. In this study, the active PSF composites were made by deploying the longitudinally poled PSFs into a polymer matrix. The PSF itself consists a silicon carbide (SiC) or carbon core fiber as reinforcement to the fragile piezoceramic shell. To predict the electromechanical properties of PSF composites, the micromechanics analysis was firstly conducted with the dilute approximation model and the Mori-Tanaka approach. The extended Rule of Mixtures was also applied to accurately predict the transverse properties by considering the effects of microstructure including inclusion sizes and geometries. The piezoelectric finite element (FE) modeling was developed with the ABAQUS software to predict the detailed mechanical and electrical field distribution within a representative volume element (RVE) of PSF composites. The simulated energy or deformation under imposed specific boundary conditions was used to calculate each individual property with constitutive laws. The comparison between micromechanical analysis and finite element modeling indicates the combination of the dilute approximation model, the Mori-Tanaka approach and the extended Rule of Mixtures can favorably predict the electromechanical properties of three-phase PSF composites.

8689-11, Session 3

Feasibility study of shape control with zero applied voltage utilizing hysteresis in strain-electric field relationship of piezoelectric ceramics

Tadashige Ikeda, Tomoki Takahashi, Nagoya Univ. (Japan)

To enhance shape accuracy of antenna reflectors, active shape control of the reflectors in obits have been studied. Piezoelectric ceramic plates, which expand and contract with electrical stimulation, are one of the candidates of actuators used for the active control. They are usually bonded on the structural elements of the reflectors and voltage is applied to them to control the shape. To keep the controlled shape, the voltage must be also applied continuously. The electric power itself is low but amount of electricity must be accumulated to become big. To reduce the amount of electricity usage, a new control method is proposed. In this method the hysteresis in strain-electric field relationship is utilized effectively, in which some amount of strain remains even at zero voltage once the voltage is applied. In this paper to examine feasibility of this control method residual strain of piezoelectric ceramic plates and residual displacement of a beam with a piezoelectric ceramic plate bonded are measured. The obtained result shows that the residual strain and the residual displacement depend on the initially applied voltage and time over which the voltage is applied. This result suggests that the shape can be kept with zero applied voltage within some level of accuracy and the amount of electricity usage can be reduced by using the proposed method.

8689-12, Session 4

Nonlinear dynamics and thermodynamics of azobenzene polymer networks *(Invited Paper)*

William S. Oates, Garret Vo, The Florida State Univ. (United States)

The interaction of photons and electrons in photoresponsive azobenzene liquid crystal polymer networks is analyzed to understand thermodynamic efficiency characteristics in conversion of light energy into mechanical work. A modeling framework based on a Lagrangian density is developed and numerically implemented to include time-dependent Maxwell's equations, finite deformation mechanics, and a set of dynamic optical displacements. The results illustrate how the flux of photons and interactions with electrons fit into a continuum theorem using a conserved Lagrangian density with losses associated with light absorption and emission. Key thermodynamic parameters are identified and implemented in a finite element framework to illustrate how electromagnetic light waves interact with time-harmonic optical displacements within a solid continuum.

8689-13, Session 4

Morphing structures using ionic transistors through digital combinatorial logic

Vishnu Baba Sundaresan, The Ohio State Univ. (United States)

The integration of nanofluidic diodes and conducting polymer into a thin-film device results in a three-port device that resembles an ionic transistor. A sodium-ion rectifying nanofluidic diode made from PET and polyimide has been integrated with polypyrrole-based polymer [PPy(DBS)] and mathematical formulation of transistor function has been developed. The PET and polyimide membranes measure 6 microns thick and have a wide aspect ratio conical pore with the small end of the measuring 10nm and the big end of the pore measuring 1 micron and fabricated through ion tracking and chemical etching. The interior of this pore is functionalized with positive and negative charges with surface adsorption of cations for its function as a nanofluidic diode. The membrane on one side is sputtered with gold and PPy(DBS) is electropolymerized on one side. The combination of nanofluidic diode and the conducting polymer leads to a thin-film transistor in which local stresses can be generated by individually controlling the applied voltage across the diode. Localized stress results from two inputs applied to this thin-film device and can be controlled independent of the neighboring transistor. This transistor framework has been developed into digital combinatorial logic for the performance of morphing function of a 2D-plane. This proceedings article will discuss the concept, fabrication procedure and characterization techniques for this ionic transistor and realization of various functional configurations through combinatorial logic.

8689-14, Session 5

Development of novel multifunctional biobased polymer composites with tailored conductive network of micro-and-nano-fillers

Siu Ning Leung, Hani E. Naguib, Univ. of Toronto (Canada)

Biobased/green polymers and nanotechnology warrant a multidisciplinary approach to promote the development of the next generation of materials, products, and processes that are environmentally sustainable. The scientific challenge is to find the suitable applications and thereby to create the demand for large scale production of biobased/green polymers that would foster sustainable development of these eco-friendly materials in contrast to their petroleum/fossil fuel derived counterparts. In this context, this research aims to investigate the synergistic effect of green materials and nanotechnology to develop a new family of multifunctional biobased polymer composites with tailored electrical, mechanical, and thermal properties. A special focus is to develop a novel thermally conductive biobased/green polymer composite with tailored electrical properties that can be used as a heat management material in the electronics industry. A series of parametric studies were conducted to elucidate the science behind materials behavior and their structure-to-property relationships. Using biobased polymers (e.g., polylactic acid

(PLA) or biobased polyamide (bPA)) as the matrix, heat transfer networks were developed and structured by embedding hexagonal boron nitride (hBN) and carbonaceous nano- and micro-fillers of different sizes and shapes. The use of hybrid fillers, with optimized material formulations, was found to dramatically promote the composite's effective thermal conductivity. This was achieved by promoting the development of an interconnected thermally 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, lightweight, and eco-friendly microelectronic enclosures with superior heat dissipation performance.

8689-15, Session 5

Network modeling of membrane-based artificial cellular systems

Eric C. Freeman, Michael K. Philen, Donald J. Leo, Virginia Polytechnic Institute and State Univ. (United States)

Computational models are derived for predicting the behavior of artificial cellular networks for engineering applications. The systems simulated involve the use of a biomolecular unit cell, a multiphase material that incorporates a lipid bilayer between two hydrophilic compartments. These unit cells may be considered building blocks that enable the fabrication of complex electrochemical networks. These networks can incorporate a variety of stimuli-responsive biomolecules to enable a diverse range of multifunctional behavior. Through the collective properties of these biomolecules, the system demonstrates abilities that recreate natural cellular phenomena such as mechanotransduction, optoelectronic response, and response to chemical gradients.

A crucial step to increase the utility of these biomolecular networks is to develop mathematical models of their stimuli-responsive behavior. While models have been constructed deriving from the classical Hodgkin-Huxley model focusing on describing the system as a combination of traditional electrical components (capacitors and resistors), these electrical elements do not sufficiently describe the phenomena seen in experiment as they are not linked to the molecular scale processes. From this realization an advanced model is proposed that links the traditional unit cell parameters such as conductance and capacitance to the molecular structure of the system. Rather than approaching the membrane as an isolated parallel plate capacitor, the model includes the impact of the surrounding electrolyte and the electrostatic forces that govern the bilayer response. This model is then applied towards experimental cases in order that a more complete picture of the underlying phenomena responsible for the desired sensing mechanisms may be constructed. In this way the stimuli-responsive characteristics may be understood and optimized.

8689-16, Session 5

Meso-decorated self-healing gels: network structure and properties

Jin Gong, Kensuke Sawamura, Susumu Igarashi, Hidemitsu Furukawa, Yamagata Univ. (Japan)

Gels are new soft and wet materials having three-dimensional network structures of macromolecules. They possess excellent properties that hard materials like metals and plastics hardly have, for example, swellability, high permeability, low friction, shock absorbability, and biocompatibility. However, some degree of strength is necessary for gels to use actually as industrial materials. New high-strength gels like Topological Gel, Nanocomposite Hydrogels, Double-Network Hydrogels, Tetra-PEG Gels were developed since 2001. In our group, novel strength shape-memory and thermoreversible gels were developed. These novel gels have bright promising applications as new flexible actuator materials in many fields like machinery, robot, electronics, health, and so on. In this study, we tried to create new multi-functional and high-value added polymer gels by using one new method of hierarchical structure decoration at intermediate mesoscale. This method is named Meso-Decoration (Meso-Deco). High-performance polymer fine crystals of polybenzimidazole, polyamide and polyurethane were synthesized firstly through reaction-induced phase-separation during solution polycondensation. Many kinds of morphologies for these polymer fine crystals were generated: brush, chestnut-like, coral-like, nanofiber, microsphere, and so on. These rigid-rod polymer fine crystals with various morphologies are introduced into soft gels to create novel functional Meso-Deco strength gels. Functions of self-healing and thermal responsiveness, as well as low frictional property are provided to Meso-Deco gels through molecular design to control network structure at mesoscale.

8689-17, Session 5

Observation instrument of dynamic frictional interface of gel engineering materials with polarized optical microscopic

Naoya Yamada, Masato Wada, M. Hasnat Kabir, Jin Gong, Hidemitsu Furukawa, Yamagata Univ. (Japan)

Gels are soft and wet materials that differ from hard and dry materials like metals, plastics and ceramics. These have some unique characteristic such as low frictional properties, high water content and materials permeability. A decade earlier, DN gels having a mechanical strength of 30MPa of the maximum breaking stress in compression were developed and they are expected as the biomaterial of the human body. Indeed its frictional coefficient and strength are comparable to our cartilages. In this study, we focus on the dynamic frictional interface of hydrogels and aim to develop a new apparatus with a polarization microscope for observation. The dynamical interface is observed by the friction of gel and glass with hudroxypropylcellulose (HPC) polymer solution sandwiching and the polarization microscope image of interface is taken due to orientation of HPC. At the beginning, we rubbed hydrogel with HPC solution on glass plate. The frictional interface was observed successfully with a polarization microscope and recorded as moving image. Second, we designed a new system through combining microscope with friction measuring machine. A glass ball is set in place of glass plate in this feature with consideration that the friction measurement of gels runs with this ball. The comparison between direct observation with this instrument and measurement of friction coefficient will become a foothold to elucidate distinctive frictional phenomena that can be seen in soft and wet materials.

8689-18, Session 6

Aging effects of epoxy shape-memory polymers

Kannan Dasharathi, John A. Shaw, Univ. of Michigan (United States)

Thermo-responsive Shape Memory Polymers (SMPs) are a class of materials which exhibits a strain recovery behavior when thermo-mechanically cycled across the rubber-glass transition temperature (Tg). SMPs are being considered for adaptive tooling in manufacturing and as matrix material for advanced composites. In some SMPs, operating temperatures may exceed a nearby chemo-rheological temperature (Tcr) resulting in chemical aging/degradation due to oxidative scission and recross-linking. This manifests as either irrecoverable residual strain or as embrittlement of the polymer, both of which can limit the useful life of an SMP device.

The purpose of this research is to study the chemo-rheological degradation of SMPs and to develop a constitutive model that can be used to predict its useful operating range for particular applications. We present an experimental study of evolution of the uniaxial thermo-mechanical behavior of a commercially available epoxy SMP, Veriflex-E (Tg=105°C), subjected to temperature conditions of 100-150°C. Similar to the approach originated by Tobolsky, a combination of constant strain and intermittent relaxation experiments are used to deduce the kinetics of scission of original cross-links and the generation of newly formed cross-links. A comparison of the thermo-mechanical behavior of virgin and aged specimens is performed to assess the effects of chemical aging on shape memory behavior. These results are used to calibrate a constitutive model within a continuum multi-network framework to predict the evolution of behavior for general cyclic thermo-mechanical histories.

8689-19, Session 6

Shape-memory effect in crosslinked polymers: effects of polymer chemistry and network architecture

Jacob D. Davidson, Yali Li, Nakhiah C. Goulbourne, Univ. of Michigan (United States)

The thermal shape memory effect in polymeric materials refers to the ability of a sample to retain a deformed shape when cooled below Tg, and then recover its initial shape when subsequently heated. Although these properties are thought to be related to temperature-dependent changes in network structure and polymer chain mobility, a consistent picture of the molecular mechanisms which determine shape memory behavior does not exist. This, along with large differences in the shape memory cycling response for different materials, has made model development and specific property optimization difficult. In this work we use coarse-grained molecular dynamics (MD) simulations of the thermal shape memory effect to inform micro-macro relationships and systematically identify the salient features. We first show that the simple bead-spring polymer model is insufficient to capture property changes across Tg. A more detailed microscopic picture is then used, featuring an energy barrier to chain rotation. The simulated shape memory cycling behavior from MD is compared to experimental results from similar cycling tests on different materials. These results show the level of detail required to capture the temperature and deformation-dependent response; we show that the entropic restoring force above Tg may be understood in terms of the simple bead-spring model, and that the temperature-dependent behavior may be understood in terms of local chemical structure. We discuss these results in relation to multiscale modeling and material optimization for both passive and active shape memory polymer applications.

8689-20, Session 6

A thermoviscoelastic constitutive model of epoxy shape-memory polymers

Jianguo Chen, Liwu Liu, Yanju Liu, Jinsong Leng, Harbin Institute of Technology (China)

A thermoviscoelastic constitutive equation was developed considering the structure relaxation and viscoelasticity properties of Epoxy-Shape Memory Polymers (SMP). By introducing the internal variable temperature and Adam-Gibbs structure relaxation model, a new thermal expansion model was proposed. The thermal expansion model could predict nicely the influence of the temperature on thermal strain contribution within the glass transition region. The deformation of Epoxy-SMP was decomposed into the time-independent hyperelastic equilibrium term and time-dependent viscoelastic nonequilibrium term. This paper model the hyperelastic term with the Mooney-Rvilin model, and the Hencky elastic model and Newton fluid model with the viscoelastic term. The material parameters of the constitutive model were got through isothermal uniaxial tensile, thermal expansion, and dynamic mechanical analysis test. The process of isothermal uniaxial tensile, thermalmechanical cycle test were also simulated in software ABAQUS by using the proposed constitutive model. The results showed that the constitutive model could predict nicely the static properties of Epoxy-SMP, such as the material hardening phenomenon in the glass state of Epoxy-SMP, the strain-rate dependent and the temperature dependent influence on the mechanical properties. The proposed constitutive model could also predict nicely the complex thermomechanical behavior state of Epoxy-SMP such as the tensile process and the yielding process, and the time-dependent stress change in the thermalmechanical cycle. The proposed constitutive model could predict nicely the complex thermomechanical behavior of Epoxy-SMP in the glass transition region. The model is useful for the design of SMP structures.

8689-21, Session 6

A constitutive theory for fiber reinforced shape-memory polymer composite

Qiao Tan, Liwu Liu, Yanju Liu, Jinsong Leng, Harbin Institute of Technology (China)

A considerable amount of interest has developed for use of shape memory polymer based composite in constructing deployable space structure. Shape memory polymer composite(SMPC) can be soften significantly and can be packaged and deployed at elevated temperature. In order to enhance the ability of space deployable structures, the constitutive relationship is required to pursuit the better performance of SMPC. In the present study, the finite deformation thermo-mechanical behaviors of SMPC are experimentally investigated. Based on the experimental observations, a mathematical formulation is presented to describe the finite deformation thermo-mechanical response of fiber reinforced SMPC. This formulation is based on the composite's bridging model, and considering the material's (the fiber and matrix) mechanical property and geometric parameters, including the volume content and arrange style of carbon fiber. Additionally, the shape memory polymer's creep and stress relaxation phenomenon are also considered. This model will serve as a modeling tool for the design of more complicated SMPC-based structures and devices.

8689-23, Session 7

Thermo-mechanical behavior and constitutive modeling of epoxy-based SMPs and their hybrid composites

Mohammad Souri, Spandana Pulla, Anil Erol, Haluk E. Karaca, Charles Y. Lu, Univ. of Kentucky (United States)

In this study, the thermo-mechanical properties of epoxy-based Shape memory polymer and metal powder (and wire) composites were investigated. In some cases, composites were fabricated under magnetic field to align the magnetic powders. The change in glass transition temperature, mechanical and damping properties as functions of powder content, temperature and magnetic field were revealed. Stress generation capability of composites has also been determined. Their shape memory effect has been modeled using Lagoudas model and compared with experimental results.

8689-24, Session 7

The preparation and characterization of nanocomposites based on polyhedral oligomeric silsesquioxane (POSS) reinforced shape-memory polymer

Zhongyu Liu, Fang Xie, Liwu Liu, Yanju Liu, Jinsong Leng, Harbin Institute of Technology (China)

Shape memory polymer (SMP) is a kind of smart material which can return from temporary shape to its permanent shape induced by an external stimulus. However, the weak mechanical properties of SMP itself usually cannot meet the actual requirements well. Researchers are trying to improve its mechanical properties with various reinforced materials. Polyhedral oligomeric silsesquioxane (POSS) is a nanoscale particles

used as reinforcement to improve mechanical properties and heat resistance of polymer matrix. In order to integrate good shape memory properties and excellent mechanical properties, we prepared two kinds of shape memory composites with phenyl POSS particles and the shape memory polymer matrix synthesized in our own group.

First, shape memory composite POSS/SMEP were prepared by mixing POSS particles and epoxy-based shape memory (SMEP). The study found that the POSS particles could obviously improve the mechanical properties of the epoxy-based shape memory polymer. When the content of POSS is about 2.0wt%, tensile strength increases about 20%, and elastic modulus approximately doubled. Moreover, POSS particles could also increase the surface hardness of the composites. Due to the presence of the POSS particles, the thermal decomposition temperature of SMEP improved about 20°C, showing excellent thermal stability. The shape memory recovery rate of the shape memory composite is more than 96%, and shape memory response time is 10s less than pure SMEP.

Secondly, shape memory composite POSS/SMPU were prepared by mixing POSS particles and polyurethane-based shape memory (SMPU). Results show that the POSS particles and SMPU have a very good compatibility. Although POSS particles have a slight influence on the thermal properties of SMPU, with the increase of the POSS particles content, it can obviously improve the mechanical properties. When the POSS content is about 5wt%, the recovery time of shape memory composite POSS/SMPU reduced 10s (about 25%) comparing to the pure SMPU.

8689-25, Session 7

In composition of few-layer grapheme and carbon nanofiber in nanopaper for rlectrical actuation of shape-memory polymer

Haibao Lu, Harbin Institute of Technology (China)

In order to improve the through-thickness conductivity of few-layer graphene (FLG) in buckypaper, a unique synergistic effect of FLG and carbon nanofiber (CNF) was explored for the buckypaper enabled shape-memory polymer (SMP) composite. In the FLG/CNF buckypaper, FLGs were used to significantly improve the electrical conductivity along horizontal orientation, as well as CNFs were expected to bridge the gap between FLGs and improve the through-thickness electrical conductivity. Therefore, an entangled and continuous network of FLG and CNF was expected to synergistically enhance electrical performance of buckypaper. Furthermore, the ratio between FLG and CNF in the buckypaper was varied to characterize the efficiency in determining the electrical conductivity. Finally, the electrical actuation and optimization in temperature distribution of SMP composite have been testified experimentally by coating with the FLG/CNF buckypaper.

8689-50, Session PTues

Fabrication and characterization of shape-memory polystyrene foams

Yong Tao Yao, Harbin Institute of Technology (China)

Shape-memory polymer is a new type of smart materials, having attracted significant attention from researchers due to its excellent properties, such as the molding process are simple, light weight, large deformation, simple driving method, high reply rate, low manufacturing cost, and greatly adjustable properties. In this project, shape memory polystyrene foam was fabricated from shape memory polystyrene and sodium bicarbonate as chemical foaming agent based on suspension polymerization method. The foam of uniform pore structure with porosity ranging from 36%?45% have been made successfully. Both shape memory properties and physical properties were characterized. The highest mechanical property of SMP foam has been obtained as adding chemical foaming agent up to a maximum content of 8%wt. Shape memory polystyrene foam exhibited good shape memory properties--completely recovery the initial undeformed shape after multiple cycles. The higher thermal stability was achieved compared with pure shape memory polystyrene. The glassy state property of the foam was increased from 75°C to 85°C as the content of thickener increased from 0 to 30%.

8689-51, Session PTues

Comparative study of nanomaterials for interlaminar reinforcement of fiber-composite panels

Karen R. Chiu, Terrisa Duenas, NextGen Aeronautics Inc. (United States); Yuris A. Dzenis, Jase Kaser, Precision Nanotechnologies LLC (United States); Charles E. Bakis, Pennsylvania State Univ. (United States); Keith Roberts, Daniel Carter, U.S. Army Research, Development and Engineering Command (United States)

Carbon-fiber reinforced polymer (CFRP) composites offer the benefits of reduced weight and increased specific strength, however they can have relatively weak interlaminar toughness. The first modes of damage include delamination and micro-cracking, which can easily be initiated by low-velocity impact and often remain undetected since failure is not always visually apparent on the surface of composite materials. In this study, several nano-sized materials and integration approaches are investigated for their ability to improve Mode I interlaminar toughness. The nanomaterials include 1) commercially available surface-modified silica nanoparticles and 2) continuous polyacrylonitrile (PAN) nanofibers. Test articles are manufactured using hand-layup vacuum bagging and feature woven carbon-fiber material and an epoxy-based resin system. The nanosilica particles are integrated into the fiber composite structure by mixing with the resin system prior to layup. The PAN nanofibers are produced by an electrospinning process; these fibers were integrated by collecting the fibers of various areal densities as respective “nanomats” on an interim substrate for subsequent transfer during layup. Test articles are characterized according to ASTM D5528 for finding Mode I strain energy release rates. Results are compared to baseline coupons to determine fracture toughness performance. Preliminary results show that the nanosilica-reinforced coupons increased an average of 22% in strain energy release rate as compared to the baseline, whereas the nanomat-reinforced composites decreased. Current studies will focus on demonstrating improved strain energy release rate of composites reinforced with PAN nanofibers directly-deposited on the ply surface.

8689-52, Session PTues

Computational modeling of bio-mechanical behavior of microtubules

K. M. Liew, City Univ. of Hong Kong (Hong Kong, China)

This work proposed an atomistic-continuum computational model for the simulation of micro-mechanical behaviors of microtubules. As a typical kind of polyatomic bio-structures, a single long microtubule contains up to billions of different types of atoms. In order to understand the mechanical behavior of microtubules, conventional atomistic simulation approaches has obvious size limitations, traditional continuum mechanical models do not consider interatomic information in small scales. In this research, we aim to develop a more practical theory to consider this kind of polyatomic bio-structure with both result accuracy and computing efficiency. This approach involves a bridging-scales technique based on intrinsic interatomic potential and a continuum description method. The microscopic energy between proteins is evaluated using a homogenization technique. Without tracing every single atom, a fictitious bond is proposed in this research to represent the mutual interaction between proteins. By incorporating a higher-order Cauchy-Born rule, an atomistic-continuum constitutive relationship is established based on higher-order gradients continuum. The evaluation of strain energy in higher-order gradients continuum approach depends on both the first- and second-order deformation gradients and is determined by deformation of fictitious bonds. Further, a mesh-free computational framework is specifically developed to fit the higher-order scheme. The microscopic structure of microtubule and its macroscopic continuum counterpart are considered simultaneously by equalizing energy in both scales. With this attempt, different scales have been schematically bridged to smooth away drawbacks. Some practical applications, concerning elasticity, deformation and buckling of microtubules, are numerically simulated based on this model. Results are presented and discussed.

8689-53, Session PTues

Laser pinning of shape-memory alloy for controlling functional fatigue

Rajendra P. Prasath, Gopalkrishna M. Hegde, D. Roy Mahapatra, Indian Institute of Science (India)

In this study we present experimental results on the functional fatigue of NiTi thermal actuator wires modified by various conditions of laser pinning. Published literature indicates strong influence of surface annealing properties and oxide thickness on the defect nucleation mechanisms and functional fatigue of NiTi SMA materials. Hence laser pinning may be a useful way to alter defect nucleation and fatigue degradation. With this idea, we perform experiments which show interesting fatigue behavior. A pulsed laser with tunable wavelength and pulse shaping is used. Laser spot size and intensity are varied. Change in the hysteresis loop and the local critical temperatures are analyzed. Stress-temperature phase diagram are constructed which indicates shift in the transformation barriers as function of laser intensity and increasing number of pinning spots. Preliminary results are analyzed considering the possibility of using this technique to recover SMA actuation performance and functional healing against fatigue degradation.

8689-54, Session PTues

Nonlocal elasticity theory for lateral torsional buckling of nanobeam

Md Z. Islam, City Univ. of Hong Kong (Hong Kong, China)

In this study, the lateral torsional buckling instability of nanobeam is performed under the external bending moment, based on the nonlocal elasticity theory and thin beam theory. The total strain energy and work done for a nanobeam having doubly cross-sectional symmetry are derived and the variational energy principle is applied to derive the governing equation of equilibrium, equations of motion and the corresponding boundary conditions. In order to investigate the effect of nonlocal nanoscale, the derived equations of motion are solved for exact solutions and the critical instability buckling moments for various end constrains are presented and discussed in detail. It is observed from the analytical solutions that the critical buckling moment decreases with increasing nonlocal nanoscale. The conclusion is insightful with respect to the solutions of transverse bending and vibration of nanobeams and CNTs which insure that the stiffness of nanostructures softens in the presence of nonlocal nanoscale.

8689-55, Session PTues

Fatigue damage evaluation of plain woven carbon fiber reinforced plastic (CFRP) modified with MFC (micro-fibrillated cellulose) by thermo-elastic damage analysis (TDA)

Ryohei Aoyama, Doshisha Univ. (Japan)

Previous study experimentally showed the effect of the addition of MFC (Micro Fibrillated Cellulose) on the fatigue life of plain-woven CFRP (Carbon Fiber Reinforced Plastic) with the modified epoxy resin. However, the test results were not explained with clear understanding the damage process of the modified CFRP under fatigue loading. The aim of this study is to investigate characteristics of fatigue damage of CFRP modified with MFC by thermo-elastic damage analysis (TDA) under tensile cyclic loading. CFRP plates were prepared by conventional hand lay-up method with plain woven carbon fibers attaching the modified resin with commercially available MFC after eliminating 90wt% of contained water by ethanol substitution method.

Damage state of the specimen was observed in flat-wise direction of the specimen under cyclic loading by TDA subtracting images of thermo-elastic stress analysis (TSA). The results of micro droplet tests suggested that the improvement of fatigue life of CFRP should be contributed by the improvement of interfacial strength due to the modification. Characteristic damage progressions were certainly detected by the TDA method under cyclic loading. The result of TDA evaluation showed characteristic stage of damage progression was shifted to the middle of fatigue before fatal failure. This means that unstable damage progression would be prevented in the modified specimen due to gradual progression of fatigue damage. Fatigue life should be extended by the change of damage progression when CFRP was modified with MFC. Eventually, TDA was effective in evaluating the progress of fatigue damage of CFRP modified with MFC.

8689-56, Session PTues

Computational design of multifunctional composites made of shape-memory alloys and fibre-reinforced plastics

Björn Senf, Fraunhofer-Institut für Werkzeugmaschinen und Umformtechnik (Germany); Iñaki Navarro y de Sosa, Technische Univ. Chemnitz (Germany); Christoph Eppler, Holger Kunze, Fraunhofer-Institut für Werkzeugmaschinen und Umformtechnik (Germany)

Shape memory alloys (SMA) like NiTi posses a very high mechanical energy density in relation to conventional drives. Fibre reinforced plastics (FRP) will be increasingly applied to create lightweight structures. Combining both innovative materials will evolve synergy effects. Due to functional integration of SMA plates into a base of FRP it is possible to realize adaptive composites for resource-efficient constructions as for instance flaps or spoilers on cars. For this purpose the interaction between SMA as an actuator and FRP as a return spring need to be designed in a suitable way. The computation of such structures is complex because of its non-linear (SMA) and anisotropic (FRP) mechanical behavior. Therefore, a structural simulation model based on the finite element method was developed by means of the software ANSYS. Based on that simulation model it is possible to determine proper geometrical parameters for a composite made of SMA and FRP to perform a certain mechanism. The material properties of SMA or FRP could also be varied to investigate their influence. For exemplary components it could be shown that the stress-strain behavior is computable. Based on those results further and more sophisticated devices shall be calculated, too. This paper presents results of a research project that was supported by the “Sächsische Aufbaubank”. The project was realized in collaboration with the Institute of Lightweight Engineering and Polymer Technology (ILK) Dresden, Germany.

8689-57, Session PTues

Effects of transformation temperature in SMA wire-reinforced FRP composites

Shashishekarayya R. Hiremath, Rajendra P. Prasath, D. Roy Mahapatra, Indian Institute of Science (India)

Shape Memory Alloy (SMA) reinforced composite has been of interest

for quite some time, particularly in contexts morphing aircraft structures, flexible actuators and enhancement of impact energy absorption capacity in advanced composite structures. Embedding SMA wires in polymer based composites can be done for tailoring some of its effective properties such as to improve the impact strength. These composites can also be used for actuation purpose. One of the important aspects of using thermo-mechanically actuated SMA in polymer composites is the effect of its transformation temperature on the effective functional properties of the composite. This paper is aimed at understanding this effect in NiTi SMA composite considering various different grades of epoxy resin. Experiments are done by embedding the SMA wires with glass and carbon fiber reinforced composites. SMA wires with transformation temperature in the range of 70 to 120oC are used. Various different fiber orientations with respect to SMA wires are used in the specimens. These alter the polymer cure process and residual stress in the composites. For superelastic SMA wires, only residual stress is of importance when the cure temperature is below the austenite finish temperature. Due to elevated temperature of curing in superelastic wires, an annealing like condition reduces the original characteristics. On the other hand, in thermal actuator wires, a strongly coupled regime is analyzed where the curing temperature introduces a single cycle of spring loaded partial thermal actuation leading to two way shape memory effect. Various aspects of stress relief and performance issues are discussed.

8689-58, Session PTues

An effective theoretical approach to chemo-responsive shape-memory effect in polymers

Haibao Lu, Harbin Institute of Technology (China)

In this work we presented an effective theoretical approach to studying the state transition and working mechanism of chemo-responsive shape memory effect (SME) in polymers. The intrinsic plasticizing effect and generalized plasticizing effect were separated and qualitatively identified as the driving force for chemo-responsive SME in shape memory polymers (SMPs), in combination of the Gordon-Taylor (GT) theory and free-volume (FV) theory. Finally, the theoretical model had been testified and demonstrated to be well agreement with Gibbs-DiMarzio (GD) model and experimental results, respectively. With the estimated model parameters, we constructed the state diagram, which could provide a powerful tool for design and analysis of chemo-responsive SME in SMPs.

8689-59, Session PTues

Simulation and experiment research on smart metamaterial structures for wave isolation

Yun Li, Jiangsu Automation Research Institute (China)

This paper presents modeling and analysis methods for design of a smart metamaterial structure consisting of an isotropic beam and small spring-mass-damper subsystems for broadband absorption of transverse elastic waves. Two models of a unit cell are derived and used to demonstrate the existence of a stopband right to the high-frequency side of the local resonance frequency of spring-mass absorbers. A linear finite element method is used for detailed modeling and analysis of simply supported finite beams with different designs of absorbers. We show that the actual working mechanism is that, if the propagating elastic wave's frequency is within the absorbers' stopband, the wave resonates the integrated spring-mass absorbers to vibrate in their optical mode to create shear forces and bending moments to stop the wave propagation. We demonstrate that this unique phenomenon can be used to design broadband absorbers that work for elastic waves of short and long wavelengths. Numerical simulations validate the concept of broadband absorbers and reveal the cause of stopbands. Results show that different distributions of absorbers and their resonance frequencies result in different vibration isolation characteristics. With appropriate design optimization calculations, finite discrete spring-mass absorbers can be used, and hence expensive micro- or nano-manufacturing techniques are not needed for such metamaterial beams for broadband vibration absorption/isolation. At last we do experiment to verify the simulation result.

8689-60, Session PTues

A study of damping characteristics of alumina-filled epoxy nano-composites

Anand Kumar, Anand Kumar, Anand Kumar, Harcourt Butler Technological Institute (India); Priyanka Katiyar, Krishna Institute of Technology (India)

Damping behaviour of polymeric composites with nano structured phases is significantly different from usual polymer composites. Visco-elastic homo polymers exhibit high material damping over a relatively narrow range of temperature and frequency. In many practical situations, a polymeric structure is required to possess better strength and stiffness properties together with a reasonable damping behaviour. Visco-elastic polymers show higher loss factor beyond the glassy region which comes with a significant drop in the specific modulus. Addition of nano alumina particles to epoxy leads to improved strength and stiffness properties with an increase in glass transition temperature while retaining its damping capability. Experimental investigations are carried out on composite beam specimens fabricated with different compositions of alumina nano particles in epoxy to evaluate loss factor, tan ?. Impact damping method is used for time response analysis. A single point Laser is used to record the transverse displacement of a point on the composite beam specimen. The experimental results are compared with theoretical estimation of loss factor using Voigt estimation for visco-elastic nano composites. The effect of inter phase is included in theoretical estimation of loss factor. Passive vibration suppression may be introduced in the polymeric structures along with improved structural properties by tailored dynamic characteristics using nano alumina particles filled epoxy composites.

8689-61, Session PTues

Fundamental physics of IPMC transduction: mechanoelectrical voltage relaxation explained

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A physics based model of IPMC electromechanical and mechanoelectrical transduction was developed and validated. The model is general and based on the underlying physics of the phenomena – namely, the same set of equations and a common set of boundary conditions describe both transduction types. This is possible due to the fact that both electromechanical and mechanoelectrical transduction of IPMC are related to the ionic current inside the material. The main governing equations to describe the state of the ionic current are the Poisson's equation and the Nernst-Planck equation that are solved for free cations in the IPMC polymer backbone. The model also includes the electrodes of IPMC. Importance of the electrodes in the model is discussed. It is shown that the electrode effect on the electromechanical and mechanoelectrical transduction is different – they cause potential gradients in the former case and dissipate induced voltage in the latter case. A comprehensive mechanoelectrical transduction study is presented. The experiments showed that when the tip of an IPMC is subjected to a periodic or even ramp displacement, the induced voltage at the clamp peaks before the displacement. This indicates underlying voltage/charge relaxation. The developed IPMC transduction model captures this phenomenon. It is shown that the only way to describe it within the developed modeling framework is by considering anion concentration changes due to volumetric effects. Validation of the model is provided for different IPMC thicknesses and various applied deformation frequencies

8689-62, Session PTues

Thermoelectric properties of Al and Y-doped CaMnO3

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Thermoelectric materials can be used to covert heat energy into electrical energy directly via the Seebeck effect. The performance of a thermoelectric material is evaluated by the figure-of-merit $Z=\sigma\alpha2/\kappa$ where σ, α, and κ are the electrical conductivity, Seebeck coefficient, and thermal conductivity, respectively. Comparing with conventional thermoelectric materials such as metal chalcogenides, transition metal disilicides, and Si–Ge alloys, metal oxides have been recognized as good candidates for applications in thermoelectric power generation. The metal oxides show high thermal and chemical stability at high temperature in air, easy manufacture, and low manufacturing cost. In the present study, Al and Y were added, in an effort to improve the thermoelectric properties of CaMnO3. Doped CaMnO3 samples were fabricated by the solid-state reaction method. X-ray diffraction (XRD) and scanning electron microscope (SEM) were used to investigate the microstructure and crystal structure, respectively. The fabricated samples formed the perovskite structure with orthorhombic symmetry. The values of the Seebeck coefficients were all negative, indicating n-type conduction. The effect of the dopants was investigated by evaluating the microstructure and thermoelectric properties. We found that the addition of Al and Ye was effective for enhancing thermoelectric properties.

8689-63, Session PTues

Study on self-healing effect of concrete cracks based on microbial technique

Chunxiang Qian, Hui Rong, Southeast Univ. (China)

The self-healing effect of concrete cracks based on microbial technique were researched by the gauge for cracks width, scanning electron microscopy (SEM) and thermogravimetric analysis technology (TG) in this paper. The experimental results indicated that the concrete cracks could be fully filled by the microbial induced calcium carbonate precipitation afer cuing of 40 days. The quantities of microbial induced calcium carbonate reduced with the increasing of cracks depth. There was no calcium carbonate formation in the concrete cracks when the cracks depth is over 10 mm. In addition, the microorganisms could induce a large number of calcium carbonate formation away from the cracks surface of 1.5 mm. However, when the distance away from the cracks surface was over 1.5 mm, it could be found that the quantities of microbial induced calcium carbonate reduced with the incrasing of distance away from the cracks surface.

8689-26, Session 8

Shape-memory thermal lag and superelastic rate sensitivity of SMA cellular structures

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The use of shape memory alloys (SMAs) in thin-walled honeycomb structures is a relatively new approach to realize high performance, adaptive structures. Honeycomb specimens with a relative density near 5% have been fabricated from commercially available NiTi ribbon using a novel Nb-based brazing technique. Under in-plane compression, honeycombs take advantage of bending-dominated kinematics while shape memory alloys utilize a solid-to-solid state phase transformation, both of which result in enhanced recoverable deformation.

An experimental characterization of the thermo-mechanical responses of SMA honeycombs and corrugations is presented. Of particular interest are the shape memory cycle, the superelastic response, the shape memory thermal lag, the superelastic rate sensitivity, and effects of honeycomb geometry on performance. A series of in-plane compression experiments were performed on fabricated honeycombs and their responses are compared to typical monolithic SMAs, such as NiTi wire. It was found that NiTi honeycombs exhibit an order of magnitude increase in recoverable deformation, both in the shape memory effect and superelastic effect, in exchange for a reduced (homogenized) compressive stress by two orders of magnitude. Due to their sparse structure and enhanced heat transfer characteristics, SMA honeycombs exhibited less superelastic rate sensitivity by two orders of magnitude and a faster shape memory recovery by one order of magnitude than comparable NiTi wire. The implications of these scaling results will be discussed, including possible new regimes of application of SMAs for reusable energy absorption devices and high stroke actuators.

8689-27, Session 8

Fatigue properties of NiTi shape-memory alloy thin plates

Hiroshi Yamamoto, Minoru Taya, Yuanchang Liang, Onur C. Namli, Univ. of Washington (United States); Makoto Saito, Nabtesco Corp. (Japan)

Our research group focuses on novel actuators, such as some of FSMA actuators may use superelastic (SE) grade NiTi shape memory alloy (SMA) thin plates. The advantages of using SE-grade NiTi thin plates instead of general materials for actuators are its large strain capacity of over several percent and its superelastic behavior caused by stress-induced martensitic transformation. However, using the advantage of superelastic behavior of NiTi, the fatigue characteristics of NiTi plate in the large strain area is indispensable to design the actuators, since a significant reduction in fatigue life can be expected for large plastic strain, as a common knowledge of engineering materials. Very limited data exist in technical literatures on the fatigue strength and fatigue fracture mechanisms of NiTi thin plates since most research focuses on more common NiTi forms such as tubes or wires. This paper will present the relationship between the maximum bending strain and the number of cycles to failure as well as an analysis of the fatigue fracture surfaces of NiTi thin plates. The fracture surfaces were observed using a scanning electron microscope (SEM) to determine the fracture mechanisms and crack origins. In addition to the above, NiTi thin plates have oxide layers on the surfaces initially and the effect of these oxide layers on fatigue life will also be discussed.

8689-28, Session 8

Experiments on functional fatigue of thermally activated shape-memory alloy springs and correlations with driving force intensity

Ashwin Rao, Arun R. Srinivasa, Texas A&M Univ. (United States)

With growing applications of shape memory alloy (SMA) components in different engineering applications, the issue of material performance over its designed life is of great concern to researchers lately. Researchers have used traditional fatigue theories like S-N, e-N theories in analyzing fatigue response of SMA components that primarily focus only the mechanical loading with temperature being an external control parameter. Such an effort is suitable for superelastic responses but not shape memory responses. In this work, a concept of ``Driving force amplitude v/s no of cycles" will be proposed to analyze functional fatigue of SMA extension springs that can capture both mechanical and thermal loading in a single framework. A custom designed thermomechanical test rig is used to simulate shape memory effect by thermal cycling SMA springs held under constant deformation. For every thermomechanical cycle, load and temperature sensor readings are continually recorded as a function of time using LabVIEW software. The sensor data is used as inputs to the proposed functional fatigue model to capture ``Driving force

amplitude" variation over the specimen lifetime. In addition, fractographic analysis of the tested samples using SEM would provide deeper insights for designers in analyzing fatigue behavior of SMA springs.

8689-30, Session 9

Semi-empirical modeling of hysteresis compensation in magnetostrictive actuator

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Hysteresis causes a delayed response to a given input in a magnetostrictive actuator (MA). It becomes critical when the MA has to be controlled in precise and real-time mode. An efficient way to compensate hysteresis must be considered. The Jiles-Atherton and Preisach models have been applied mostly in the literature, but these models need complex mathematics that makes them difficult to be applied in precise and real-time mode. Thus, this paper presents a semiempirical modeling to compensate hysteresis in the MA.

The idea comes from the similarity of the shapes between the hysteresis-compensated input voltage to the MA, and the output voltage of R-C circuit. The respective hysteresis-compensated input voltage and R-C circuit are expressed as polynomial and exponential equations, resulting in two closed-form equations about capacitance. One set of capacitance values is selected for each frequency by simulating the derived equations. Experiments are performed to choose one capacitance value among a set of capacitance values from simulation, based on trial-and-error. The concept of the hysteresis loss is introduced and defined as the ratio of areas between the hysteretic and reference curves. From the experimental results, it is observed that the percent change of hysteresis loss increases as the frequency increases up to 400 Hz, but decreases with further increase of the frequency up to 800 Hz.

It can be concluded that the proposed approach is effective to compensate hysteresis in the MA. Also, it can be concluded that hysteresis loss definition introduced by us can be used as a helpful measure of hysteresis compensation.

8689-31, Session 9

Characterization and finite element modeling of Galfenol minor magnetization loops

Zhangxian Deng, Marcelo J. Dapino, The Ohio State Univ. (United States)

Magnetostrictive gallium-iron alloys, known as Galfenol, are a recent class of smart materials that are promising for sensing and actuation applications. To optimize Galfenol performance in applications, a system level model combining constitutive Galfenol modeling and passive components is essential.

Evans and Dapino proposed a high accuracy, computationally efficient model which uses energy averaging (EA) considering local energies near Galfenol's six easy crystallographic directions, and incorporated this model into a finite element framework applicable to 2-D static hysteretic systems. Chakrabarti and Dapino extended this framework to 3-D static and dynamic responses without hysteresis.

To overcome this limitation, a 3-D hysteretic FEA model is presented in this study. For this geometry, the air gap between the flux return path and Galfenol rod is taken into consideration to eliminate flux concentrations. For the internal configuration of this set-up, the model will switch from hysteretic to anhysteretic mode when the flux density reaches the elbow of the magnetization versus field curve. In this study, both the SR1 method and the Trust-Region-Reflective (TRR) method are used. The hysteretic property in the EA model is described in an incremental form which maintains its accuracy only for small input increments. The SR1 method sometimes converges to a solution having large input increments, but the TRR method is more appropriate because of its user-defined minimization bounds.

Simulation results are compared with minor loops measurements of <100> oriented textured polycrystallineFe_18.4 Ga_81.6. To accelerate the computations, the anhysteretic model first drives the model to the bias position before the hysteretic simulation of minor loops starts.

8689-32, Session 9

Effects of low-magnetic field on the electrical resistivity and piezoresistivity of Ni-CNT filled epoxy-based composites

Huigang Xiao, Jinbao Jiang, Hui Li, Harbin Institute of Technology (China)

The effects of low magnetic field on the electrical properties of nickel-coated carbon nanotubes (Ni-CNTs) filled epoxy-based composites were investigated in this paper. A set of Helmholtz coils was employed to generate an uniform magnetic field for aligning the Ni-CNTs. The Ni-CNT dispersed epoxy resin, using Ni-CNTs in the amount of 2.0 vol.%, was first prepared by combined high-speed stirring and sonication methods. Then, the Ni-CNT dispersed epoxy resin was cast into an aluminum mold to form specimens measuring 10?10?36 mm. During the curing procedure of the epoxy resin, various magnetic fields (50Gs and 150Gs) were applied along directions parallel and transverse to the longitudinal axes of the specimens. After curing, DC electrical resistance measurements were performed along the longitudinal axis using the four-probe method, in which copper nets served as electrical contacts. Experimental results show that the employed low magnetic fields can effectively improve the electrical conductivity of the composites in the direction of paralleling the magnetic field. The relationship between the resistivity and the magnetic field strength was obtained as almost a straight line in the low zone, indicating that such low magnetic fields could induce an orientation of Ni-CNTs in the composites. The piezoresisitivity of such Ni-CNT filled epoxy-based composites was also studied. Compressive testing of these specimens was conducted using a Materials Testing System. The experimental results showed the strain gauge factor of the specimen increased upon the magnetic filed, i.e. the piezoresistivity of the composite was improved by aligning the Ni-CNTs in a preferred direction.

8689-33, Session 10

A two species thermodynamic preisach approach for superleastic shape-memory alloys under tension, torsion, and bending loading conditions

Ashwin Rao, Arun R. Srinivasa, Texas A&M Univ. (United States)

Modeling superelastic behavior of shape memory alloys under different loading conditions has received considerable attention lately. In this work, a simple mechanics of materials modeling approach for simulating responses of superelastic shape memory alloys (SMA) components under tension, torsion and bending loading conditions is developed. Following Doraiswamy, Rao and Srinivasa's approach (Smart Materials and Structures, 2011), the key idea here would be in separating the thermoelastic and the disspiative part of the hysteritic response with a Gibbs potential based formulation which includes both thermal and mechanical loading in the same framework. The dissipiative part is then handled by a discrete Preisach model. The model is formulated based on experimentally measurable quantities like tensile stress--strain, torque--angle of twist or bending Moment--curvature rather than solving for non-homogeneous stress and strains across the specimen cross-sections

and then integrating the same especially for bending and torsion loading conditions. The model is capable of simulating complex superelastic responses with multiple internal loops and provides an improved treatment for temperature dependence associated with superelastic responses. The model results are verified with experimental results on SMA components at different temperatures.

8689-34, Session 10

A three species thermodynamic preisach approach for simulating complete torsional response of shape-memory alloys

Ashwin Rao, Arun R. Srinivasa, Texas A&M Univ. (United States)

The focus on understanding the torsional response of shape memory alloy (SMA) components has been of keen interest as SMA springs have found many engineering applications. In this work, a three species model is proposed to capture the complete torsional response of SMA components. The three species corresponds to volume fractions of austenite and two martensite variants. Extending Doraiswamy, Rao and Srinivasa's approach (Smart Materials and Structures, 2011), a Gibbs potential based formulation that combines both thermal and mechanical loading for all the three species is developed. The model is formulated directly in terms of experimentally measurable quantities torque--angle of twist rather than solving for these using non-homogeneous shear stress across the specimen (i.e generally by integrating stress resultants). The key idea would be in separating the elastic and dissipiative parts of the response and using a discrete Preisach model to capture the dissipiative part of the response. Such an approach can simulate both superleastic and shape memory response under clockwise and anticlockwise torsional loading cases. The model can be used to estimate the strokes at different temperatures. The model results are verified with the available experimental data in the literature.

8689-35, Session 10

Modeling the magneto-mechanical behavior of MSMAs subject to general 2D and 3D loadings

Douglas H. LaMaster, Heidi Feigenbaum, Constantin Ciocanel, Isaac Nelson, Northern Arizona Univ. (United States)

Magnetic Shape Memory Alloys (MSMAs) are a type of smart material that exhibit a large amount of recoverable strain when subjected to an applied compressive stress in the presence of a magnetic field or an applied magnetic field in the presence of a compressive stress. These macroscopic recoverable strains are the result of the reorientation of martensite variants. Potential applications for MSMAs include power harvesters, sensors, and actuators. For these applications, the stress is assumed to be applied only in the axial direction, and the magnetic field is assumed to be applied only in the transverse direction.

To realize the full potential of MSMA and optimized designs, a mathematical model that can predict the material response under all potential loading conditions is needed. Keifer and Lagoudas developed a phenomenological model that characterizes the response of the MSMA to axial compressive stress and transversely applied magnetic field from thermodynamic principles. In this paper, a similar thermodynamic framework is used, however, a simpler hardening function is proposed based on the idea that the reorientation phenomenon is the same in both forward and reverse loading and in both magnetic and mechanical loading. This simplified model is shown to adequately predict the magneto-mechanical response of the MSMA in 2D loading, i.e. axial compressive stress and transversely applied magnetic field. Furthermore, based on the idea that the reorientation phenomenon should be the same in any direction, this simpler hardening function provides a basis for a rudimentary 3D model of MSMAs.

8689-36, Session 10

Magnetic field and stress-induced phased transformation in single crystalline of NiMnCoIn metamagnetic shape-memory alloys

Peizhen Li, Haluk E. Karaca, Ali S. Turabi, Hirobomi Tobe, Univ. of Kentucky (United States)

Magnetic shape memory alloys have attracted a great deal of attention due to their high frequency response and high actuation strains for sensors, actuators and energy harvester applications. NiMn-based metamagnetic shape memory alloys have ferromagnetic austenite and paramagnetic martensite phase and exhibit large magnetostress levels.

In this study, magneto-thermo-mechanical experimental results of NiMn-based metamagnetic shape memory alloys including shape memory effect under constant stress and magnetic field and isothermal stress cycling under magnetic field will be presented. It will be shown that magnetostress levels are linearly dependent on applied field and NiMn-based alloys can be used as high temperature magnetic actuators.

8689-37, Session 10

Thermal response of infinitely extended layered Nickel-Titanium shape-memory alloy thin films with variable material properties

Abhijit Bhattacharyya, Mehmet M. Ozturk, Univ. of Arkansas Little Rock (United States)

A Shape Memory Alloy (SMA) thin film is an important candidate for the fabrication of micro actuators. Its shape memory effect (SME) is due to a solid–solid phase transformation between a high temperature phase of austenite and a low temperature phase of austenite. The phase transformation is also accompanied by a change in material properties. Thus, for example, the thermal conductivity, electrical resistivity and heat capacity areal change with temperature hysterically. Further, research reported in the literature has shown that these films have a layered structure – amorphous layer, non-transforming austenite layer and phase transformation layer – with the amorphous layer being adjacent to the substrate. While thermal studies of thin films have a rich history in the literature, such studies for shape memory alloys with variable material properties and layered structure are sparse and need to be carried out in order to have an accurate understanding of the thermal response of SMA thin films.

In this study, an infinitely extended, 3-layered NiTi SMA thin film is modeled and analyzed with commercially available finite-element software ANSYS. The temperature variation of the 3 layered thin film is investigated under the following conditions: convective cooling on the free surface, adiabatic boundary condition on the bottom surface (at the interface with the substrate) and uniform heat source. The steady state response is validated by comparison with analytical results. The thermal response of the film during a cycle of heating and cooling is also compared with the thermal response of a single layered phase transforming SMA thin film.

8689-38, Session 11

Sensing of retained martensite during thermal cycling of shape-memory alloy wires via electrical resistance

Christopher B. Churchill, HRL Labs., LLC (United States)

Shape memory alloys (SMAs) remain one of the most viable active materials, thanks to their high energy density and the wide availability of high quality material. Still, significant challenges remain in predicting

the degradation of SMA actuators during thermal cycling. One of the challenges in both the motivation and verification of degradation models is the measurement of retained martensite fraction during cycling. Direct measurement via diffraction is both impossible for thin wires (<0.5mm) and prohibitively difficult for long (10000+) cycle lives.

We investigate the use of electrical resistivity to indirectly measure the evolution of retained martensite during thermal cycling of SMA wires via joule heating. Heat transfer in the wire is carefully controlled to enable temperature prediction without direct measurement. Two different resistivity features, one absolute and one derivative-based, are compared.

8689-39, Session 11

Thermo-mechanical self-adaptive ball screw drive using thermal shape-memory effect

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Ball screw drives (BSD) are conceivably the most widespread type of lead screw drives used in industrial machinery like machine tools or measuring equipment. They convert rotatory into linear motion and possess high efficiency, repeatability and life expectancy. In order to remove the inherent axial backlash and to reduce the axial displacement due to material elastic deformation, BSDs are preloaded. Depending on the processing status, there are two preload-depending requirements: high positioning accuracy high feed rate. However, both of them are not simultaneously feasible because of their mutual dependence. In long term, preloading likewise affects heat generation and thus varies the preload.

Shape memory alloys (SMA) directly transform thermal energy into mechanical energy by generating work output with high power/weight ratios. Using the heat generated by the process as thermal source, enables to implement SMA actuators in BSDs to change the preload during operation. In this case, the SMA actuator works as an energy harvester and the system is self-sufficient.

In this paper we present a self-adaptive BSD based on SMAs that is able to adjust the preload whilst processing. According to the temperature of the surrounding material, the actuator either expands or contracts to increase or decrease the preload. For this purpose, no external energy and control is required. Using the investigated principles, adaptive mechanisms to adjust the BSD´s preload has been developed and compared. The preferred approach has been designed and investigated to verify the system capabilities.

8689-40, Session 11

Assessing local strain in NiTi-scaffolds prepared by selective laser melting

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The biocompatible NiTi is a promising material for bone implants as it combines low stiffness with high strength. Furthermore, it exhibits properties including pseudoelasticity, the one-way shape memory effect and high damping capacities caused by a reversible crystalline transformation between austenite and martensite. The mechanical stimulation of bony tissues enhances re-modeling and therefore osseointegration. In porous scaffolds both tensile and compressive microstrains simultaneously occur when compression load is applied. The cells might therefore behave in different fashions depending on their location within the scaffold. As a consequence we evaluated the local stains in a scaffold during heating taking advantage of synchrotron-based micro computed tomography (SRµCT) and sophisticated software tools for non-rigid registration.

Lattice-shaped scaffolds with 300 µm thin struts exhibiting the shape memory effect were fabricated from pre-alloyed NiTi powder by selective laser melting. During the SRµCT measurement, the deformed scaffold was subjected to a temperature ramp inducing the shape memory effect. By non-rigid registration of the three-dimensional µCT datasets at different time and temperature points, respectively, the local deformations generated during the shape recovery process were identified. The scaffold exhibited tensile and compression strains of up to 4% in the junction point of the struts, even if the scaffold was subjected to a compressive deflection of 3.25% of its total height.

This permits a better estimation of strains acting on cells in a shape memory scaffold. The data will support the search for optimized scaffold and implant designs that mechanically stimulate bony cells.

8689-41, Session 11

Lagoudas model for optomechanical mountings: parametric study and characterization campaign

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This paper wants to show the work developed in the framework of Smart structures for Astronomical Instrumentations. In particular it is focused onto the modeling and characterization of Shape Memory Alloy (SMA) as functional devices for opto mechanical mountings. In this activity the pseudo elastic effect has been exploited. When mechanically loaded, a pseudo-elastic alloy deforms reversibly to very high strains - up to 6-8% - by the creation of a stress-induced phase. When the load is removed, the new phase becomes unstable and the material regains its original shape. Thanks to this feature, these materials can be positively exploited in opto mechanical mounts to provide enough mechanical stability to the optical element by absorb the structure Vs glass CTE mismatching. The flexure kinematic mounting configuration has been studied by comparing traditional stainless steel flexure w.r.t. pseudo elastic alloys. This paper mainly address the numerical work done with the Lagoudas SMA constitutive model. A parametric study has been conducted to understand in detail the real effect of each parameter to the material performances (stress-strain temperature dependent curve). A deep characterization campaign has been done in order to be able to deploy a reasonably representative modeling technique. A dummy opto mechanical mounting has been realized, thermally cycled and monitored in order to validate the numerical results.

8689-42, Session 11

Thermo-mechanically coupled analysis of shape-memory alloy plates

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Use of shape memory alloy (SMA) in bulk form like plate, films and cables is finding increased attention for various industrial applications. This motivates development of a finite element (FE) formulation which suitably couples the multiple physics involved in SMA, viz. thermal and mechanical boundary value problem with multi-axial loading. In the present work a two-dimensional macroscopic thermo-mechanical FE procedure for SMA plate is obtained by using plane stress assumption. Square plate with and without hole is analyzed under uniaxial tensile loading, biaxial tensile loading and shear loading. In case of plate without hole under shear loading an inhomogeneous distribution of

martensite fraction is obtained and their spatial and temporal variations are discussed. The self heating effect due to exothermic release enthalpy of phase transformation is shown. Coupled analysis shows a zone of untransformed austenite in between two zones of completely detwinned martensite which suitably brings out its efficacy. Next analysis of plate with a notch is attempted which shows a qualitative distribution of strain similar to as experimentally obtained by Daly et. al. (2007). This suggests that the present multiphysics simulation of SMA can be very useful in understanding the intricate mechanics and physics of this material.

8689-43, Session 12

The challenges of achieving good electrical and mechanical properties when making structural supercapacitors

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The paper discusses the challenges associated with the development of carbon fiber structural supercapacitors to exhibit, simultaneously, good electrical and mechanical properties. The properties of interest are capacitance per unit volume, leakage resistance, electrical series resistance (ESR), tensile strength and flexural strength. Ideally, one would aim for the highest possible capacitance, leakage resistance as well as tensile and flexural strength, and the smallest possible (ideally zero) ESR. The key constituent influencing these properties is the electrolyte. A number of chemical compositions of the solid polymer electrolytes used to date are discussed together with their impact on the overall material properties. To this end, the results indicate that the solid nature of the electrolyte used to fabricate the supercapacitor requires that a compromise be made with respect to which electrical and mechanical property to be maximized.

8689-44, Session 12

Aligned nanowire-graphene aerogel for lithium-ion battery

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Lithium ion battery (LIB) has been receiving extensive attention due to its high specific energy density for wide applications such as electronic vehicles, mobile electronics, and military applications. In LIB, graphite is the most commonly used material as anode materials; however, graphite has limited lithium ion intercalation property which hinders battery charge rate and capacity. To overcome this obstacle, nanostructured carbon anode assembly has been extensively studied to increase the lithium ion diffusion rate. Among these approaches, high specific surface area metal oxide nanowire connecting with nanostructured carbon based material has shown propitious results for enhanced lithium intercalation. More recently, nanowire/graphene hybrids have been developed for the enhancement of LIB performance; however, all previous efforts employed nanowires on graphene in a random fashion, which results in limited lithium ion diffusion rate. Therefore, we demonstrate a new approach by growing aligned nanowire on graphene aerogel to further improve the LIB performance. This nanowire/graphene aerogel hybrid not only uses the high surface area of the graphene aerogel but also increases the specific surface area for electrode-electrolyte interaction. Therefore, this new nanowire/graphene aerogel hybrid anode material could enhance the specific capacity and charge-discharge rate. Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD) and Atomic Force Microscopy (AFM) are used for materials characterization. Battery Analyzer and Potentio-galvanostat are used for measuring electrical performance of the battery. The testing results show that with vertically aligned metal oxide nanowires, the LIB performance has been significantly improved compared to those with random nanowires.

8689-45, Session 12

Environmental degradation of nano-enhanced composite materials through durability and electrical resistance measurements

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Nanoreinforced epoxies as well as Carbon Fibre Reinforced Composites with nanoreinforced matrix were studied in terms of their durability in hydrothermal loading and thermal shock. For the purposes of this study, dynamic mechanical analysis and mechanical testing were employed in conjunction with the electrical resistance change method. 0.5 % by weight Carbon Nanotubes was employed as nanoreinforcement. The employed material properties were measured at specific intervals of the hydrothermal loading and after cyclic thermal shock. The change in the interlaminar shear strength of the CFRPs was also examined.

8689-46, Session 13

A finite element modeling of a multifunctional hybrid composite beam with viscoelastic materials

Ya D. Wang, Daniel J. Inman, Univ. of Michigan (United States)

Functionally graded hybrid composites are emerging as a potential solution to lightweight skins for aircraft that will operate in extreme conditions and hence will need to combine the best attributes of ceramics, metals and polymer composites. The multifunctional hybrid composite structure studied here consists of a ceramic outer layer capable of withstanding high temperatures, a functionally graded ceramic layer combining shape memory alloy (SMA) properties of NiTi together with Ti2AlC (called Graded Ceramic/Metal Composite, or GCMeC), and a high temperature sensor patch, followed by a polymer matrix composite laced with vascular cooling channels all held together with various epoxies. The key effect to model this multifunctional hybrid composite structure is the vibration properties. Due to the recoverable nature of SMA and adhesive properties of Ti2AlC, the damping behavior of the GCMeC is largely viscoelastic. This paper presents a finite element formulation for this multifunctional hybrid structure with embedded viscoelastic material. In order to implement the viscoelastic model into the finite element formulation, a second order three parameter Golla-Hughes-McTavish (GHM) method is used to describe the viscoelastic behavior. Considering the parameter identification, a strategy to estimate the fractional order of the time derivative and the relaxation time is outlined. Curve-fitting aspects are focused, showing good agreement with experimental data. Numerical simulation is carried out to predict its damping behavior and vibration property. Various effects such as geometric and mechanical factors have on the dynamic response are discussed for this multifunctional hybrid structure.

8689-47, Session 13

Acoustic impedance matching using dynamic homogenization

Hossein Sadeghi, Ankit Srivastava, Siavouche Nemat-Nasser, Univ. of California, San Diego (United States)

In this paper we present a new method for designing materials which are acoustically impedance matched with homogeneous materials at any desired frequency. We use dynamic homogenization of periodic composites to calculate their effective dynamic acoustic impedance (EDAI). We show that by using dynamic homogenization the microstructure of a periodic composite can be designed so that its EDAI matches the impedance of a desired homogeneous material at a desired frequency. Consequently, the reflection at the interface of such

a periodic composite with the homogeneous material is minimized. We present transfer matrix calculation and finite element modeling of wave propagation through a finite layered periodic composite made of steel and PMMA in contact with homogenous semi-infinite Aluminum bars on either ends of the composite. We show that the steel/PMMA composite which has matched impedance with Aluminum at 300 kHz minimizes the reflection at its interface with the homogeneous Aluminum bars. Also, it is shown that not only does the designed composite minimize the reflections at the interface, but it also attenuates the wave propagating through it. This property suggests the potential application of this method to design for materials which may be used for transducers backing.

8689-48, Session 13

Modifying the acoustic impedance of polyurea-based composites

Wiroj Nantasetphong, Alireza V. Amirkhizi, Zhanzhan Jia, Siavouche Nemat-Nasser, Univ. of California, San Diego (United States)

Acoustic impedance is a material property that depends on mass density and acoustic wave speed. An impedance mismatch between two media leads to the partial reflection of an acoustic wave sent from one medium to another. Active sonar is one example of a useful application of this phenomenon, where reflected and scattered acoustic waves enable the detection of objects. If the impedance of an object is matched to that of the surrounding medium, however, the object may be hidden from observation (at least directly) by sonar. In this study, polyurea composites are developed to facilitate such impedance matching. Polyurea is used due to its excellent blast-mitigating properties, easy casting, corrosion protection, abrasion resistance, and various uses in current military technology. Since pure polyurea has impedance higher than that of water (the current medium of interest), low mass density phenolic microballoon particles are added to create composite materials with reduced effective impedances. The volume fraction of particles is varied to study the effect of filler quantity on the acoustic impedance of the resulting composite. The composites are experimentally characterized via ultrasonic measurements. Computational models based on the method of dilute-randomly-distributed inclusions are developed and compared with the experimental results. These experiments and models will facilitate the design of new elastomeric composites with desirable acoustic impedances.

8689-49, Session 13

Ultrasonic studies of fly ash/polyurea composites

Jing Qiao, Harbin Institute of Technology (China); Alireza V. Amirkhizi, Siavouche Nemat-Nasser, Univ. of California, San Diego (United States); Gaohui Wu, Harbin Institute of Technology (China)

Due to the excellent thermo-mechanical properties, polyurea is attracting more and more attention in blast-mitigating applications. In order to enhance its capability of blast-induced stress-wave management, we seek to develop polyurea-based composites in this work. Fly ash which is a kind of hollow particles with porous shell and low density was chosen as fillers and a series of fly ash/polyurea composites with various fly ash volume fractions were fabricated. The dynamic mechanical behavior of the composites was determined by a personal computer (PC) based ultrasonic system in the 0.5-2MHz frequency range between -60ºC to 30ºC temperatures. Velocity and attenuation of both longitudinal and shear ultrasonic waves were measured. The complex longitudinal and shear moduli were then computed from these measurements. Combining these results provided an estimate of the complex bulk and Young's moduli of the fly ash/polyurea composites at high frequencies. These results will be presented and compared with those of pure polyurea elastomer.

Sunday - Thursday 10–14 March 2013

Part of Proceedings of SPIE Vol. 8690 Industrial and Commercial Applications of Smart Structures Technologies 2013

8690-1, Session 1

Active structures to reduce torsional vibrations

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In the past years a lot of investigations were done to develop new concepts for active measures to reduce the transmission of noise and vibrations in engine mounts, dampers or coupling elements like eg. bearing, fasteners and so on.

All these measures are based on the three physical principles vibration compensation, vibration damping, or vibration isolation.

In general, vibration absorbers and vibration neutralizers are applied for the purpose of vibration compensation. An example for a vibration isolation device is an elastic mount.

Other concepts based on inertial mass actuators, are generating additional forces at appropriate locations. Depending on the control strategy an inertial mass actuator can be used for compensation or vibration damping concepts. The additional forces are controlled with respect to frequency, phase, and amplitude in such a way that they counteract the unwanted excitation and, therefore, significantly reduce the overall vibration.

Most of these concepts can be implemented as passive (no additional energy required), active (require additional energy, e.g., electric or magnetic energy), or even adaptive (adapt automatically to varying conditions) devices.

Some of them are based on innovative mechatronic add-on concepts; others are directly integrated into the mechanical load path and thus are based on adaptronic (i.e., smart structure) concepts. Both approaches allow using smart materials or mechatronic devices as sensors and/or actuators. Both, the potential level of noise and vibration reduction and the resulting system complexity (e.g., development, component, and system costs) depend, among other factors, strongly on the particular vibration source (kind of the engine), its operational conditions and so on.

The results of these investigations had shown the big potential of active measures in noise and vibration reduction. Some products based on these investigations are already available in commercial applications.

Another potential application for measures of active vibration reduction is to reduce torsional vibrations eg. in the power train of cars, ships or in tooling machines. Therefor the different concepts based on the physical principals behind active mounts were transmitted into concepts for rotational systems.

To show their mode of operation to influence the torsional vibrations these concepts were implemented in numerical models of powertrains. First experimental test with rotational absorbers and rotational inertial mass actuators on a reduced power train were done to align the numerical models.

The paper shows results of numerical and experimental simulations using different concepts to reduce torsional vibrations in power trains.

8690-2, Session 1

Magnetostrictive aluminum composite with electrically tunable stiffness

Justin Scheidler, Marcelo J. Dapino, The Ohio State Univ. (United States)

This paper details the development of metal-matrix composites containing active magnetostrictive elements manufactured by ultrasonic additive manufacturing (UAM). UAM is an emerging solid-state welding process that creates metallurgical bonds between metal foils at temperatures that peak at less than 35% of the foil melting points. UAM therefore offers the unique opportunity to seamlessly embed a wide range of temperature sensitive smart materials. The composites in this study contain an aluminum matrix and an embedded Galfenol element. Galfenol (Fe100-xGax) is a magnetostrictive material with structural strength comparable to steel and a magnetic field and mechanical stress-dependent stiffness. Modal analysis of the composite was conducted to understand the effect of the variable Galfenol stiffness on the composite behavior. Shifts in modal frequencies as a function of applied magnetic field for a cantilevered, proof-of-concept composite were measured. Natural frequency shifts up to 1.4% were measured for applied magnetic fields up to 17.8 kA/m. To improve the stiffness tuning effect, a parametric study on the effect of Galfenol volume fraction and composite layup I conducted by modeling the composite in a multiphysics FE simulation. An increase in the natural frequency shifts with increasing Galfenol volume fraction is observed, and an optimal composite layup I identified. The stiffness tuning effect is nonlinear, with dependence on the excitation force amplitude and vibration mode considered. From the simulation results, a composite optimized for active stiffness tuning was manufactured using UAM. The optimized composite shows a threefold increase in modal frequency shifts compared to the proof-of-concept.

8690-3, Session 1

Active damping for wind-tunnel aeroelastic models of large civil structures

Gabriele Cazzulani, Francesco Ripamonti, Daniele Rocchi, Tullio Balduzzi, Politecnico di Milano (Italy)

Structures aero-elastic models are reduced-scaled models designed to reproduce the dynamic behavior of the real system under the wind action. Typically the aim of these models is the evaluation of the wind-structure coupling effects, which can generate high vibrations or structural instability.

Structural damping is one of the most important parameters able to affect these phenomena. In particular an increase of structural damping strongly reduces (or even cancels out) the vibrations induced by these coupling effects. For this reason wind tunnel tests on aero-elastic models want to define the minimum structural damping so that wind-induced vibrations are lower than an imposed limit. This value is then used to design proper damping devices (such as TMDs) for the full-scale structures.

During the test stage the aero-elastic models damping increase is usually obtained applying damping elements or connecting external passive dampers to the structure. Anyway, these solutions make the tuning of the structural damping difficult. Moreover, these elements can modify the dynamic behavior of the structure in terms of natural frequencies and modal shapes.

For all these reasons, the present work proposes different solutions, based on active control, to modify the damping of wind-tunnel aero-elastic models. These solutions, described in detail in the paper, are experimentally tested on a 1:100 aero-elastic model of a bridge tower, showing the possibility to tune the model damping with high precision and repeatability. The results achieved with these active logics are compared with those obtained considering the standard methods.

8690-4, Session 1

Miniature multifunctional high-performance three-axis positioning and scanning platform

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This study proposes a novel concept for a three-axis positioning and scanning platform that overcomes the existing gap in technology towards meeting the requirements for displacements, resolution, weight carrying capacity and velocity at smaller dimensions. The novelty of this work stems from the fact that our three-axis stage design utilizes only two actuators. This system was developed to meet the specific requirements needed for implementation of Multifunctional Image Guided Surgical (MIGS) platform. Mathematical model accounting for the open and closed loop operation of the stage was developed. The stage can provide displacements between 10-20mm in each axis, resolution of less than 10μm and scanning velocity in the range of 10-40mm/s. It can carry weights up to 10grams while meeting the desired requirements. Additionally, the stage has small footprint (50mm x 50mm x 34mm), modular design and extremely cost-effective fabrication. Integration of computer controlled three-axis stage with MIGS platform will provide the opportunity for conducting intricate surgical procedures using remote control or joystick. We demonstrate novel applications that became possible due to the development of this stage.

8690-5, Session 2

High-strain measurement using fiber Bragg grating sensors

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Fiber Bragg Grating-based (FBG) strain sensor has been widely used in engineering application due to its small size, light weight, amenability to multiplexing, and high sensitivity. It is capable of measuring as low as submicrostrain and as high as 1% strain in tension and higher under compression. In this paper, we will discuss the development of FBG based real-time instrumentation system to conduct high strain measurement during an impact. A high speed FBG interrogation system is designed with streamlining FBG sensor data analysis capability for efficient post processing. In order to capture high strain data during an impact event, we need to increase strain measurement capability of an FBG sensor and simultaneously maintain its survivability. A high strain FBG fixture is designed accordingly using a lumped parameter model. Our high strain fixture allows the FBG strain sensor to measure the actual field strain with a reduction factor. A K-factor is defined to relate the FBG strain measurement to the actual field strain value. Numerical simulation results using finite element analysis (FEA) are used to validate the high strain fixture design. Finally, a proof-of-concept FBG-based high strain measurement system is developed. Both static and dynamic impact tests are conducted to collect strain measurements. These strain data are used to validate our fixture design as well and good correlation is achieved.

8690-6, Session 2

Three-axis distributed fiber optic strain measurement in 3D woven composite structures

Matt Castellucci, Evan M. Lally, Sandra Klute, Luna Innovations Inc. (United States); David Lowry, NASA Johnson Space Ctr. (United States)

Recent advancements in composite materials technologies have broken further from traditional designs and require advanced instrumentation and analysis capabilities. Success or failure is highly dependent on design analysis and manufacturing processes. By monitoring smart structures throughout manufacturing and service life, residual and operational stresses can be assessed and structural damage identified. Composite smart structures can be manufactured by integrating fiber optic sensors into existing composite materials processes such as layup, filament winding and three-dimensional weaving. In this work optical fiber was integrated into 3D woven composite parts at a commercial woven products manufacturing facility. The fiber was then used to monitor the structures during a VARTM manufacturing process, and subsequent static and dynamic testing. Low cost telecommunications-grade optical fiber acts as the sensor using a high resolution commercial Optical Frequency Domain Reflectometer (OFDR) system providing distributed strain measurement at spatial resolutions as low as 2mm. Strain measurements using the optical fiber sensors are correlated to resistive strain gauge measurements during static structural loading.

8690-7, Session 2

Powering embedded electronics for wind-turbine monitoring using multi-source energy harvesting techniques

Steven R. Anton, Stuart G. Taylor, Eric Y. Raby, Los Alamos National Lab. (United States); Kevin M. Farinholt, Commonwealth Ctr. for Advanced Manufacturing (United States)

With a global interest in the development of clean, renewable energy, wind energy has seen steady growth over the past several years. Advances in wind turbine technology bring larger, more complex turbines and wind farms. An important issue in the development of these complex systems is the ability to monitor the state of each turbine in an effort to improve the efficiency and power generation. Wireless sensor nodes can be used to interrogate the current state and health of wind turbine structures, however, a drawback of most current wireless sensor technology is their reliance on batteries for power. Energy harvesting solutions present the ability to create autonomous power sources for small, low-power electronics through the scavenging of ambient energy, however, most conventional energy harvesting systems employ a single mode of energy conversion, and thus are highly susceptible to variations in the ambient energy. In this work, a multi-source energy harvesting system is developed to power embedded electronics for wind turbine applications in which energy can be scavenged simultaneously from several ambient energy sources. Field testing is performed on a full-size, residential scale wind turbine where both vibration and solar energy harvesting systems are utilized to power wireless sensing systems. Two wireless sensors are investigated, including the wireless impedance device (WID) sensor node, developed at the Los Alamos National Laboratory, and an ultra-low power RF system-on-chip board that is the basis for an embedded wireless accelerometer node currently under development. Results indicate the ability of the multi-source harvester to successfully power both sensors.

8690-8, Session 2

Multi-source energy harvesting for wireless SHM systems

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In wireless SHM systems, energy harvesting technology is essential for a reliable long-term energy supply for wireless sensors. Conventional wireless SHM systems using single source energy harvesting (vibration, solar, and etc.) have limitations because it could not be operated adequately without enough ambient energy present. To overcome this obstacle, multi-source energy harvesting which utilizes several ambient energy sources simultaneously is necessary to accumulate enough electrical energy to power wireless embedded sensor nodes. This study proposes a multi-source energy harvesting technique using a MISO (Multiple Input, Single Output) circuit board developed and studied by the authors. For multi-source energy harvesting, piezoelectric bimorph and electro-magnetic energy harvesters are excited at the first natural frequency of each harvester, 126.7 and 12.5 Hz, respectively. Then,

generated voltage from each energy harvester is combined using the MISO circuit and then used to charge a 0.1 F capacitor. Combined energy harvesting results demonstrated better performance than that of a single energy source, demonstrating that this multi-source system could be a promising energy harvesting solution for wireless sensing systems.

8690-9, Session 2

Piezoelectric wind turbine

Ravi A. Kishore, Shashank Priya, Virginia Polytechnic Institute and State Univ. (United States)

There has been significant focus in past few years towards developing small scale renewable energy based power sources for powering wireless sensor nodes in remote locations such as highways and bridges to conduct continuous health monitoring. These prior efforts have led to the development of microscale solar modules, hydrogen fuel cells and various vibration based energy harvesters. However, the cost effectiveness, reliability, and practicality of these solutions remains a concern. Harvesting the wind energy using micro-to-small scale wind turbines can be an excellent solution in variety of outdoor scenarios provided they can operate at few miles per hour of wind speed. The conventional electromagnetic generator used in the wind mills always has some cogging torque which restricts their operation above certain cut-in wind speed. This study aims to develop a novel piezoelectric wind turbine that utilizes bimorph actuators for electro-mechanical energy conversion. This device contains a Savonius rotor which is connected to a disk having magnets at the periphery. The piezoelectric actuators arranged circumferentially around the disk also have magnets at the tip which interacts with the magnetic field of the rotating disk and produces cyclical deflection. The wind tunnel experiments were conducted between 2-10 mph of wind speeds to characterize and optimize the power output of the wind turbine. Further, testing was conducted in the open environment to quantify the response to random wind gusts. An attempt was made towards integration of the piezoelectric wind turbine with the wireless sensor node.

8690-10, Session 3

Adaptive magnetorheological seat suspensions for adaptive shock mitigation

Wei Hu, Univ. of Maryland, College Park (United States); Gregory J. Hiemenz, Techno-Sciences Inc. (United States); Norman M. Wereley, Univ. of Maryland, College Park (United States)

An adaptive magnetorheological seat suspension (AMSS) was developed to protect occupants from shock loads, as well as to provide a measure of vibration isolation. The AMSS system consists of an adaptive linear stroke magnetorheological shock absorber (MRSA), and a rebound spring set, and is integrated into the seat structure of a military vehicle. The MRSA provides a large controllable yield force, as well as relatively low viscous damping, to accommodate both shock attenuation and vibration performance requirements. The MRSA can adapt its stroking load to accomodate varying occupant weights (ranging from a 5th percentile female up to a 95th percentile male) as well as varying shock load severity. A control algorithm was developed that maximizes the energy absorbed during a shock event in order to minimize the load transmitted to the occupants by fully utilizing the available vertical stroking distance of the suspension. Shock attenuation tests were conducted using a shock effect simulator. The system was experimentally proven to automatically adapt and provide approximately equal occupant protection across the occupant weight range within a specified stroke range. Failsafe capability was demonstrated by controlling lumbar loads in a 50th percentile male occupant for a shock event in the event of power failure. Moreover, the same system was also shown experimentally to be capable of substantial vibration isolation performance. Via these tests, the AMSS was shown to exceed all design objectives.

8690-11, Session 3

Online acoustic emission monitoring of combustion turbines for compressor stator vane crack detection

Jaya Prakash Koduru, Sepandarmaz Momeni, Miguel Gonzalez, Obdulia Ley, Boris Zarate, Valery F. Godinez, MISTRAS Group, Inc. (United States)

The power industry primarily relies on combustion turbines to extract electricity from a flow of combustion gas or oil. The turbines consist of axial compressors with both static (stator) and rotating (rotor) air-foils. Mid-compressor stator vane cracking is a well known problem in the industry which leads to the liberation of the vanes in their later stages and a resulting collapse of the compressor. Per insurance statistics the losses from these failures is around $7 to $10 million not including the revenue lost from the 55 day average forced outage for repair. Current practices in the industry involves periodic inspection during outage using traditional visual, borescope or UT inspection of the blades requiring extensive downtime. Structural health monitoring (SHM) solutions that permanently monitor these combustion turbines in real-time and provide information about incipient failure can lead to significant savings and increased productivity. Acoustic emission being a global, in-service monitoring technique can be used to monitor the turbines permanently. Using an array of sensors permanently installed on the turbines, acoustic emission data continuously. Utilizing signal processing and pattern recognition techniques it is possible to accurately locate the areas of cracking in the stator vanes. The acoustic combustion turbine monitoring system (ACTMS) consisting of sensors and associate electronics for data acquisition is developed for permanent deployments. Early deployments were able to detect the onset of cracks in S1 vanes in an F-class combustion turbine at Next-Era Energy Resources.

8690-12, Session 3

Actuation needs for an adaptive trailing-edge device aimed at reducing fuel comsumption on regional aircraft

Gianluca Diodati, Italian Aerospace Research Ctr. (Italy); Antonio Concilio, Ctr. Italiano Ricerche Aerospaziali (Italy)

This paper deals with the definition of the actuation capabilities, needed to implement an Adaptive Trailing Edge Device (ATED) for a medium-size aircraft (3-hours flight range).

It is well known that the weight reduction during flight, consequence of the burned fuel, moves the optimal aerodynamic configuration away from the design working point. The aircraft then flies into a non-optimal pattern for a great extension of its mission, leading to larger fuel consumption. An ATED is able to compensate these effects, resulting in significant fuel savings (more than 3%) or, alternatively, increasing range.

Starting from preliminary aerodynamic calculation of the pressure field over the wing profile and a model of the segmented structure able to reproduce the targeted profile shapes during cruise, a multibody model has been set up. The force levels on the actuator system have then been computed. Based on this information and the reference geometry, the main characteristics necessary actuation force and angular displacement have been herein calculated. A kinematic chain able to amplify the actuator torque has been also identified.

The presented activity is part of the larger research project SARISTU (Smart Intelligent Aircraft Structures), funded inside the VII European Framework Programme EU-FP7.

8690-13, Session 3

An adaptive control system for wing TE shape control

Ignazio Dimino, Antonio Concilio, Ctr. Italiano Ricerche Aerospaziali (Italy)

This paper presents an approach to control the static shape of an adaptive wing by employing internal, integrated actuators.

The adaptive-wing concept employs active ribs, driven by servo actuators, controlled in turn by a dedicated algorithm aimed at shaping the wing cross section, according to a pre-defined geometry. The adaptive structural elements, working during aircraft cruise are modeled via a standard FE code; a suitable control algorithm is then implemented in a dedicated routine for real-time simulations.

The work is organized as follows. A finite element model of the uncontrolled, non-actuated structure is employed to obtain the multiple-input, multiple-output gain matrices for actuator-load and displacement control. Both open-loop and closed-loop simulations are then carried out. In the open-loop simulations, aerodynamic loads are not included in the problem as the effects are not fed back to the control system. After having characterized pure actuators behavior over the structure, selected target wing shapes are achieved through closed-loop simulations, including external loads.

8690-14, Session 3

Estimated performance of an adaptive trailing-edge device aimed at reducing fuel consumption on a medium-size aircraft

Gianluca Diodati, Antonio Concilio, Italian Aerospace Research Ctr. (Italy); Sergio Ricci, Alessandro De Gaspari, Polytechnic of Milan (Italy); Cedric Liauzun, Jean-Luc Godard , ONERA (France)

This paper deals with the estimation of the performance of a medium-size aircraft (3-hour flight range) equipped with an adaptive trailing edge device (ATED) that runs span-wise from the wing root in the flap zone and extends chord-wise for a limited percentage of the MAC. Computations are calculated referring to the full wing and do not refer to the complete aircraft configuration.

Aerodynamic computations, taking into account ideal shapes, have been performed by using both Euler and Navier-Stokes method in order to extract the wing polars for the reference and the optimal wing, implementing an ATED, deflected upwards and downwards. A comparison of the achieved results is discussed.

Considering the shape domain, a suitable interpolation procedure has been set up to obtain the wing polar envelop of the adaptive wing, intended as the set of “best” values, picked by each different polar.

At the end, the performances of the complete reference and adaptive wing are computed and compared for a symmetric, centered, leveled and steady cruise flight for a medium size aircraft. A significant fuel burn reduction estimate or, alternatively, an increased range capability is demonstrated, with margins of further improvements.

The herein presented activity is part of the research project SARISTU (Smart Intelligent Aircraft Structures), funded inside the VII European Framework Programme (EU-FP7).

8690-15, Session 3

Design and development of an active Gurney flap for rotorcraft

Jon Freire Gómez, Julian D. Booker, Phil H. Mellor, Univ. of Bristol (United Kingdom)

The EU’s Green Rotorcraft programme will develop an Active Gurney flap (AGF) for a full-scale helicopter main rotor blade as part of its ‘smart adaptive rotor blade’ technology demonstrators. AGFs can be utilized to provide a localized lift increment on the rotor, enabling a redistribution of loading on the rotor blade around the rotor azimuth. Further advantages include the possibility of using AGFs to allow a rotor speed reduction, which subsequently provides acoustic benefits. Designed to be integrable into a commercial helicopter blade, and thereby capable of withstanding real in-flight centrifugal loading, blade vibrations and aerodynamic loads, the demonstrator is expected to achieve a high technology readiness level (TRL). The AGF will be validated initially by a constant blade section 2D wind tunnel test, and latterly, by full blade 3D whirl tower testing. This paper presents first the methodology adopted for the AGF concept topology selection, based on a series of both qualitative and quantitative performance criteria. Two different AGF candidate mechanisms are compared, both powered by a small commercial electromagnetic actuator. In both topologies, the link between the actuator and the control surface consists of two rotating torque bars, pivoting on flexure bearings. This provides the required reliability and precision, while making the design virtually frictionless. The engineering analysis and static bench test results presented suggest that both candidates would perform satisfactorily in a 2D wind tunnel test, but that equally, both have design constraints which limit their potential to be further taken into a whirl tower test. Future work will focus on assessing other promising topologies, as well as on design optimization and design for manufacture issues.

8690-16, Session 4

Acoustic linear adaptable regression model (ALARM) methodology for psycho-behavioral sound quality quantification to improve automotive door experience

Suhant Prajwal Reddy Ranga, Jonathan E. Luntz, Diann E. Brei, Univ. of Michigan (United States); Alan W. Moyer, Paul W. Alexander, Imad Bazzi, Nancy L. Johnson, General Motors Corp. (United States)

Sound quality during door closure is a key, forward-facing component of the consumer’s non-driving vehicle experience that can influence their purchasing decisions. For critical door components, such as seals and latches, this heavily factors into relevant design tradeoffs and decisions. Unfortunately, the sound quality as perceived by the consumer is primarily qualitative and sensitive to the environment and user, making it challenging to incorporate into typical engineering design methods. This paper presents a rigorous method for converting consumer/expert experimental sound ratings into a quantified model which can be used to extract discrete rating contributions of various door components, including those based on smart material technologies. In this method, significant psycho-acoustic metrics are extracted from measured sound data for a door closure event. The dimensionality of this metric set is reduced using Principal Component Analysis to generate an orthogonal principal component basis. An Acoustic Linear Adaptable Regression Model (ALARM) is developed to correlate the sound bite projections with existing subjective ratings given by an expert or consumer focus group. Trained in this manner with data from vehicles spanning the sound quality spectrum, the ALARM model was used to predict the expert ratings for additional data outside of the model set. The ALARM models were able to predict user ratings with absolute mean error of 9%, demonstrating its capability as a useful predictive design tool for door closure events. The validated ALARM model was then used in a study to assess and evaluate the individual sound quality effects of conventional as well as novel, smart material-based door components.

8690-17, Session 4

SMA-actuated vertical deploy air dam, part 2: operation and test performance of prototype unit

Alan L. Browne, Nancy L. Jonson, General Motors Corp. (United States); Jeffrey Brown, Dynalloy Inc. (United States)

Airflow over/under/around a vehicle can affect many important aspects of vehicle performance including vehicle drag (fuel economy) and cooling/heat exchange for the vehicle powertrain and A/C systems. Devices in current use to control airflow, with the exception of a few active spoilers, are of fixed geometry, orientation, and stiffness. Such devices can thus not be relocated, reoriented, etc. as driving conditions change and thus vehicle airflow cannot be adjusted to better suit the changed driving condition. Additionally, under-vehicle airflow control devices also reduce ground clearance presenting a challenge to designers to provide the needed control of airflow while maintaining sufficient ground clearance.

This collaborative study was successful in developing an SMA actuator based approach to reversibly deploying an air dam through vertical translation of its structure. Beyond feasibility, vehicle mounted prototype fully functional units demonstrated that this approach would add little weight to the existing stationary system, and could potentially perform well in the harsh under vehicle environment due to a lack of exposed bearings and pivots. This demonstration showed that actuation speed, force, and cyclic stability all could meet the application requirements. The solution, a dual point balanced actuation approach based on shape memory alloy wires, uses straight linear actuation to produce a reversible height change of 50 mm. On vehicle wind tunnel and on-road tests verified the potential for a reversibly deployable air dam to meet the otherwise conflicting goals of large ground clearance for off-road performance and optimum lower ground clearance for optimum fuel economy benefits.

8690-18, Session 4

Nonlinear magnetostrictive modeling for smart material electro-hydraulic actuator development

John P. Larson, Marcelo J. Dapino, The Ohio State Univ. (United States)

Smart material electro-hydraulic actuators use hydraulic rectification by one-way check valves to amplify the motion of smart materials, such as magnetostrictives and piezoelectrics, in order to create compact, lightweight actuators for aerospace and automotive applications. A piston pump driven by a smart material is combined with a hydraulic cylinder to form a self-contained, power-by-wire actuator that can be used in place of a conventional hydraulic system without the need for hydraulic lines and a centralized pump. The actuator developed in this paper uses Terfenol-D as the driver material. The response of this magnetostrictive material is nonlinear, especially at the high frequencies and drive levels at which peak performance occurs. A fully coupled axisymmetric modeling framework is developed to understand and optimize the magnetostrictive response; the framework includes Maxwell's equations for electromagnetics and Navier's equation for mechanical systems coupled with an energy-averaged constitutive law for Terfenol-D. Additionally, the fluid-structure interaction between the pumping piston driven by the magnetostrictive rod and the hydraulic fluid circuit is considered, including the dynamics of the reed valves used to rectify flow. The modeling framework is implemented using the commercial finite element package COMSOL. The model is validated through an experimental study of a test actuator with a peak performance of 37 W. Additional tests are conducted to quantify the dynamic behavior of the one-way reed valves used in the system. The model is then utilized to identify the key parameters limiting the actuator performance at high frequencies and to optimize the system for improved efficiency and power-to-weight ratio.

8690-19, Session PTues

Semi-active magnetorheological seat suspension for vibration isolation of a helicopter crew seat

Gregory J. Hiemenz, Pablo Sztein, Techno-Sciences Inc. (United States); Wei Hu, Norman M. Wereley, Univ. of Maryland, College Park (United States); William C. Glass, Naval Air Warfare Ctr. Aircraft Div. (United States)

A magnetorheological (MR) seat suspension system was retrofitted to the SH-60 Seahawk crew seat to provide semi-active control of harmful cockpit vibrations. Current seating systems are designed primarily to meet crashworthiness requirements rather than vibration isolation. They employ crashworthy fixed or variable load energy absorbers (FLEAs or VLEAs) to minimize the potential for occupant spinal and pelvic injuries during harsh vertical or crash landings of these aircraft and increase the chances of occupant survival during these events. These energy absorbers, however, will not stroke until a tuned load threshold is reached and therefore act as a stiff link between the seat and the floor during normal rotorcraft vibration. Because of this, these systems provide no isolation to cockpit vibration. The MR suspension was implemented in series with the existing FLEAs in order to minimize added weight and was designed such that crashworthiness capabilities of the seat were not impaired. Experimental vibration testing results have shown that this system reduces the dominant rotor-induced vertical vibration at the blade passage frequency transmitted to the occupant by over 90%, which is a 86% improvement over the original SH-60 crew seat. Furthermore, full-scale dynamic crash testing performed on this retrofitted seat has demonstrated that crash safety is preserved. Through this dynamic testing in the laboratory, it has been shown that the MR suspension reduces peak lumbar loading as compared to the original SH-60 crew seat from 1,950 lb down to 1,250 lb. The results of a flight test are also presented.

8690-20, Session PTues

Structural design and analysis of a kind of improved pneumatic muscle fiber

Ning Feng, Shanbo Chen, Yanju Liu, Jinsong Leng, Harbin Institute of Technology (China)

In this paper, a kind of improved pneumatic muscle fiber is proposed from the bionics perspective. Four kinds of commercial latex tubes of different specifications are selected for pneumatic muscle fiber and the output force and contraction of pneumatic muscle fiber are tested with internal air pressure varying from 0 to 0.7 MPa. The experiment results show that a kind of proper latex tube could be chosen from four kinds of different latex tubes, so as to get greater output force and relatively larger contraction. The elastic modulus of the improved pneumatic muscle fiber utilizing the chosen latex tube is experimentally determined. And then the effect of lengths of different pneumatic muscle fibers is considered in this paper, so the pneumatic muscle fibers with four representative lengths are made. The pneumatic muscle fibers with different lengths are tested to get independent output force and contraction ratio. For analyzing the properties of pneumatic muscle fibers the independent output force and contraction ratio of pneumatic muscle fibers are compared. A new sealed and interconnected joint which is used as connection parts of pneumatic muscle fiber is also designed and analyzed in this paper to realize the purpose of more convenient application. Moreover the properties of this pneumatic muscle fiber with the new joint are tested. Finally it could be realized that morphing skin, especially variable stiffness skins would employ this kind of improved pneumatic muscle fiber to accomplish the morphing target.

8690-21, Session PTues

Proton exchange membrane based on sulfonated poly(ether ether ketone) and sulfonated poly(1,4-Phenylene ether ether sulfone) for vanadium redox flow battery

Suraluck Macksasitorn, Sairung Changkhamchom, Anuvat Sirivat, Kitipat Siemanond, Chulalongkorn Univ. (Thailand)

The currently used proton exchange membrane (PEM) in vanadium redox flow batteries (VRB) is Nafion, due to its excellent proton conductivity in the fully hydrated condition, although it is very expensive. In order to reduce the cost of the membrane used in VRB and to reduce vanadium permeability across the membrane, sulfonated poly(ether ether ketone) (PEEK), and poly(1,4-phenylene ether ether sulfone) (PPEES) membranes are fabricated and studied for the effect of the sulfonation time. The degree of sulfonation, which increases from 46% to 86%, induces the water uptake, ion exchange capacity, proton conductivity, and vanadium permeability enhancements. The vanadium permeabilities of S-PEEK and S-PPEES membranes are in the range of 0 to 24.95?10-7 cm2 min-1, which are significantly lower than that of Nafion 117 whose value is 30.84?10-7 cm2 min-1. The proton conductivity of S-PEEK is nine times higher than that of sulfonated poly(arylene ether ketone) in a previous work and more suitable for using in VRB.

8691-1, Session 1

Development of sensing techniques for weaponry health monitoring *(Keynote Presentation)*

Ebonee A. Walker, Eugene Edwards, Paul B. Ruffin, Christina L. Brantley, U.S. Army Research, Development and Engineering Command (United States)

Due to the costliness of destructive evaluation methods for assessing the aging and shelf-life of missile and rocket components, the identification of nondestructive evaluation methods has become increasingly important to the Army. Verifying that there is a sufficient concentration of stabilizer is a dependable indicator that the missile's double-based solid propellant is viable. The research outlined in this paper summarizes the Army Aviation and Missile Research, Development, & Engineering Center's (AMRDEC's) comparative use of nanoporous membranes, carbon nanotubes, and optical spectroscopic configured sensing techniques for detecting degradation in rocket motor propellant. The first sensing technique utilizes a gas collecting chamber consisting of nanoporous structures that trap the smaller solid propellant particles for measurement by a gas analysis device. In collaboration with NASA-Ames, sensing methods are developed that utilize functionalized single-walled carbon nanotubes as the key sensing element. The optical spectroscopic sensing method is based on a unique light collecting optical fiber system designed to detect the concentration of the propellant stabilizer. Experimental setups, laboratory results, and overall effectiveness of each technique are presented in this paper. Expectations are for the three sensing mechanisms to provide nondestructive evaluation methods that will offer cost-savings and improved weaponry health monitoring.

8691-2, Session 2

Nano-particle coating based point-of-care diagnostic system

Xiao Qun Zhou, Institute for Infocomm Research (Singapore); Weihua Hu, Chang Ming Li, Nanyang Technological Univ. (Singapore)

A major class of POC diagnostic tests is the lateral flow test, which uses a membrane or paper strip to indicate the presence of protein markers. On a membrane, addition of sample induces capillary action without user intervention. As the sample flows across the membrane, it gathers labeling reagents embedded in the membrane, and flows over an area that contains capture molecules; the labeled captured analytes are interpreted by eye to form a visible band. For targets present at low native concentrations, the assay systems are not applicable.

Fluorescence based immunoassay technology is an excellent platform for POC diagnostic applications [1, 2]. However, the most fluorescence measurement systems suffer from the insufficient sensitivity, bulky, complex and expensive. To solve these problems, we increase the fluorescent signals by coating nano-particles on the substrate. [3,5]. Such enhancement could significantly increase an assay's detection sensitivity and hence is very desirable in many situations such as early detection of cancers.

We developed a microfluidic POC diagnosis system based on nano-particles coated capillary tube. Such coating based tube immunoassay device makes microfluidic system run simply, and overcome the problems of blockage, leakage, and mixing problem. The system is in a compact, portable and robust package, and furthermore, it does not require extensive laboratory training or equipment. We use a disposable capillary tube with dry reagents coating to avoid the need for refrigeration and no manual sample processing is required.

8691-3, Session 2

Wireless health monitoring helmet for football players to diagnose concussion and track fatigue

Sechang Oh, Prashanth S. Kumar, Hyeokjun Kwon, Pratyush Rai, Vijay K. Varadan, Univ. of Arkansas (United States)

Football players are regularly exposed to violent impacts. Concussions are mild traumatic brain injuries that are one of the most common injuries experienced by football players. These concussions are often overlooked by football players themselves and the clinical criteria used to diagnose them. The cumulative effect of these mild traumatic brain injuries can cause long-term residual brain dysfunctions. In addition, an athlete's fatigue level should be monitored to prevent any secondary injuries due to over exertion. Nitric Oxide acts as a metabolic adjustment factor that controls the flow of oxygen in blood and the contraction/relaxation of muscles. Fatigue can be evaluated by measuring the concentration change of nitric oxide in blood. However, measuring the concentration of nitric oxide in blood is not feasible during exercise. Nevertheless, the degree of fatigue can be measured with SpO2 during exercise because the change of nitric oxide also influences the SpO2. In this paper, we propose a wireless health monitoring helmet to diagnose concussions and evaluate fatigue in real time and on the field. The helmet is equipped with sensors and a transmitter module. As sensors, textile based electrodes are used to sense EEG and oximeter sensors are used to derive SpO2. The sensed physiological signals are amplified and processed in the transmitter module. The processed signals are transmitted to a server using Zigbee wireless communication. The EEG signals are classified to diagnose concussion or any abnormality of brain function. In conclusion, the system can monitor and diagnose concussions and evaluate fatigue in football players in real time by measuring their EEGs and SpO2.

8691-4, Session 2

E-bra for monitoring pericardial effusion: a dancing heart

Vijay K. Varadan, Univ. of Arkansas (United States)

No Abstract Available

8691-5, Session 3

200 years of electrical impedance spectroscopy (EIS) in healthcare : progress and challenges *(Keynote Presentation)*

Ajit Khosla, Simon Fraser Univ. (Canada)

This paper focuses on progress made in the area of Electrical Impedance Spectroscopy (EIS) over last 200 years in healthcare. Although Electrical Impedance Spectroscopy was first Introduced by Oliver Heaviside in the 1880s, it has yet to play a major role in diagnostics. EIS has the potential to be of every day clinical value and play an important role in diagnostics and monitoring of a large number of disease such as detection of breast cancer, skin cancer, body composition, bladder abnormalities, body water and biological tissues. However, it has yet to be routinely used as a tool in everyday clinical practice. Various state of the art EIS diagnostic systems will be discussed such as SIM-technika's - MEIK® Version 5.0, Siemen's-T-scan and SciBase-SI-1 & 2. Also, discussed will be challenges involved and innovation required in implementing EIS systems as routinely used tools in everyday clinical practice.

8691-6, Session 4

Smart real-time cardiac diagnostic sensor systems for football players and soldiers under intense physical training

Prashanth S. Kumar, Sechang Oh, Pratyush Rai, Hyeokjun Kwon, Vijay K. Varadan, Univ. of Arkansas (United States)

Sudden cardiac death (SCD) and acute myocardial infarctions (AMIs) have been reported to be up to 7.6 times higher in rate of occurrence during intense exercise as compared to sedentary activities. The risk is high in individuals with both diagnosed as well as occult heart diseases. Recently, SCDs have been reported with a high rate of occurrence among young athletes and soldiers who routinely undergo vigorous training. Pre-screening Electrocardiograms (ECG) and echocardiograms have been suggested as potential means of detecting any cardiac abnormalities prior to intense training to avoid the risk of SCDs, but the benefits of this approach are widely debated. Moreover, the increased risk of SCDs and AMIs during training or exercise suggests that ECGs are of much greater value when acquired in real-time during the actual training. The availability of immediate diagnostic data will greatly reduce the time taken to administer the appropriate resuscitation. Important factors to consider in the implementation of this solution are: - cost of overall system, accuracy of signals acquired and unobtrusive design. In this paper, we evaluate a system using printed sensors made of inks with functional properties to acquire ECGs of athletes and soldiers during physical training and basic military training respectively. Using Zigbee, we show that a large number of athletes and soldiers can be monitored in real time, simultaneously.

8691-7, Session 4

Micromotion-induced dynamic effects between a neuron probe and brain tissue

Michael Polanco, Old Dominion Univ. (United States); Hargsoon Yoon, Norfolk State Univ. (United States); Sebastian Bawab, Old Dominion Univ. (United States)

The brain cells inevitably interface with neural probes that are typically much stiffer in comparison and are susceptible to mechanical damage due to mechanical motion of the brain. A series of dynamic simulations are conducted to better understand the design enhancements needed for the neuron probe and how the brain tissue deformation near the interface of the neuron probe will be affected by the relative micromotion of the probe. The simulation uses a nonlinear transient explicit finite element code, LS-DYNA. Results of a calibrated quasi-static three-dimensional quarter-symmetry model with viscoelastic properties are employed on the brain to capture the time dependent dynamic deformations from the probe as a function of different analytical parameters such as displacement frequency and interface friction.

8691-8, Session 4

Motion artifact removal algorithm by using ICA for e-bra: women ECG measurement system

Hyeokjun Kwon, Sechang Oh, Prashanth S. Shyamkumar, Vijay K. Varadan, Univ. of Arkansas (United States)

Wearable ECG(ElectroCardioGram) measurement systems have increasingly developed for people suffering from CVD(CardioVascular Disease) who have also very active lifestyle. Especially, in case women CVD patients, several abnormal CVD symptoms are accompanied with CVD. Therefore, periodic ECG monitoring is significant diagnostic method to prevent from sudden heart attack. An E-bra ECG measurement system in our previous work gives more convenient option for women than Holter monitor system. The critical concern in the system is that the motion artifact (MA)by induced from body movement action has a deleterious effect on distortion of pure ECG signal. In this paper, ICA(independent component analysis) theory is suggested to remove MA in the e-bra system. The basic assumption of ICA algorithm is that components mixed in each signal are independent, and all signals can be mixed with multiplying independent components and different weighed vector. Basically, MA and ECG signal are independent because ECG and MA are created from different physical processes. However, to adapt ICA, we at least need two ECG measurement signals including pure ECG component and MA component. E-bra system has implemented with only one ECG measurement system. To solve the problem, the two pseudo ECG signals are created by mixing with measured ECG measurement signal in e-bra system, selected arbitrary weighed vectors, and wandering baseline noise component. Finally, the two pseudo ECG signals are adapted by ICA algorithm to extract pure ECG signal. Sitting, walking, and running activities are performed for the suggested algorithm performance evaluation.

8691-9, Session 5

Flexible paper transistor made with ZnO-cellulose hybrid nano-composite for electronic applications

Hyun-u Ko, Inha Univ. (Korea, Republic of); Gwang-Hoon Kim, Chosun Univ. (Korea, Republic of); Sang Yeol Yang, Jaehwan Kim, Inha Univ. (Korea, Republic of); Joo-Hyung Kim, Chosun Univ. (Korea, Republic of)

Growth mechanism of semiconducting ZnO layer chemically grown on regenerated cellulose and its flexible paper transistor were studied. ZnO layer-cellulose composite was prepared by simple chemical reaction including alkaline hydrolysis at room temperature and utilizing wet state regenerated cellulose as a hydrophilic substrate. By increasing the concentration of ZnO seeding layer, the number of ZnO cluster also increases. Interestingly, the rod shape particles are also formed on cellulose substrate. From our observation, in low concentration from 25mM to 50mM, the size of ZnO rod increases as the seeding concentration increases. However, in high concentration, flower shaped ZnO structure is observed, which indicates that the flower shape is due to clustering effect during the growth of ZnO rods. Crystalline nano-rod based thin ZnO layer was analyzed by XRD and SEM measurements. Nano-rod based thin ZnO layer was well grown on cellulose substrate and the thickness of ZnO layer was well controlled by reaction time. Structural data of as grown ZnO/cellulose provides the crystal orientation limited growth mechanism of ZnO nano-rod by the reaction time of chemical process. By lift off process, a source and a drain electrode was fabricated transistor using sputtering process. Bottom gate electrode was deposited on the cellulose which plays a role of gate dielectric layer. More detailed ZnO-cellulose based transistor is also investigated and discussed.

8691-10, Session 5

High-k dielectrics in II-V semiconductors for innovative electronics

Aswini K. Pradhan, Norfolk State Univ. (United States)

Compound III-V semiconductors such as GaAs have the potential to replace Si as the channel material in metal-oxide-semiconductor-field-effect-transistors (MOSFET) due to their extraordinary high electron mobility. Some III–V compounds have unique optical, electronic and chemical properties; their ability to efficiently emit and detect light means they are often used in lasers, light-emitting diodes and detectors for optical communications, instrumentation and sensing. In order to enable low power and high-speed III-V (GaAs or InGaAs) metal oxide semiconductor (MOS) logic device applications at 22 nm technology nodes and beyond, a high quality high-k on III-V interface is important.

For instance, Gallium Arsenide (GaAs) surfaces were self-cleaned (SC) through fast pulsing of the Trimethyl aluminum (TMA) precursor by reducing and restraining the regrowth of native oxides on GaAs surface using the atomic layer deposition (ALD). The thermal conversion of As-O in to Ga-O reduction during the pulsing of TMA was evaluated by the x-ray photoelectron spectroscopy (XPS). Metal oxide semiconductor (MOS) capacitor was fabricated by ALD using ZrO2 as high-k gate dielectric on SC n-GaAs substrates, and their superior performance has been demonstrated. The amount of bulk and interface fixed charges in ZrO2 is reduced by improving the ZrO2/GaAs interface through restraining the oxidation of surface chemical species and controlled thermal treatment. The MOS capacitor improvement is qualitatively demonstrated. We will also discuss other II-V semiconductors, such high-k on GaN. This strategy has remarkable significance for the development of high-throughput innovative electronics.

8691-11, Session 5

CuIn0.81Al0.19Se2thin films preparation and Al/p-CuInAlSe2 Schottky diode formation

Usha Parihar, Univ. of Jammu (India); Chetan J. Panchal, The Maharaja Sayajirao Univ. of Baroda (India); Naresh Padha, Univ. of Jammu (India)

Polycrystalline chalcopyrite compound CuIn1-xAlxSe2 (CIAS) with x = 0.19 was synthesized by melt quenching technique, wherein, all the elemental components, ie, copper, indium, aluminium and selenium in stoichiometric proportions were reacted in an evacuated quartz ampoule. Structural and compositional characterization of the synthesized pulverized material confirms the polycrystalline nature of tetragonal phase and stoichiometry. The synthesized compound material was used as an evaporant material to deposit CuInAlSe2 thin films onto organically cleaned soda lime glass substrates using flash evaporation technique. The deposited thin films were then undertaken for structural, electrical, optical measurements. The crystallinity in the films increases with increasing substrate temperature up to 473 K, and subsequently degrades at substrate temperatures higher to this; it also increases with increase in layer thickness from 200nm to 700nm. P-type conductivity of the deposited films was established by using Hall measurement setup and provided optimized parameters at a layer thickness of 700nm at a substrate temperature of 473K. The current-voltage (I-V) characteristics of Al/p-CuInAlSe2 Schottky diode has been measured over a temperature range of 233 K to 353 K. The electronic parameters such as ideality factor (?), barrier height (?bo) and series resistance (Rs) were determined from the downward curvature of current-voltage characteristics using Cheung's method. The extracted parameters were found to be strongly temperature dependent; BH increases, while Ideality factor and Rs decreases with increasing temperature. The behavior of BH and ideality factor with change in temperature has been explained on the basis of barrier inhomogenities over the interface by assuming a Gaussian distribution (GD) of the barrier heights at the M-S interface.

8691-12, Session 5

Fault detection in word-level nano ICs using vector Boolean derivatives

Samuel C. Lee, The Univ. of Oklahoma (United States)

This paper consists of four parts: (1) The word-level representations of digital circuits which include (a) word-level arithmatic representation, (b) word-level sum-of-products representation, and (c) word-level Reed-Muller representation. (2) The three word-level nano IC circuit designs. (3) The introduction of the vector Boolean derivative. (4) The fault detection in word-level digital circuits using the vector Boolean derivative.

In this paper, both single and multiple faults are considered. The formulas for deriving tests for detecting struck-at-0 (s-a-0) and struck-at-1 (s-a-1) are given. For any given word-level digital circuit, presented in any of the three representations, the derivation of a minimal, complete test set, i.e., a complete test with a minimum number of essential tests, none of which can be eliminated, is presented. The theory and appliications of this word-level circuit fault-detection method are completely general and are illustrated by examples.

8691-13, Session 5

Logic design of word-level 3D, 2-dot QCA nanoICs

Samuel C. Lee, The Univ. of Oklahoma (United States)

One of the promising emerging nanotechnologies is the molecular quantum-dot cellular automata (QCA). A considerable amount of attention has been give to the 2D 2-dot QCA circuit designs and simulations at the bit level by Hook and Lee. The purpose of this paper is two-fold: (1) to introduce a new 3D QCA lattice structure, formed by 2-dot QCA cells, and (2) to present a word-level QCA nanoIC design using this 3D 2-dot QCA architecture which uses a slice of the lattice to implement one bit of the word data. For example, for an 8-bit word, there will be 8 slices of 2-dot QCA lattices embedded in the nanoIC.

Since for each Boolean function there are three general word-level representations: the word-level arithmatic representation, the word-level sum-of-products representation and the word-level Red-Muller representation, there will be three different 3D 2-dot QCA realizations. These realizations offer three design candidates. Based on their circuit complexity, manufacturing costs, non-invasive testability, etc., the final design can be determined, which could be one of the three designs plus a possible (hybrid) combination of the three designs.

8691-14, Session 6

Molecular recognition using nanomechanical responses

Anja Boisen, Technical Univ. of Denmark (Denmark)

Small mechanical structures such as diving boards, bridges and lids can be used as compact, sensitive and label free sensors. A biochemical reaction at the surface of the structure can be monitored as a bending, due to a change in surface stress. Minute temperature changes can be registered by exploring the bimorph effect. Furthermore, mass detection can be achieved by using resonating structures and monitor how the resonant frequency changes as a function of the added mass. In order to obtain high sensitivity the structures need to have micrometer and sometimes nanometer dimensions. They are fabricated by cleanroom processing using either silicon or polymer based materials.

Often cantilever-like structures are used as the sole mechanism of sensing, either for fundamental studies of i.e. surface stress generation or for specific sensor applications. We hypothesise that a combination of sensing principles facilitates increased robustness and reliability of generated data. In recently initiated projects we therefore combine cantilever-based sensing with other sensing techniques like electrochemistry, Surface Enhanced Raman Spectroscopy, and calorimetry. Either two sensor principles are integrated in a single chip or several different sensors are used for independent analysis of the same sample. In all projects the final aim is to achieve highly sensitive, reliable and miniaturized sensors. By high throughput data collection, statistical data treatment is possible. We will show examples from explosives detection, diagnostics, water analysis and nano-particle monitoring.

8691-15, Session 6

MEMS piezoelectric vector hydrophone

Yongrae Roh, Jinwook Kim, Jaeyoung Lee, Kyungpook National Univ. (Korea, Republic of)

Typical underwater acoustic sensors making use of piezoelectric

ceramics detect only the magnitude of an acoustic pressure, a scalar quantity, and convert this pressure into a proportional output voltage. The scalar sensor has no directional sensitivity. In this paper, we have proposed a new underwater sensor based on MEMS structure, which is sensitive to both the magnitude and the azimuthal direction of an acoustic wave, thus the sensor is named as an underwater vector hydrophone. The vector hydrophone consists of a bionic hair cylinder connected to a piezoelectric cantilever structure so that the cylinder can respond to the directional effects of in-coming acoustic wave pressures. Validity of this new design has been confirmed with analytic equations and finite element analyses. Further, effects of all the following structural variables on the performance of the hydrophone have been analyzed through finite element analyses: frame material, cylinder material and length, detection element (piezoelectric cantilever) length and thickness, kinds of the piezoelectric material, beam length and thickness, and whole hydrophone size. Direction beam pattern as a function of the structural variables has been thoroughly analyzed, which leads to the optimal structure of the micro-hydrophone as an underwater vector sensor.

8691-16, Session 7

Overcoming obstacles to creating complex MEMS systems: parallels with the semiconductor and computer design industries

Lesley Shannon, Simon Fraser Univ. (Canada)

The current status of MEMs is perhaps reminiscent of the early semiconductor technology industry and the development of the first computer systems. As a technology matures, a certain pattern of evolution typically ensues. This path, however, is fraught with challenges, such as efficient architectural exploration and the creation of an efficient synthesis of a problem's solution from an effective user methodology/interface, which act as discontinuities in the advancement of a technology. Overcoming these obstacles requires major innovations and, generally, the establishment of infrastructure. This paper proposes one vision for the future of MEMS technology, describing how the techniques and methodologies employed in circuit and computing system design can be adapted to MEMS system design to raise the level of abstraction and facilitate the creation of more complex architectures, thereby advancing the state-of-the art of MEMS research and industrial applications.

Specifically, the paper will focus on some of the key infrastructure needed to develop and evaluate complex systems, potential limiting factors in the advancement of a technology. For example, how does a designer know if they have the best solution to a problem? Similarly, how do they articulate the specific improvements their design has over the previous best? Furthermore, how does a designer efficiently investigate architectural trade-offs to decide what design(s) are likely to provide the best performance with any confidence (without building them all)? In discussing these questions and other similar concerns, this paper aims to provide direction for facilitating the development of complex systems design using MEMS technology.

8691-17, Session 7

Standoff sensing bioanalytes using MEMS

Thomas G. Thundat, X. Liu, S. Kim, Charles Van Neste, Univ. of Alberta (Canada)

No Abstract Available

8691-18, Session 7

Fabrication of nanotemplates using anodized aluminum oxidation for nanowire array applications

Ilwoo Seok, Jonathan Cole, Shivan Haran, Arkansas State Univ. (United States)

In recent years, nanotechnology along with nano-manufacturing has been an attractive topic for science and engineering research to employ the micro and nano-scale study. The proposed technology takes the advancements attained in micro electro-mechanical systems (MEMS) to the nano-scale which has many potential applications such as solar power conversion, or biosensors. Some of the main structures created using nano-scale manufacturing include nanotubes and nanowires. This project uses the principles of electro-chemistry to create non-porous film using anodized aluminum oxidation (AAO) process and in turn utilizing it to fabricate 3D nanowire structures. Studies have shown that these films are effective in achieving uniformly porous structures, and will be utilized as a template for the construction of nanotubes and nanowires. In addition, the proposed project evaluates the effectiveness of using the AAO templates for a nano-imprinting process which can be used as a way to produce nano-patterned materials cheaply toward a large area application. Nano-porous arrays in the Anodized Aluminum Oxide layers have been successfully created in our laboratory with the intended use to create nano-wire arrays using electo-deposition. The templates that are created will be used for growing Ag/Au nano-wire arrays for the purpose of bio-sensor applications, to begin with. Results from the outcome of this study will be presented including some additional discussion.

8691-19, Session 7

Polymer-based MEMS devices with modified organic electronics and thin film transistor

Vijay K. Varadan, Univ. of Arkansas (United States)

The advancement of silicon based micro electro mechanical systems (MEMS) is intimately intertwined with developments in the silicon semiconductor processing technology. Accordingly various processing approaches have been established for the integration of Silicon based MEMS with standard CMOS processing. For precision devices, and for devices requiring integrated electronics, silicon is presently unrivaled. However, it is not necessarily the best material for all applications. For example, silicon is brittle; it is only available in specific shapes (wafers); limited to 2-D or very limited 3-D structures; incompatible with many chemical and biological substances; fabrication requires sophisticated, expensive equipment operated in a clean-room environment. These often limit the low-cost potential of silicon based MEMS. Polymer based MEMS is gaining momentum rapidly due to its potential for conformability and other special characteristics not available with silicon. Moreover polymers are flexible, chemically and biologically compatible, available in many varieties, and can be fabricated in truly 3-D shapes. Most of these materials and their fabrication methods are inexpensive. In this talk we present schemes for the integration of polymeric MEMS sensors with organic TFTs to emulate similar approaches followed in Silicon micro fabrication.

8691-20, Session 8

Establishing electrical characteristics of DNA molecular wires in carbon-based bionanoelectronics platform *(Keynote Presentation)*

Sam Kassegne, San Diego State Univ. (United States)

Miniaturization of electronic devices into the nanometer range continues

to present a yet not-well-addressed fundamental technology challenge, particularly for applications requiring mass-scalability. The most promising approaches so far are largely based on bottom-up self-assembly concepts that entail constructing electronic components from their atomic and molecular building blocks. Subsequently, DNA-based nanoelectronics involving metal electrodes has been recently demonstrated with either bare DNA strands, or metalized DNA, or DNA as a template or carrier for nanoparticles. However, research so far has been limited to metal-based electrodes which have narrow electrochemical window that limits the degree of freedom needed to manipulate nucleic acid molecules such as DNA through scalable assembly processes such as electrophoresis and dielectrophoresis. Our recent work has shown that the electrochemical window of 3D carbon/graphite microelectrodes micromachined using polymer precursor is much larger than conventional 2D metal electrodes. As electrokinetic transport scales directly with electric field and time, this is a significant window and translates to much faster electrokinetic transport of nucleic acid molecules compared to parallel flow (diffusion and convection that scale with the square root of time).

In this talk, we present a new carbon-based bionanoelectronics platform comprising of DNA molecular wires and interconnects attached to carbon microelectrodes where the 3D structure enables suspension of DNA wires away from the substrate eliminating its effect. Key results in the electrical characterization of this 3D carbon electrode-based bionanoelectronics architecture and accelerated testing for exploring long-term viability and stability of this platform are presented.

8691-21, Session 9

Bio-inspired design: nonlinear digital pixels for multiple-tier processes

Orit Skorka, Alireza Mahmoodi, Jing Li, Dileepan Joseph, Univ. of Alberta (Canada)

The CCD or CMOS active pixel sensor array in a conventional image sensor performs worse than the human retina mainly in two ways: dynamic range and dark limit. Dynamic range measures the span of intensities simultaneously perceivable in a scene, from bright highlights to dark shadows. Dark limit is the lowest intensity at which image quality remains meaningful. These limitations may be overcome by introducing others, but biology overcomes them without trade-off. Inspired by the human retina, we design nonlinear digital pixels for multiple-tier processes, while conventional image sensors use linear analog pixels in a single-tier process. As nonlinear analog pixels exhibit low image quality, linearity is preferred. However, a wide dynamic range is easily achieved with nonlinearity and image quality is improved by giving each pixel its own analog-to-digital converter (ADC). Normally, the analog signal of each pixel's detector is converted to a digital signal outside the pixel array. With digital pixels, however, signals are protected from noise immediately upon detection. Digital pixels enjoy a synergy with multiple-tier processes. These fabrication methods enable small pixels for optical imaging and non-CMOS detectors for non-optical imaging, which tolerates large pixels. With a two-tier process, for example, CMOS or non-CMOS detectors may be stacked upon CMOS ADCs. This raises the fill factor of both detection and signal processing, and permits a leading-edge CMOS process, unsuitable for optical detection, to be used for the complex ADCs. Biological inspiration continues. The human retina is composed of multiple-tiers of cells for detection and signal processing.

8691-22, Session 9

Polyimide neural probe for chronic sensing of neural activity and micropositioning

Darryl W. Scott, Min H. Kim, Norfolk State Univ. (United States); Larry D. Sanford, Eastern Virginia Medical School (United States); Kyo D. Song, Hargsoon Yoon, Norfolk State Univ. (United States)

Several types of neural sensing devices have been developed to perform efficient neural recording in the brain. In addition to the sensitivity, biocompatibility and reliability are important factors for these devices in in-vivo use. The immune response and neural cell degeneration caused by probing these sensing devices in the brain can greatly affect the recording capabilities of the probe with time. In this research, a flexible polyimide neural probe is developed to reduce brain cell damage caused by stiff structures of neural probes and to adjust the sensing position even after implantation. We will present device designs, fabrication methods and analysis results of the neural probing system.

8691-23, Session 9

Development of magneto-impedance microsensors for the detection of buried defects using Eddy current

Johan Moulin, Institut d'Électronique Fondamentale (France)

The detection of buried defects in conductive sheets using Eddy current injection involves the measurement of a low frequency magnetic field in the range of 10-1000nT. In this frame, ultrasensitive magnetic field microsensors based on the magneto-impedance effect have been developed. Their sandwich structure consists in a conductive track surrounded by two ferromagnetic layers. By injection of a high frequency current in the conductive track, its impedance varies with the skin effect, thus with the external magnetic field through the transverse permeability of the ferromagnetic material. The sensors have been patterned using lift-off technique and both the conductive (copper) and ferromagnetic (Finemet) materials have been sputtered.

First the properties of the Finemet film have been optimized in terms of magnetoelastic properties. In this way, sputtering and annealing conditions have been studied using magnetometer, MOKE and internal stress measurement. Coercive fields as low as 10A m-1 have been obtained for a 500 nm thick film. Then a double layer lift-off technique has been developed in order to overcome the thickness and stress related to the sputtering of the Finemet film.

Microsensors have been realized with different film sizes and thicknesses. Their sensitivity has been measured from DC to 10 kHz with varying excitation frequencies. The value is constant in this frequency range and close to 1000V/T/A for a 4 mm x 200 µm sensor. Measurements in AC magnetic field have been realized using a double demodulation technique.

8691-24, Session 10

Conformal printing of sensors on 3D and flexible surfaces using direct-write aerosol jet deposition

Tyler J. Blumenthal, Vincent Fratello, Giovanni F. Nino, Keith E. Ritala, Quest Integrated, Inc. (United States)

Emerging applications for sensing and monitoring technology can no longer rely entirely on conventional sensor configurations, particularly where planar, rigid, and often fragile devices cannot meet demanding system sensing requirements. Direct-write Aerosol Jet (AJ) printing is establishing itself as an enabling technology for fabrication of sensors and circuit components on three dimensional (3D), flexible surfaces for applications ranging from structural health monitoring to human factors and performance measurement.

The AJ process is a non-contact procedure with deposition occurring at a standoff distance up to 5 mm, enabling features to be printed over steps, curved surfaces, and 3D objects. AJ printing utilizes an innovative methods to aerosolize inks and focus the dense aerosol of material-laden micro-droplets aerodynamically into a tightly controlled beam of material that can produce features as small as 10 microns (or as large as several centimeters). Though there are numerous commercial inks well-suited to AJ printing, custom inks are readily synthesized for fabrication of sensors and other components requiring specific materials; pneumatic creation of the aerosol permits use of viscous inks to 2500 cP well outside the bounds of many other printing methods. The technique lends itself well to rapid prototyping and additive manufacturing of expensive or scarce materials. Examples will describe the versatility of AJ printing as a viable method for creating sensors that are conformally matched to the surface topology of a wide variety of substrates, as well as the accompanying process development that was required to optimize the printing of each material.

8691-25, Session 10

Particle-based conductive silver ink customized for ink jet printing on cellulose electroactive paper

Mohammad A. H. Khondoker, Seongcheol Mun, Jaehwan Kim, Inha Univ. (Korea, Republic of)

Silver nanoparticles having diameter less than 50 nm were synthesized from metal precursor-silver nitrate, stabilizer-polyvinylpyrrolidone (PVP) and reducing agent-ethylene. Then, a conductive silver ink was prepared with suitable solvent. Additionally, appropriate surfactant and viscosifier were added to adjust surface tension and viscosity to make it useful for ink-jet printer. In this work, the influences of PVP molecular weight and reaction temperature on the size of silver nanoparticle were analyzed also. The final ink was coated on a cellulose film by spin coating and the effects of solvent, sintering temperature and solid content on its electrical resistivity were examined. It was found that 50% co-solvent of Deionized water & Di-ethylene glycol and solid content of around 50% exhibited the lowest resistivity of silver ink. Customization issues of the developed silver ink for ink jet printing on the cellulose film will be discussed.

8691-26, Session 10

Synthesis and characterization of polymeric binders for printing inks

Jungmin Lee, Linfeng Chen, Vijay K. Varadan, Univ. of Arkansas (United States)

Printing is one of the most cost-effective production techniques for electronic devices, such as sensors, flexible circuits, displays and smart labels. Though this technology has been widely used in military, industry and civilian life, several key technical challenges should be solved to meet up with the requirements for the fabrication of ever emerging new devices. The printing ink, which is composed of filler, binder, solvent and additives, is among the most important elements in the printing process. To obtain good dispersity of filler and control the ink's viscosity, many factors should be taken into consideration, such as curing temperature, viscosity, wetting and adhesion, mechanical stability and shrinkage. In this research, various types of polymers are synthesized and characterized for their application as binders in printing inks. The molecular weights and conversion of the polymers are optimized to achieve desirable characteristics for binders. To increase the electrical conductivities of printing inks, conductive polymers such as polyaniline and PEDOT: PSS are also studied for their applications as binders. In this work, the electrical conductivities of the synthesized polymeric binders are characterized by a four point probe automatic resistivity meter.

8691-27, Session 10

Synthesis and properties of cellulose functionalized -4, 4'-(propane-2, 2'-diyl) diphenol-SiO2/TiO2 hybrid nanocomposites materials for high-performance applications

Sivalingam Ramesh, Gwang-Hoon Kim, Chosun Univ. (Korea, Republic of); Heung Soo Kim, Dongguk Univ. (Korea, Republic of); Jaehwan Kim, Inha Univ. (Korea, Republic of); Joo-Hyung Kim, Chosun Univ. (Korea, Republic of)

The general class of organic-inorganic hybrid nano-composites materials is a fast growing area of research. The significant effort is focused on the ability to control the nanoscale structures via organic functional synthetic approaches with inorganic metal oxides. The properties of nano-composites material depends on the properties of their individual components but also their morphological and interfacial characteristics. This rapidly expanding field is generating many exciting new materials with novel properties. Mainly, cellulose is considered as the richest renewable materials are presently among the most promising candidates for use in photonics due to their versatility, flexibility, light weight, low cost and ease of modification. Cellulose-metal oxide nano-materials were developed the technologies to manipulate self-assembly and multi-functionallity, of new technologies to the point where industry can produce advanced and cost-competitive cellulose metal oxide hybrid materials. Therefore, the present study is focused on cellulose–functionalized -4, 4'-(propane-2, 2'-diyl) diphenol-SiO2/TiO2 hybrid nano-composites materials by in-situ sol-gel process. The chemical and morphological properties of cellulose-functionalized SiO2/TiO2 materials via covalent crosslinking hybrids were characterized by FTIR, XRD, TGA, DSC, SEM, TEM and optical properties.

8691-28, Session 10

Printed tandem photovoltaic/thermoelectric device

Hyun Jung Kim, National Institute of Aerospace (United States); Jungmin Lee, Vijay K. Varadan, Univ. of Arkansas (United States); Sang H. Choi, NASA Langley Research Ctr. (United States)

Thermalization during the photovoltaic process results in efficiency losses that could be recovered by a hybrid photovoltaic (PV) /thermoelectric (TE) device. The photovoltaic portion converts the solar energy into electricity using the photovoltaic process. Traditional PV systems ignore the thermal portion of the solar energy, but a hybrid PV/TE device can convert also the thermal portion of solar energy into electricity. A PV/TE tandem system typically consists of a PV module attached to an absorber plate. Not only does the absorber plate cool the PV module to improve its electrical performance, it also serves to collect the thermal energy produced, which would have otherwise been rejected to the environment as heat.

We highlight the advancement and progress in the field of flexible solar PV/TE modules. Our research is focused on developing a thermoelectric ink to improve the efficiency of the flexible PF/TE device at a low cost. The ink prepared for a roll-to-roll printing process should have low viscosity for easy application to the substrates. Drying time and temperature also need to be controlled for proper formation of the TE patch with acceptable adherence to the substrate. Bi2Te3-based alloy is a promising candidate for the tandem photovoltaic/thermoelectric generator since the Bi2Te3-based alloys show high thermoelectric performance around room temperature. Nano-scale powder of Bi2Te3 is added to epoxy resin and polystyrene to create the ink for the roll-to-roll printing process. Initial composite material properties show the proposed method as a promising low-cost, scalable method for manufacturing of photovoltaic/thermoelectric energy generators.

8691-53, Session PTues

Analysis of nano-indentation test for polycrystalline materials by modified strain gradient theory

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Indentation tests have been used to measuring the strength and hardness of materials. Moreover, micro and nano indentation have

become major tools for investigating the micromechanical properties of small scale volumes. However, it is well-known that the micro and nanoindentation hardness of materials shows the strong size effect. But the classical continuum plasticity can't predict these size effects in micro/nano scale, since the constitutive equation of the classical mechanics doesn't include the internal length as a parameter for the deformation.

The mechanism based strain gradient (MSG) plasticity is one of the methods to analyze non-uniform deformation behavior in micro/nano scale. The MSG plasticity is the multi-scale analysis connecting the micro-scale notion of the statistically stored dislocations (SSDs) and the geometrically necessary dislocation (GNDs) to meso-scale deformation using the strain gradient.

In this paper, modified strain gradient theory is proposed based on the nonhomogeneity of polycrystalline metallic materials. When the grains of crystalline metals deform, overlaps and voids appear at the grain boundary. These overlaps and voids can be corrected by the GNDs. By taking into account the nonhomogeneity of polycrystalline materials, the density of the GNDs due to the deformation is calculated. Consideration of the GNDs on the grain boundary give a relationship between the size effect and the hardness. This relationship can explain the indentation size effects in micro/nano scale. Using the proposed model, analysis of the effect of indent size and grain size under the nanoindentation test of polycrystalline materials is carried out.

8691-54, Session PTues

Film-type haptic array actuator made with cellulose acetate

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This paper reports a film type haptic actuator made with cellulose acetate. To make users more concentrated on mobile devices, film type tactile haptic actuator is essential. This film type haptic actuator can surpass the technology barriers of eccentric motor type haptic actuators in terms of transparency, broad frequency band, and positioning of haptic feeling. An element of haptic actuator is made by using cellulose acetate film, which is transparent, flexible with high dielectric constant. The haptic actuator elements arrayed to 3 x 3 to comprise a haptic device. To evaluate the performance of 3x3 array haptic actuator, its output acceleration and displacement depending on the actuation frequency and voltage are investigated. For the design of the actuator, a simple lumped parameter model is made and the model is verified by comparing the analysis results with experimental ones.

8691-55, Session PTues

Hardware efficient seizure prediction algorithm

Sergi Consul, Bashir I. Morshed, Robert Kozma, Univ. of Memphis (United States)

Epilepsy affects 2.5 million people in the USA, 20% of which cannot be treated with traditional methods. Effective treatments require reliable prediction of seizures to increase their efficacy and quality-of-life. Phase synchronization phenomenon of two distant neuron populations for a short period of time just prior to a seizure is utilized for such prediction. This paper presents a hardware efficient prediction algorithm using phase-difference method instead of the commonly used phase-locking method. The dataset has been collected from publicly available "CHB-MIT Scalp EEG Database" and consists of scalp EEG recordings from 22 pediatric subjects with intractable seizures. The seizure channel is selected based on the maximum value of the standard deviation during seizure, while the reference channel has the minimum value of the standard deviation. Data from these two channels are conditioned with a band-pass (flc = 10Hz, fhc = 12.5Hz) 6th order Chebyshev Type II filter. Analytic signals are derived using Hilbert Transform to allow phase extraction. Phase synchronization is calculated from the mean of the phase-differences using an overlapping sliding-window technique with threshold-based classification. Preliminary results for one subject (Chb1) with 7 seizure episodes correlate with the phase-locking method and show an average prediction time of 7.52 minutes with a standard deviation of 6.33 minutes with accurate prediction of each episode. The minimum prediction time is 53 seconds that would be sufficient to engage an automated treatment mechanism like VNS. The phase-difference method is 2.35 times faster than phase-locking, and yields lower hardware requirement and reduces computational complexity.

8691-56, Session PTues

The model of random signals generated by optical particle counter and the instrument improvement

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In order to study and improve atmospheric and air pollution monitoring sensor, a new mathematical model of random signal is established based on random process of light scattering signals analyzed by laser particle counter which combines the high-speed data acquisition card PCI-9812 and optical particles counting sensor. The measured random signals can be divided into stability constant part and random fluctuation part.

Theoretical analysis shows statistical distributions of random fluctuation part which reflects the randomness of measuring process obey the relationship of nonlinear transform. Statistical distributions of different characteristics such as, the signal amplitude, the signal width, the amplitude of extreme, the interval between extreme points, the subtraction of adjacent amplitudes, the product value of the quantities and the quotient value of the quantities of this part in the same random process are studied by experiments and results show statistical distributions match well with lognormal distribution with a natural number as an independent variable. The lognormal distribution plays an important role in describing the random fluctuation characteristics of random process in both theories and experiments.

Applying both model and analytical methods, a semiconductor laser particle counter based on optical sensor with mass flux, high signal-to-noise ratio, particle size resolution and counting efficiency is designed. The new optical sensor has great improvement compared to other proposed devices before since its flow rate is 28.3L/min with more than 90% counting efficiency and particle size resolution (the 0.4um, 0.6um standard particles from Duke Scientific Corporation are measured by 0.3um and 0.5um channels). The signal to noise ratio at minimum particle size could be more than 4:1. We believe this improved optical sensor could play an important role in real-time monitoring of environmental particulate pollution and other fields.

8691-29, Session 11

Microwave syntheses of graphene-based 3D hybrid nanostructures and their applications to energy storage systems

Seok-Hu Bae, Il-Kwon Oh, KAIST (Korea, Republic of)

In this study, two microwave syntheses for graphene-carbon nanotube-Nickel three-dimensional nanostructures have been developed for anode materials for lithium ion battery. These fabrication methods provide efficient solutions to the time consuming problem of the chemical vapor deposition which has been used for 3D hybrid nanostructures. The graphene-based 3D nanostructures show that the carbon nanotubes are grown on the graphene sheets and Ni nanoparticles are inducing

the growth of carbon nanotubes. The morphologies of 3D hybrid nanostructures are characterized by scanning electron microscopy and transmission electron microscopy. Furthermore, graphene-based 3D hybrid nanostructures are characterized by Raman spectroscopy, X-ray photoelectron spectroscopy and electron energy loss spectroscopy. The incorporation of graphene and CNT contributes not only to enhancing the high surface to volume ratio, but also to minimize restacking and aggregation of graphene sheets. Thus, it helps larger active sites as an anode electrode for lithium ion battery. These exceptional characteristics of graphene-based 3D hybrid structures decorated with NiO nanoparticles have high specific capacity and cycle stability and are also expected to make favorable effects for electrical devices.

8691-30, Session 11

3D rf integration at VTT

Tauno Vaha-Heikkila, VTT Technical Research Ctr. of Finland (Finland)

Integration of multiple chips and functions to the same radio module is a key issue when the size of radio front-end is tried to minimize. VTT Technical Research Centre of Finland has developed both Low Temperature Co-fired Ceramics (LTCC) and Integrated Passive Devices (IPD) integration platforms for radio frequency (RF) integrated modules. Three dimensional (3D) integration technologies are enablers for realizing compact multi-chip modules with several different technologies in the same module.

VTT has developed its LTCC technology especially for high performance and demanding applications. In RF domain this means that the focus has been in microwave and millimeter wave components and modules. Full length paper describes latest achievements especially in millimeter wave applications.

To meet high integration density, fine pitch and low cost needs, VTT has developed IPD integration platform focusing to consumer market segments. Commercial module technologies have typical pitch between two interconnects in the range of 200-300 um. On the other hand, CMOS, GaAs and other semiconductor chips are pad limited in size and would greatly benefit if fine pitch flip-chip could be used in modules. VTT's IPD can use pitch less than 100 um in chip to module integration. Full length paper shows example results on high Q inductors and capacitors as well as results on integration aspects.

8691-31, Session 11

Magnetic resonance coupling of power transmission for biomedical applications

Kyo D. Song, Hargsoon Yoon, Norfolk State Univ. (United States); Larry D. Sanford, Eastern Virginia Medical School (United States); Hyunjung Kim, National Insitute of Aerospace (United States); Sang H. Choi, NASA Langley Research Ctr. (United States); Eugene J. Song, National Insitute of Aerospace (United States)

This paper investigates magnetic resonance coupling (MRC) as a wireless power transmission source for bio-medical applications. Miniaturized coupled coil sets have been developed for implantable biomedical sensors using radio frequency waves. In this presentation, several MRC designs are tested for high efficiency of power transmission and experiment results from in vitro studies are analyzed. Their bio-safety features are also discussed and compared with microwave power transmission.

8691-32, Session 12

Nano-materials for chemical and mechanical testing applications

Behraad Bahreyni, Simon Fraser Univ. (Canada)

Synthesis, characterization, and applications of nanomaterials and nanocomposites are discussed in this talk. In the first part of the talk, application of nanomaterials for development of chemical sensors is covered. Special emphasis will be placed on the synthesis and deposition techniques as well as suitable techniques to take advantage of the opportunities offered by nanomaterials for chemical sensing. The second part of the talk overviews the application of nanocomposite materials for chemical sensing applications. The resistivity of an electrically insulating polymer can be reduced through addition conductive nanoparticles beyond a certain concentration limit, known as the percolation threshold. Conduction through the network of dispersed nanoparticles in a host material is a result of electrons hopping from adjacent conductive nanoparticles as imposed by the direction of the applied electric field. Resistors made from nano-composite polymers are sensitive to strain variations and can be used as piezoresistors. We have recently applied similar techniques to develop functionalized layers of paint. The functionalized paint can be used to measure local stresses and strains across a structure, provide information about dynamic loads, or monitor fatigue within the structure. The functionalized paint can be applied to the surface through a variety of scalable techniques. We will present experimental results obtained from various samples as well as methods to collect and process the data from a structure coated with functionalized paint.

8691-33, Session 12

Tailoring material properties with shaped femtosecond-laser pulses

Stefan Kontermann, Anna Lena Baumann, Thomas Gimpel, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany); Kay M. Guenther, Clausthal Univ. of Technology (Germany); Augustinas Ruibys, Andreas Gabler, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany); Wolfgang Schade, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany) and Clausthal Univ. of Technology (Germany)

For further driving the development of smart materials, new manufacturing technologies are necessary to obtain functionalized materials with characteristics tailored to the specific application requirements. In this work we present results from irradiating silicon, nickel, platinum, and zinc with different femtosecond laser pulses. We show first how the material surface properties can be adjusted depending on the laser pulse parameters. On all materials variable surface structure features are realized down to the nanometer range. The structural properties of the material surfaces are examined for different laser pulse parameters and investigated by Scanning Electron Microscopy. These structures find application in photovoltaics in form of homogenous surface textures of multi crystalline silicon for a very low reflectance. In the case of metals, the structrures supply a perfect surface for use as electrode material in fuel cells and new battery concepts like the air metal battery. Second, we demonstrate how the optical porperties of silicon can be changed by this laser process, resulting in absorption of light at infrared wavelengths with smaller energies than the corresponding band gap of silicon. We clarify that the origin is an intermediate band of energy states within the band gap of silicon. The absorption properties of this laser structured silicon enables the absorption of infrared light contained in the sun spectra od other sources of heat and can be used as substrate for infrared sensors. Third, for suppling a dopant in the atmosphere of the silicon laser process, silicon can be doped beyond the thermal solubility of the dopant. Further we show superhydrophobic behavior of all structured material by repelled water drops. In conclusion, we show that the femstosecond laser pulse process is a powerfull tool to synthesize smart materials featuring adjustable characterisitcs with a variety of applications in energy conversion and sensors.

8691-34, Session 12

Electromagnetic characteristics of Polyaniline/SWCNT composites

Brahmanandam Javvaji, D. Roy Mahapatra, S. Raha, Indian Institute of Science (India)

Electromagnetic field interactions with the composites made up of polyaniline (PANI) and single wall carbon nanotube (SWCNT) are simulated using the discrete dipole approximation. Recent observations on polymer nano-composites explain the interface interactions between the PANI host and the carbon nanostructures. These types of composite have potential applications in organic solar cell, gas sensor, bio-sensor and electro-chromic devices. Various nanostructures of PANI in the form of nanowires, nanodisks, nanofibers and nanotubes have been reported. In the present study, we considered the nanotube type structure of PANI. These nanotubes are modeled using coarse grained model of conducting PANI emeraldine salt form. We use first principle method to calculate the frequency dependent dielectric constant of the PANI nanotubes. Absorption spectra of PANI nanotubes are studied by illuminating a wide range of electromagnetic energy spectrum. From the absorption spectra, we observe plasmon excitation in near-infrared region similar to that in SWCNTs studied recently. Composite structures like CNT surrounded by PANI nanotubes and CNTs wrapped by pristine PANI are also simulated and their electromagnetic properties like excitation of Plasmon resonance modes, electric filed distributions etc. will be reported in the paper.

8691-35, Session 12

Strain measurements on scattered, highly oriented CNTs

Sebastian M. Geier, Thorsten Mahrholz, Johannes Riemenschneider, Peter Wierach, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany); Michael Sinapius, Technical Univ. of Braunschweig (Germany)

Since carbon nanotubes (CNTs) are public discovered 1991, worldwide scientific research reveals excellent properties. Most of the found properties refer to almost defect-free, single-walled carbon nanotubes (SWCNTs) with nano-scale dimensions. However, scientists try to incorporate CNTs into applications to transfer their properties in order to push a specific performance. Typically the results are comparably lower than expected because of the varying quality of produced CNTs.

This paper presents results of research using CNTs as actuators. While published research analysed architectures of entangled CNTs as active component, like papers or yarns, to measure their bulk-strain this paper focuses on scattered, highly aligned CNTs. This approach promises to clarify the effect of actuation, whether it is a quantum-mechanically, or rather an electro-static effect or even caused by volume-transfer.

Two experimental set-ups are presented. The first experiment is carried out using highly aligned multi-walled CNTs (MWCNT-arrays) as substrate. The CNT-array is optically analysed along the longitudinal geometry of the vertically aligned MWCNTs. The interfaces of the set-up, which may influence the measurement, have been analysed in order to avoid second-order effects like thermal swelling or chemical degradation. The results reveal comparable high deflections starting at an activation-voltage of ±1,75V. The ionic liquid is tested within a voltage-range of ±2V due to time-staple performance.

The second test-campaign is carried out using Raman-spectroscopy to analyse single SWCNTs. Results in terms of shifting peaks according to the intensity and wave number can be directly attributed to a geometry-change.

The two presented experiments intend to find correlating results in order to identify the main effects of the measured free strain.

8691-36, Session 12

Atomic layer deposited Al-doped ZnO films for optoelectronic applicatins

Aswini K. Pradhan, Rajeh Mundle, Norfolk State Univ. (United States)

Al-doped ZnO (AZO) films were deposited by the atomic layer deposition (ALD) on both glass and sapphire (0001) substrates. The Al composition of the films was varied by controlling the Zn:Al pulse cycle ratios. The films were characterized by the atomic force microscopy (AFM), X-ray photoelectron spectroscopy (XPS), X-ray diffraction (XRD) and optical measurements. The Film resistivity was measured as a function of Zn:Al cycle ratios as well as temperature for films grown at various substrate temperature used for ALD deposition. The resistivity of the ALD grown films decreases significantly, and so as the increase in the carrier concentration as the cycle ratio increases. The systematic measurements of temperature dependence of resistivity of films at various cycle ratios clearly demonstrate the crossover of the metal-semiconductor-insulator phase with the function of temperature as well as the cycle ratios. The average transmission of all films is greater than 85% and the optical absorption increases significantly in the visible region as the cycle ratio increases. We observed a remarkable dependence of photo-resistance on electrical conductivity for ALD-grown films with varying cycle ratios, which control the Al content in the film. Our results suggest that Al3+ ions are incorporated as substitutional or interstitial sites of the ZnO matrix. However, an addition of an excessive amount of Al content causes the formation of Al2O3 and related clusters as carrier traps opposed to electron donors, resulting in an increase in the resistivity and other associated phenomena.

8691-37, Session 13

Moving technology from test tube to commercial product: a case study of three inventions *(Keynote Presentation)*

Robert G. Bryant, NASA Langley Research Ctr. (United States)

No Abstract Available

8691-38, Session 14

New highly-magnetic binary phase system

Leisha M. Armijo, The Univ. of New Mexico (United States)

A new phase in the binary iron nitrogen system having high magnetic moments was predicted previously with density-functional electronic structure calculations. We have engineered and characterized highly magnetic α”-Fe16N2 colloidal nanocrystals at low temperatures while incorporating a green-chemistry method for their production. Fe16N2 nanocrystals with different morphologies may also be synthesized via our novel procedure. The metastable iron nitrides are elusive and previous work in this area has resulted in a low yield of the highly magnetic polymorph α”-Fe16N2. As a response to the lower size limit that neodymium magnets may be formed (>200 microns), the difficulty in synthesizing large homogeneous quantities of α”-Fe16N2 is elusive and the two methods may cover a broader range of magnetic materials on the nanometer and micrometer size range. Additionally, this material is more magnetic than iron-cobalt with an anticipated lower toxicity for biological applications. Also, this element will reduce our dependence on costly rare-earth magnets. In order to impart optical properties we have coated the Fe16N2 nanocrystals with phosphine, cadmium, and arsenic-free semiconductor quantum dot (QD) shells. These particles are of interest for magnetic recording devices, MRI contrast agents, magnetic gradient-guided drug or gene transport, and biolabeling.

8691-39, Session 14

Preparation and electrochemical properties of spinel lithium manganese oxide

Gaojun Wang, Shaoxing Univ. (China); Linfeng Chen, Gyanesh N. Mathur, Vijay K. Varadan, Univ. of Arkansas (United States)

Spinel lithium manganese oxide ($LiMn_2O_4$) is a favorable cathode material for lithium secondary batteries due to its low cost and environmental suitability. Further, because of its high electrochemical potential, $LiMn_2O_4$ has been considered as a promising cathode material for high power lithium ion batteries, such as the high power batteries for electric vehicles. However, the electrochemical properties of $LiMn_2O_4$ are strongly influenced by the synthesis conditions. In addition, the cycling stability and structural stability of $LiMn_2O_4$ at high temperatures should be further improved before this material can be practically used in high power lithium ion batteries. In the present paper, the electrochemical properties of spinel $LiMn_2O_4$ synthesized via a solid state reaction were studied. The influence of the synthesis conditions, such as sintering time and temperature, on the electrochemical properties of spinel $LiMn_2O_4$ was investigated.

8691-40, Session 14

Electrical and electromechanical behaviors of ZnO-cellulose hybrid nanocomposites

Seongcheol Mun, Hyun-U Ko, Inha Univ. (Korea, Republic of); Byung-Woo Kang, Samsung Electro-Mechanics (Korea, Republic of); Jaehwan Kim, Inha Univ. (Korea, Republic of)

Cellulose films coated with ZnO nanoparticles constitute an important material for practical applications ranging from the film paint industry to the technologically appealing area of optoelectronic paper. ZnO-cellulose hybrid nanocomposite was fabricated by growing ZnO on regenerated cellulose directly. This organic-inorganic nanocomposite exhibits excellent piezoelectric behavior. This paper reports electrical and electromechanical behaviors of the ZnO-cellulose hybrid nanocomposite. The fabrication process is briefly introduced, and induced voltage, remnant polarization as well as piezoelectricity between cellulose substrate and ZnO-layers are investigated. Also its charging and discharging behaviors are studied, and its application possibility for super capacitor, paper battery, field effect transistor will be discussed.

8691-41, Session 14

Study of the electrochemical properties of hematite, magnetite, and maghemite nanoparticles for their applications in lithium ion batteries

Linfeng Chen, Univ. of Arkansas (United States); Gaojun Wang, Shaoxing Univ. (China); Jungmin Lee, Pratyush Rai, Gyanesh N. Mathur, Vijay K. Varadan, Univ. of Arkansas (United States)

Iron oxide nanoparticles, including hematite, magnetite and maghemite, are promising electrode active materials for lithium ion batteries due to their low cost, high specific capacity and environmental friendliness. Though the electrochemical properties of each type of iron oxide nanoparticles have been studied by many researchers, systematic comparison of the three types of iron oxides is hardly reported. This paper reports the study and comparison of the electrochemical properties of hematite, magnetite and maghemite nanoparticles with the same shape and size. In this work, hematite and maghemite nanoparticles were obtained from commercial magnetite nanoparticles by thermal treatments at different conditions. Their crystalline structures were characterized by X-ray diffraction (XRD) and their particle morphologies were analyzed by scanning electron microscopy (SEM). Composite electrodes were made from iron oxide nanoparticles with carbon black as the conducting material and PVDF as the binding material (iron oxide : carbon black : PVDF = 70 : 15 : 15). Prototype lithium ion batteries (CR2032 button cells) were assembled with the composite electrodes as cathodes, metal lithium as anodes, and Celgard 2400 porous membrane as separators. The impedance and discharge/charge behaviors were characterized by a Solartron electrochemical workstation and an Arbin battery tester, respectively.

8691-42, Session 15

Review of Sn and Se based binary/turnery semiconductors and schottky diodes: material aspects and current transport

Naresh Padha, Univ. of Jammu (India)

No Abstract Available

8691-43, Session 15

Visualization of interior substructures with nanoscale resolution using ultrasonic-atomic force microscopy

Dongryul Kwak, Taesung Park, Ikkeun Park, Chiaki Miyasaka, Seoul National Univ. (Korea, Republic of)

Nondestructively visualizing interior structures of a material is an important task for an application in the field of material science. As the increase the reliability and repeatability of the nano structured material, many advanced techniques have been developed to obtain subsurface images with nano-scale resolution. In this study, Ultrasonic-Atomic Force Microscopy (U-AFM) has applied to visualize the interior structures of an ultra-thin film system. The cantilever of U-AFM is vibrated, and the tip of cantilever is in contact with sample surface. The cantilever vibration includes information about local tip-sample contact stiffness. The stiffness may be able to measured by using cantilever contact resonances. The amplitude and the phase of the cantilever resonance frequency may be changed by the contact stiffness between the cantilever tip and the condition of the sample surface. Therefore, the U-AFM can obtain the topographic and the elastic images (i.e., amplitude and phase images) of surface/subsurface. We have manufactured a specimen including a nano-structured resolution patterns deposited on the surface of the silicon (100). The surface is covered by a polymer (i.e., SU-8) by spin coating method. We clearly visualized the pattern via the SU-8 by using the U-AFM. Therefore, we have proved the U-AFM can visualize the nano-scale interior structures within the specimen.

8691-44, Session 15

Hybrid nanocomposites made with cellulose and ZnO nanoparticles and its biosensing application

Mohammad Maniruzzaman, Ulo Kersen, Mohammad A. H. Khondoker, Jaehwan Kim, Inha Univ. (Korea, Republic of)

This paper reports an inexpensive, flexible and disposable cellulose-ZnO hybrid nanocomposite (CZHN) and its feasibility for a conductometric glucose biosensor. CZHN was fabricated by simply blending ZnO nanoparticles with cellulose solution prepared by dissolving cotton pulp with lithium chloride/N, N-dimethylacetamide solvent. In this process, sodium dodecyl sulphate was used as a dispersing agent of ZnO. CZHN was cured in isopropyl alcohol and water mixture and free standing film was obtained. CZHN was characterized by taking its morphology and elemental analysis. For biosensor application, the enzyme glucose oxidase was immobilized into this CZHN by physical adsorption method.

The enzyme activity of the glucose biosensor increases as the ZnO weight ratio increases. The linear response of the glucose biosensor is obtained in the range of 1-12mM. This study demonstrates that cellulose-ZnO nanohybrid film can be a disposable type glucose biosensor.

8691-45, Session 15

1D ZnO nanoarray using electron-beam lithography

Aswini K. Pradhan, Norfolk State Univ. (United States)

We have prepared Al: doped ZnO (AZO) seed layers of ~280 nm thick on the glass substrate using RF magnetron sputter at an ambient of 3500C. The samples were patterned using Electron beam lithography at different beam energies of 20, 10, 5, and 2 keV. Patterned samples were processed for growth of ZnO nanorods using hydrothermal technique in a solution of using Zn (NO3)2 and hexamethylenetetramine (HMT) at 900C for 4 hrs. After successive ZnO growth, it was coated with PMMA and the unexposed PMMA were lifted-off. At higher beam energy (~ 20 keV), the incident electron beam decelerates due to the accumulated negative charges that already built on the surface in due course of irradiation. This causes a negative shielding potential close to the surface at micron level, and completely unfavorable for the attachment of the negative ZnO carriers. However, at a comparatively lower beam energy (~ 5 keV or less), the secondary electrons (SE) are responsible for the pattern with the irradiation zone centered by the local positive field. Therefore, the negatively charged ZnO NRs can be controlled at lower voltages and put site selective attachments at increasing the dose.

8691-46, Session 15

Fabrication of CZTS-based thin film solar cells using all-solution processing and pulsed light crystallization

Ilwoo Seok, Carson Munn, Shivan Haran, Arkansas State Univ. (United States)

Solar cells are a viable solution for the production of environmentally friendly energy. In this research, a thin film based photovoltaic material is being developed, which will be highly efficient when it comes to its optical properties and manufacturing cost. The thin film solar cell is composed of Copper, Zinc, Tin, and Sulfide or 'CZTS' and contains chemicals which are both earth-abundant and non-toxic. All-solution process is based on a single-step electro-chemistry deposition that provides all constituents from the same electrolyte. This was investigated earlier by our group with a high degree of success. This is followed by a photo-thermal energy driven sintering process to form a CZTS material from as-deposited chemicals. This enables as-deposited chemicals to be covalently bonded and crystallized without using costly vacuum process. In post-heat treatment, a home-made intense pulsed lighting (IPL) system was utilized for rapid thermal annealing. The successful deposition of the CZTS thin film was then evaluated and analyzed using cyclic voltammetry (CV), SEM/EDAX, and XRD. It has been concluded that this method of photovoltaic thin film fabrication is truly comparable to the conventional deposition and annealing methods in terms of photovoltaic efficiency and cost-effectiveness.

8691-47, Session 15

Detection and control of sigma-3 twin defects in semiconductor ingot and epitaxy growth

Yeonjoon Park, Hyunjung Kim, National Institute of Aerospace (United States); Jonathan R. Skuza, NASA Langley Research Ctr. (United States); Kunik Lee, Turner-Fairbank Highway Research Ctr. (United States); Sang H. Choi, NASA Langley Research Ctr. (United States)

No Abstract Available

8691-48, Session 16

Nanoscale imaging of mesh size distribution in gel engineering materials with visual scanning microscopic light scattering

Yosuke Watanabe, M. Hasnat Kabir, Jin Gong, Hidemitsu Furukawa, Yamagata Univ. (Japan)

Gels have unique properties such as low frictional properties, external-field responses, high water content like soft tissues in the human body. By using these superior properties, gels have been tried to apply to medical devices. In the scene of developing medical devices and materials, the importance of characterizing the structure and mechanical properties of gels is rising. However, the static inhomogeneities in gels prevented people from observing the structure of gels by scattering method. To solve this problem, scanning microscopic light scattering (SMILS) was originally developed. In this system, the resulting data are the relaxation-time distribution corresponding to the mesh size distribution of gels, which are very important in characterizing physical properties of soft matters. Here we show the new system named Visual-SMILS that can output the 2-dimentional data of the distribution. We tried to develop a new apparatus and implement original software to the system. On the hardware side, the new apparatus differs from SMILS in that it use three laser sources, inverted microscope and the galvanometer mirror that can scan the laser in 2D field in order to get the 2D data at fixed scattered angle. On the software side, the mapping data is represented in Visual-SMILS. To confirm whether it measures the size accurately, polystyrene particles were used as the samples. In addition, poly-N,N-Dimethylacrylamide (DMAAm) gels were analyzed for comparing the results from diverse systems. In both cases, the results of the Visual-SMILS are close to another one. We believe the Visual-SMILS will provide user-friendly interface and promote research in gels.

8691-49, Session 16

Characterization of shape-memory gels using scanning microscopic light scattering

M. Hasnat Kabir, Yosuke Watanabe, Jin Gong, Hidemitsu Furukawa, Yamagata Univ. (Japan)

Soft and Wet material explore the new area of application as an industrial material especially for medical applications. Shape memory gels are one kind of unique soft and wet material bearing a shape recovery property which is suitable for medical application such as bandage for broken bone or making optical lens and so on. Several fundamental characteristics of gels, for instant, softness, water absorbance, transparence, extremely low friction, and biocompatibility, are promising as a next generation of industrial materials. In the present study, we characterize internal structure of shape memory gels by scanning microscopic light scattering (SMILS), which is a dynamic light scattering system specialized for analyzing the microscopic structure in gels. SMILS is our own laboratory equipment. It has scanning as well as multi-angle facilities. Photo multiplier tube is used as a photon detector whereas He-Ne laser of 532 nm wavelength is used as a light source. A computer

GUI environment can acquire data and able to analysis. The mesh size of internal structure of shape memory gels is determined by SMILS and it is found in several nm in size. The density of elastically effective chain is possibly calculated from the mesh size of internal structure. The relation between the internal network structure and mechanical properties of the gels is discussed.

8691-50, Session 16

Modelling of the structure-property relationships in the α-quartz structures

Yong Tao Yao, Harbin Institute of Technology (China)

An auxetic material is one which gets fatter when it is stretched. Thus, unlike most materials, it has a negative Poisson's ratio. Materials with a negative Poisson's ratio can have enhancements in other physical properties, including increased indentation resistance, increased plane strain fracture toughness and an ability to form synclastic doubly curved surfaces. In order to develop this area further, a detailed understanding of the mechanisms and geometries necessary to realise auxetic behaviour at the nanoscale is required. In this project, the Cerius2 molecular modelling software (Accelrys Inc) is used to model structure-property relationships of auxetic materials (such as quartz and cristobalite) at the atomistic and molecular level. Such materials subject to hydrostatic and uniaxial stress loading in each of the 3 principal directions will be investigated. The strain-dependent structure and mechanical properties will be predicted from the simulations, including the transformation from positive-to-negative Poisson's ratio behaviour and vice versa.

8691-51, Session 17

Design and development of nanostructured artificial materials for radar and ladar applications

Vijay K. Varadan, Univ. of Arkansas (United States); Paul B. Ruffin, Eugene Edwards, Christina L. Brantley, U.S. Army Research, Development and Engineering Command (United States)

In this paper, a new generation of nanostructured artificial materials incorporating negative refractive index using nano-and micro-coils, periodic arrangement of plasmonic conductors, Frequency Selective Surface (FSS), is designed, implemented and characterized for their potential application in the development of RADAR and LADAR applications. Microstereo Lithography and Electron Beam Lithography are used to fabricate these micro-and nano-structures. Potential applications of these materials for broad band EM absorbers, military remote sensing, spectroscopic identification of explosives or chemicals, battlefield medical diagnosis, etc will be presented in the talk.

8691-52, Session 17

A novel nanoscaled force sensor based on silicon photonic crystal

Tianlong Li, Longqiu Li, Wenping Song, Guangyu Zhang, Yao Li, Harbin Institute of Technology (China)

With advantages of ultracompact size, high resolution, and easy integration, nano-scaled force sensors based on photonic crystal are widely used in microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS). The performances of these nano-scaled force sensors are mainly determined by nanocavity and line defect. The principle of the sensor is that the output wavelength of the force sensor using photonic crystal varies as a function of force and pressure. In this work, a novel nano-scaled force sensor based on silicon photonic crystal, in which a nanocavity is embedded in an S-shaped elastic body, is developed and studied numerically and experimentally. The relationship between the force and the output wavelength is determineded using finite element method and finite difference time-domain method. The effect of the nanocavity geometry, length of the line defect and material properties of photonic crystal are investigated. In addition, the nano-scaled force sensor is developed by deep reactive ion etching (DRIE). A comparison between the numerical and experimental results is provided.

Conference 8692: Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems

Sunday - Thursday 10–14 March 2013

Part of Proceedings of SPIE Vol. 8692 Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2013

8692-1, Session 1

Structural health monitoring of large-scale structures: from diagnostics to prognostics

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The development of structural health monitoring (SHM) technology has evolved for over fifteen years in Hong Kong since the implementation of the "Wind And Structural Health Monitoring System (WASHMS)" on the suspension Tsing Ma Bridge in 1997. Five cable-supported bridges in Hong Kong, namely the Tsing Ma (suspension) Bridge, the Kap Shui Mun (cable-stayed) Bridge, the Ting Kau (cable-stayed) Bridge, the Western Corridor (cable-stayed) Bridge, and the Stonecutters (cable-stayed) Bridge, have been instrumented with sophisticated long-term SHM systems. Recently, an integrated structural health monitoring and maintenance management system (SHM&MMS) has been designed and will be implemented on twenty-one sea-crossing viaduct bridges with a total length of 9,283 km in the Hong Kong Link Road of the Hong Kong – Zhuhai – Macao Bridge of which the construction commenced in mid-2012. The successful implementation and operation of SHM systems for the bridges and experiences gained by practice and research in the past two decades have also promoted extended applications of this technology from long-span bridges to high-rise structures. The instrumented Canton Tower of 600 m high is such an engineering paradigm of the application of SHM technology to high-rise structures.

Over the past fifteen years, the SHM system deployed on the Tsing Ma Bridge has acquired the monitoring data of the environmental effects on and structural responses of the bridge during 47 typhoons (gales, storms and hurricanes). The instrumentation system for the Canton Tower has monitored the structural responses during nine typhoons and over ten earthquakes in the past five years. The long-term data continuously acquired under normal and extreme loading conditions are forming important assets that are greatly beneficial to offering solutions to a number of 'grand challenge' problems in the SHM field: How did the SHM system provide economic and technical benefits to the life-cycle structural maintenance and management? How about the survival rate of the deployed sensors and the performance deterioration of the sensors, data acquisition and transmission units after long periods of time? Can the cumulated monitoring data be used for predictive structural assessment or damage prognosis? Is the SHM useful when the service life of the sensors is shorter than the service life of the structure? Is the target of structural health assessment and damage detection still achievable when the deployed sensors are partially damaged/malfunctioning after a time period? In this presentation, the author tries to get answers to some of the above issues through exploring a self-evolutionary framework for structural health/condition diagnosis and prognosis intended to progressively track and predict the evolution of structural performance with the help of long-term monitoring data.

8692-2, Session 1

Sensing platforms for structural health monitoring

Shijie Zheng, Northwestern Univ. (United States); Gautam Naik, Northwestern Univ. Ctr. for Quality Engineering (United States); Zhongbi Chen, Northwestern Univ. (United States); Yinian Zhu, Northwestern Univ. Ctr. for Quality Engineering (United States); Sridhar Krishnaswamy, Northwestern Univ. (United States)

The emerging concept of structural health management relies on extensive onboard diagnostic sensors that can provide near real-time information about the state of a structure so that informed prognostic assessment can be made of the continuing reliability of a structure. In this talk, we will discuss two types of sensing platforms that can provide valuable information about the state of a structure: 1D fiber-optic sensors and 2D thin-film sensors. Both fiber-optic and thin film sensors are easily integrated with structures, and can provide local and/or distributed sensing capabilities. Parameters that can be sensed include: static and dynamic strains, acoustic emission, vibration, corrosion products, moisture ingression etc.

We will first describe some recent developments in dynamic strain sensing using optical Fiber Bragg Grating sensors. Applications to detection of acoustic emission and impact will be described. In the area of chemical sensing, we will describe a Nanofilm-coated Photonic Crystal Fiber (PCF) long-period grating (LPG) sensing platform. PCF-LPG sensors can be designed to provide greater interaction between the analyte of interest and the light propagating in the fiber, thereby increasing the sensitivity of detection. Applications to humidity sensing will be described. Finally, 2D thin-film sensors on polymer substrates will be discussed. One type of sensor we have been fabricating is based on reduced graphene-oxide for large-area chemical sensing applications. It is expected that these 1D and 2D sensing platforms will form part of a suite of sensors that can provide diagnostic structural health information.

8692-3, Session 2

An analysis of fabrication methods for embedding particles sensors into a composite structure

Dustin L. Spayde, Oliver J. Myers, Mississippi State Univ. (United States)

The properties of highly magnetostictive materials, such as Terfenol-D, have opened the door to a wide variety of application possibilities. One such developing application is embedding magnetostictive particles (MSP) as sensors for determining the structural integrity of composite materials over the course of the operating life. The process of embedding these particles during the fabrication of the composite structure presents many challenges. This paper will briefly discuss and show the relationship between particle density and the output of a uni-axial induction based sensor. This relationship is critical for defining the goal of embedding process in this paper, to create a uniform uni-axial distribution of particles within the composite structure. Multiple methods of embedding magnetostrictive particles into a composite structure are detailed and then compared to determine their relative effectiveness. Methods included are: a simple by-hand spread of particles onto uncured prepreg composite, using the controlled adhesiveness of the prepreg to separate particles, applying the particles using a unidirectional application tool, introducing the particles into the epoxy mix to create a slurry during a VARTM layup, and spraying the particles onto a tacky composite surface during layup. Each method is used to embed particles into a composite beam or analog beam. That beam is then scanned with the uni-axial induction sensor to determine the effectiveness of the method. Results show promise for the unidirectional application tool, and spray methods while the remaining processes show critical flaws.

8692-4, Session 2

Integrated strain sensor for damage detection using shape-memory polymer and carbon nanotubes

Yingtao Liu, Arizona State Univ. (United States); Abhishek

Rajadas, McClintock High School (United States) and Peggy Payne Academy (United States); Aditi Chattopadhyay, Arizona State Univ. (United States)

Sensor development is critical for the damage detection, localization, and prognosis of composite structures. The ideal sensors should be robust to environmental effects, sensitive to damage initiation, and reliable during the service life. A novel strain sensor which can be integrated within carbon fiber reinforced composites will be developed in this paper using aliphatic urethane shape memory polymers (SMP) and multi-walled carbon nanotubes (MWCNTs). The SMP will be synthesized using two monomers: N,N,N',N'-tetrakis (hydroxypropyl) ethylenediamine (HPED) and hexamethylene diisocyanate (HDI). MWCNTs will first be treated using a mixed solvent of nitric acid and sulfuric acid, and then uniformly dispersed within monomers during the fabrication of SMP. The developed SMP reinforced by MWCNTs will be fabricated into fibers. The piezoresistance capability will be characterized and used as the sensing function for the strain measurement. The novel strain sensors will be integrated within carbon fiber reinforced composites and used for the damage detection under complex loading conditions.

8692-5, Session 2

Simultaneously monitoring of electrical resistance and optical absorbance signals of an polyaniline membrane coated on an gold jacketed optical fiber for gas sensing

Shiquan Tao, Shuai Shao, Yu Huang, West Texas A&M Univ. (United States)

Abstract: Electrical conductivity sensors and optical sensors are the mostly reported gas sensors. The transducer of an electrical conductivity gas sensor is usually a semiconductor membrane or a conductive polymer membrane. When exposed to a gas sample containing the target analyte, the resistance of the membrane changes, which is detected with an electrical device as a sensing signal. In an optical gas sensor using a membrane coating, the adsorption of analyte gas molecules to the membrane or the reaction of analyte gas molecules with sensing reagents in the membrane changes the optical properties of the membrane. In almost all the reported gas sensors, only an electrical signal or an optical signal was monitored as a sensing signal. However, the adsorption of analyte molecules onto the sensing membrane or the reaction of analyte with sensing reagents in the membrane can cause the change of both electrical and optical properties. This paper reports a new method in designing a special optical-electrical sensor, which measures both electrical resistance and optical absorption spectrum as sensing signals. A gold-jacketed optical fiber was used in sensor design. The gold jacket of a short part of the fiber was removed, and a polyaniline membrane was coated on the surface of the optical fiber core. The electrical resistance and optical responses of such a coated optical fiber probe to ammonia and moisture in nitrogen gas samples were monitored as examples to demonstrate usefulness of the reported technique in sensor development.

8692-6, Session 2

Effects of coating thickness of metal-coated optical fiber sensors on strain transfer

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The optical fiber sensors (OFSs) have been widely used for various applications. To predict the exact straining condition of the structures, much research on strain transfer analysis considering shear deformation has been undertaken. However, they cannot exactly measure the strain for the metal coated optical fiber sensors (OFSs), which achieve long-term stability, since the coating materials such as aluminum, indium, tin, zinc, copper, nickel, etc., show the elasto-plastic behavior when they transfer the load. Thus, considering elasto-plastic characteristics is required to evaluate accurate measurement. In this study, we focused on the aluminum coated OFSs bonded on composite structures. The theoretical model was proposed to derive the strain transfer solution for the elastic behavior. In addition, the numerical technique considering the elasto-plastic properties of the metal coating was developed for investigating the strain distribution of the OFS. The results of the present method were validated with those of finite element analysis (FEA) using commercial software ABAQUS, and they showed good agreement. Finally, the experimental verification was performed by using one of the OFSs, fiber Bragg grating (FBG) sensors with the different coating thickness. They were bonded on the surface of the unidirectional carbon fiber reinforced polymer (CFRP) composite specimens. As a result, the tendencies of strain transmission indicate that the strain transmission from the composites to the sensor core increase as the thickness of coating increase.

8692-7, Session 2

Graphene oxide nanosmart paint for structural health monitoring of composite structures

Inpil Kang, Pukyong National Univ. (Korea, Republic of)

This paper presents graphene oxide (GO) based nano smart paint which can monitor impact and structural deterioration of composite. The nano smart paint can monitor composite structure in real time for electrical impedance and piezoresistive signals indicating structural deterioration and impact which may be sufficient to cause damage. The smart nano paint can be easily installed on composite structures using a spray-on technique, making the sensor low cost and practical.

An impact applied to the composite structure can be detected by the highly sensitive nano smart paint. The impact makes deformation of the structure and it brings change of piezoresistivity of the paint and those converts into voltage output consequently by means of simple signal processing system. Deterioration due to cross-sectional damage or a crack can be detected using the dynamic strain response and electrical impedance changing patterns of the smart nano paint. Under crack propagation, the resistance of the smart paint is increased and the capacitance is decreased which can be converted into a voltage response change using a bridge electrical circuit. The increased resistance due to damage causes a higher amplitude voltage and the reduced capacitance induces a phase shift of the dynamic response

The nano smart paint is lightweight and easily applied to the structural surface, and there is no stress concentration. The nano smart paint is expected to be a cost effective and sensitive multi-functional sensor for composites and other damage monitoring applications in the field of structural health monitoring.

8692-8, Session 3

Vibration-based damage identification of reinforced concrete member using optical sensor array data

Chin-Hsiung Loh, Chi-Hang Li, National Taiwan Univ. (Taiwan); Chi-Hang Li, National Taiwan Univ (Taiwan)

The objective of this paper is to develop damage identification algorithm by suing the vibration data (displacement) from a dense optical sensing array data. The spatial dynamic displacement data is collected from an optical sensing system which consists of two major devices. One is the Target-based Photogrammetry that provides the ability to conduct dynamic measurement functions and full three dimensional tracking. The other device is OPTOTRAK® Certus which is the optical tracker. It will

track the optical laser flashed by the target system that marks on the specific points of the structure. The tracker has the ability to track how these three dimensional measurements change over time for dynamic motion measurement with RMS accuracy up to 0.1 mm. Data from a series of shaking table test of a reinforced concrete frame is used in this study. To analyze the recorded displacement data, first, the 3-D Affine transformation is used. Then the Singular Spectrum Analysis (SSA) is applied to the dense array data in order to construct the geometry deformation of each local element. The displacement non-continuity of each concrete block during the series of excitations is examined. Since the measured spatial locations can be treated as the nodes in each discrete element (or block), the concept of 2-D finite element model in which a four nodes quadrilateral (Q4) element is applied to each concrete block to generate the strain field. Finally, the correlation of damage identification among the local deformation, the reconstructed element strain and the dynamic features extracted from global information data (using both PCA and SSI) is discussed. It demonstrated that the strain values generated using optical sensor data can extract the features of local damage information.

8692-9, Session 3

Structural health monitoring of reinforced concrete shear walls by acoustic emission

Alireza Farhidzadeh, Ehsan Dehghan-Niri, Salvatore Salamone, Univ. at Buffalo (United States)

Reinforced Concrete (RC) shear walls are widely used in conventional building and safety-related nuclear structures. They provide much or all of a structure's lateral strength and stiffness to resist earthquake and wind loadings. The cracking behavior of these critical structural elements is crucial due to its harmful effects on structural performance such as serviceability and durability requirements. Currently the vast majority of inspections are visual, and unfortunately, even with the recent advances in automated ground-based nondestructive evaluation (NDE) methods, there is a potential that indications of structural degradation could be missed. In the past two decades, significant efforts have been made toward the development of structural health monitoring (SHM) systems in order to reduce life-cycle costs and improve safety of civil infrastructures. A technique that shows promises for monitoring RC structures is the acoustic emission (AE). This paper presents an experimental investigation of fracture processes of two large scale RC shear walls using AE parameters based on novel probabilistic algorithms

8692-10, Session 3

Hybrid networking sensing system for structural health monitoring of a concrete cable-stayed bridge

Marco Torbol, Ulsan National Institute of Science and Technology (Korea, Republic of); Sehwan Kim, Ting-Chou Chien, Masanobu Shinozuka, Univ. of California, Irvine (United States)

The purpose of this study is the remote structural health monitoring to identify the torsional natural frequencies and mode shapes of a concrete cable-stayed bridge using a hybrid networking sensing system. The system consists of one data aggregation unit, which is daisy-chained to one or more sensing nodes. A wireless interface is used between the data aggregation units, whereas a wired interface is used between a data aggregation unit and the sensing nodes. Each sensing node is equipped with high-precision MEMS accelerometers with adjustable sampling frequency from 0.2 Hz to 1.2 kHz. The entire system was installed inside the reinforced concrete box-girder deck of Hwamyung Bridge, which is a cable stayed bridge in Busan, South Korea, to protect the system from the harsh environmental conditions. This deployment makes wireless communication a challenge due to the signal losses and the high levels of attenuation. To address these issues, the concept of hybrid networking system is introduced with the efficient local power distribution technique. The theoretical communication range of Wi-Fi is 100m. However, inside the concrete girder, the peer to peer wireless communication cannot exceed about 20m, which is further decreased by the installed locations. However, the wired daisy-chained connection between sensing nodes is useful because the data aggregation unit can be placed in the optimal location. To overcome the limitation of the wireless communication range, we adopt a high-gain antenna that extends the wireless communication distance to 50m. Additional help is given by the multi-hopping data communication protocol. The 4G modem, which allows remote access to the system, is the only component exposed to the external environment.

8692-11, Session 3

A dual-mode imaging array for damage detection in concrete structures

Lingyu Yu, Zhenhua Tian, Liuxian Zhao, Univ. of South Carolina (United States)

Concrete structures have been widely used in civil engineering. Monitoring of defect in concrete structures is one of the important objectives of structure health monitoring. This paper presents a dual mode sensing methodology by using the Rayleigh surface waves with permanently installed piezoelectric sensors (PES). The PES are capable of exciting and receiving surface Rayleigh wave. When a crack is developing, acoustic emission (AE) occurs and the disturbance can propagate outwards along the surface as Rayleigh wave. A novel AE source imaging algorithm has been developed to detect and locate the AE source by back propagating the received AE signals which adapts beamforming tools developed for passive sonar and seismological applications. Once the AE source is located, the sensor array switches to its active mode. The active ultrasonic array imaging algorithm is similar but slightly different from the passive algorithm. One sensor in the array is used to excite Rayleigh wave for the ultrasonic interrogation, while all the others are used as the wave receivers. The data collection happens in a round robin pattern and all the sensory data are processed by the active ultrasonic array imaging algorithm. Through the dual mode imaging approach, a surface crack in the subject concrete can be ascertained. This method uses relatively high frequency Rayleigh waves and requires only a small array of 4 to 8 sensors. The imaging method is promising and economically beneficial for solving a key source localization problem in damage detection on large concrete structures.

8692-12, Session 3

A novel vehicle weigh-in-motion method by using smart aggregate array

Shuang Hou, Lei Jinfang, Dalian Univ. of Technology (China)

Vehicle overloading is the main cause for the damages of road pavement and bridges, and vehicle weigh-in-motion (WIM) technology is essential for solving this problem. In this paper, a novel WIM technology based on the PZT-based smart aggregates (SA) array, which are embedded on the bottom of wearing layer of the asphalt concrete (AC) pavement, is proposed. Firstly, the finite element(FE) model of a single SA embedded in the center of the bottom surface of a AC block(300mm by 300mm by 50 mm) was established for obtaining the ratio of the stress on SA surface to the local average stress. Then, the single SA and the AC block with designed detail of FE model is applied with cyclic compressive load through a servo-hydraulic machine, and the ratio of stress measured by SA to local average stress is compared with the FEA results. It is found that test results agree well with the FEA results, implying that the established FE model of SA and AC block is reliable; finally, the SA layout of AC under standard tire pressure was optimized through the finite element analysis and the accuracy of the sensing system is discussed in sense of probability. It can be concluded from the preliminary study that the proposed technique based on the SA array is suitable for vehicle WIM with low cost and considerate accuracy.

8692-13, Session 4

PVDF piezo-film as dynamic strain sensing for local damage detection of steel frame buildings

Masahiro Kurata, Xiaohua Li, Kohei Fujita, Liusheng He, Mayako Yamaguchi, Masayoshi Nakashima, Kyoto Univ. (Japan)

To develop prompt and effective seismic damage detection techniques for mid-to-high-rise buildings is an urgent issue in earthquake-prone areas as the local damage in structural elements that exert critical influence on the normal operation of buildings are difficult to detect by visual inspection due to building finishing. While acceleration has been a primary measure utilized in most current structural health monitoring systems, a technique to pragmatically and accurately capture strain information of structural elements has been demonstrated much more efficacious for detecting local damage. This paper presents the use of polyvinylidene fluoride (PVDF) piezo films as dynamic strain sensors for detecting local damage in a steel frame building. The major advantages of PVDF piezo films are their high sensitivity, excellent flexibility, and wide-range frequency. Unlike the conventional piezoceramic PZT sensors, PVDF piezo films allow direct attachment to structural surface, and thus are well suited to strain sensing in structural vibration applications. The results of shaking table testing using a 1/3.75-scale steel frame testbed constructed in the laboratory of DPRI, Kyoto University showed that the normalized standard deviation of signals measured from piezo film sensors can be used as a damage-related feature to detect the existence, location and severity of local damage such as fracture around beam-to-column connections simulated in the steel frame testbed under any levels of loadings including minor earthquakes and ambient excitations. The characteristics of a dynamic strain sensing network with piezo films and the comparison between experimental results and numerical simulations are also discussed.

8692-14, Session 4

A resetting semi-passive stiffness damper for response mitigation of civil infrastructure

Kenneth K. Walsh, Ohio Univ. (United States)

Earthquakes have the potential to cause large-scale destruction of civil infrastructure often leading to significant economic losses or even the loss of human life. Therefore, it is vital to protect civil infrastructure during these events. Structural vibration control provides a method for mitigating the damage to civil infrastructure during earthquakes by absorbing seismic energy from the structure. Semi-active control has emerged as an attractive form of structural control due to its effectiveness, inherent stability, and reliability. One semi-active control device particularly effective in reducing the response of civil structures subject to near-field earthquakes is the resetting semi-active stiffness damper (RSASD). Substantial research has been conducted to develop the RSASD and demonstrate its control performance. However, like other semi-active control technologies, the RSASD relies on a multi-component feedback control system that is subject to reliability issues. The purpose of the proposed research is to develop a novel resettable stiffness system that is capable of achieving a similar control performance to the RSASD, but with fewer feedback components. The resulting device, the resetting semi-passive stiffness damper (RSPSD), will offer increased reliability without compromising effectiveness. The objective of the present work is to present the concept for the RSPSD, develop a mathematical model describing its output force, identify critical design parameters, and then evaluate its control performance for single-degree-of-freedom structures subject to an earthquake ground motion. Numerical results indicate that the RSPSD is capable of comparable control performance to the RSASD for the structures and earthquake ground motion considered.

8692-15, Session 4

Development of an adaptive seismic isolator for ultimate seismic protection of civil structures

Jianchun Li, Yancheng Li, Univ. of Technology, Sydney (Australia); Weihua Li, Univ. of Wollongong (Australia); Bijan Samali, Univ. of Technology, Sydney (Australia)

Base isolation is the most widely used seismic protection technique for civil structures. However, research has revealed that the traditional base isolation system is vulnerable to two kinds of earthquakes, i.e. the near-source and far-source earthquakes, due to its passive nature. A great deal of effort has been dedicated to improve the performance of the traditional base isolation system for these earthquakes but without much success. This paper summarizes the recent research and development on a smart seismic isolation system by authors. The research focuses on utilizing the field-dependent property of the magnetorheological (MR) elastomer for development of an adaptive seismic isolator that forms the key element of the smart seismic isolation system. This novel isolator retains laminated structure of traditional seismic isolators with steel and MR elastomer layers, which enable applications for large-scale structures. It integrates an innovative magnetic circuit to provide required magnetic field for energizing the MR elastomer for changing its properties. With the controllable shear modulus/damping of the MR elastomer, the proposed smart seismic isolator has shown ability in altering shear stiffness while maintaining adequate vertical loading carrying capacity. An experimental investigation was conducted to examine its behaviour under various cycling loadings when it is applied with various current inputs. To further demonstrate the effectiveness of the smart seismic isolation system, a simplified building model is built with such device. Extensive experimental testing shows that building with such device can withstand any type of earthquakes, including the most dangerous near-source earthquake and far-source earthquake.

8692-16, Session 4

Real-time seismic monitoring of hospital buildings in the United States

Hasan S. Ulusoy, Erol Kalkan, U.S. Geological Survey (United States)

This paper describes the recent efforts made by the US Geological Survey National Strong Motion Project (NSMP) in real-time seismic monitoring of hospital buildings. In collaboration with the US department of Veterans Affairs, the NSMP has been instrumenting twenty-nine hospital buildings located in seismically active regions in the US. The instrumentation in each building includes accelerometers deployed on all floor levels, multi-channel digitizers, and a local server to measure, record, and store the building's response to evaluate the structural integrity of the buildings immediately after severe earthquakes. To this end, the instrumentation is complemented by developing an open source structural health monitoring software (OpenSHM). OpenSHM consists of several data processing and analysis modules running in near real-time. Four different algorithms are implemented in four separate modules to compute shear wave travel time, modal parameters, base shear force, and inter-story drift ratio from measured vibration data. The algorithms then track the time variations in the computed parameters and compare them with predetermined threshold values to detect and locate any possible damage in the buildings. The information extracted from measured vibration data can be used to support decisions regarding the structural safety of the hospital buildings, and to guide further inspections and necessary repairs and replacements.

8692-17, Session 4

A framework for rapid post-earthquake assessment of bridges and restoration of transportation network functionality using structural health monitoring

Shahab Ramhormozian, Piotr Omenzetter, The Univ. of Auckland (New Zealand)

Quick and reliable assessment of bridge condition after an earthquake can greatly assist immediate post-disaster response and long-term recovery. However, experience shows that available resources, such as qualified inspectors and engineers, will typically be stretched for such tasks. Structural health monitoring (SHM) systems can therefore make a real difference. SHM, however, needs to be deployed in a strategic manner to maximise its benefits. This study presents a framework of how this can be achieved.

Since it will not be feasible, or indeed necessary, to use SHM on every bridge, it is required to prioritise entire networks and bridges within individual networks for SHM deployment. A methodology for such prioritisation based on structural and geotechnical seismic risks affecting bridges and their importance or criticality within a network is proposed. An example using the methodology application to a medium-sized transportation network is provided. The second part of the framework is concerned with using monitoring data for quick assessment of bridge condition and damage after an earthquake. Depending on the bridge risk and criticality profile, it is envisaged the data here will be obtained from either wide-range local or national seismic monitoring arrays or an SHM system installed on the bridge. Finally the framework includes recommendations on how the quick, SHM-assisted bridge condition assessment can be integrated into emergency response planning and procedures of the responsible authorities.

8692-18, Session 5

Fatigue crack localization with near-field acoustic emission signals

Yunfeng Zhang, Changjiang Zhou, Univ. of Maryland, College Park (United States)

This paper presents a fatigue crack localization technique using near-field acoustic emission (AE) signals induced by fatigue crack initiation and growth. Experimental data from real bridge monitoring and fatigue testing of welded steel tubular joints are compared with analytical results from moment tensor analysis. Stress wave-induced surface strain due to a nearby surface pulse can be used as the basis for calibration of broadband AE strain sensors in near-field monitoring use. The aperture effect of AE strain sensor is also investigated to provide insight of AE strain signal characteristics for practical use. Piezoelectric film AE sensor has a potential to monitor the growth of fatigue crack, which can be used for fatigue remaining useful life prognosis.

An application of the near-field AE film sensor is demonstrated in a field test of a steel I-girder bridge located at Maryland, which has active fatigue cracks. A bridge prognosis procedure that involves statistical data analysis based on piezoelectric film AE sensor is described in this paper to show its potential use in bridge health management.

8692-19, Session 5

Noncontact structural damage detection using electromagnetic impedance sensing

Jiong Tang, Qi Shuai, Univ. of Connecticut (United States)

Magnetic transducers have been explored for impedance-based damage detection recently. Due to its electromagnetic interaction, a magnetic transducer can excite the host structure by the Lorenz force, and its electrical impedance is directly related to the host structure's mechanical impedance. Therefore, the change of electrical impedance before and after damage occurrence can be used as the damage indicator. Since there is no direct contact between the magnetic transducer and the host structure, it is believed that the magnetic transducer has advantages in online healthy monitoring of structures with complicated geometries and boundaries. One key issue, however, is that the coupling between the magnetic transducer and the host structure is significantly influenced by the lift-off distance (i.e. the distance from the transducer to the host structure) which may be subject to variations due to environmental disturbances and operation condition changes. In this research, we propose a new detection algorithm that can explicitly take into consideration of the lift-off distance change to facilitate efficient and robust decision making. This algorithm is incorporated into an enhanced magnetic sensor with circuitry integration of properly chosen capacitance, and it is identified that the algorithm can further improve the sensor performance. Comprehensive analytical and experimental studies are carried out to demonstrate the new algorithm and sensor development.

8692-20, Session 5

Damage classification using support vector machines in guided-wave structural health monitoring

Xiang Li, Daewon Kim, Yi Zhao, Embry-Riddle Aeronautical Univ. (United States)

A methodology to multi-classify crack and corrosion damages using time-frequency representations and support vector machines is investigated. Different damage features, such as types, locations, and extent of damage, are artificially created on aluminum beam coupons to examine the developed evaluation algorithm. Piezoceramic actuators and sensors are used to generate the guided waves and to detect the reflected signals from damage. Among the time-frequency methods tested, spectrogram based on short-time Fourier transform is used with support vector machines for damage classification.

A finite element analysis tool is utilized to simulate various damage samples and obtain measured signals for training of support vector machines. The testing samples are obtained from both experimental beam tests and finite element results. The machine learning classification is carried out using eight-bit color depth information of the spectrograms and rearranging them to create feature vectors. The frequency information stored in each pixel of the spectrogram is also used as additional feature in the feature vectors to improve classification accuracies. The algorithm developed cannot only classify two metallic damages, crack and corrosion, but is also able to distinguish the severity of damage by classifying damages of different sizes.

8692-21, Session 5

Design of a curvature sensor using Ba0.64Sr0.36TiO3 (BST) flexoelectric material

Xiang Yan, Wenbin Huang, Xiaoning Jiang, Fuh-Gwo Yuan, North Carolina State Univ. (United States)

In this paper, a new sensor to measure curvature directly is proposed using flexoelectric (FE) sensing material Ba0.64Sr0.36TiO3 (BST). The measurement is made by attaching a FE sensor on the side face of an aluminum beam under four point bending. The curvature relates the charge output to the strain gradient (i.e., curvature) from BST. Since the strain gradient in the host material (aluminum beam) cannot be perfectly transferred to BST caused by bonding layer with low shear stiffness, the calculation of strain gradient transfer coefficient from host material to BST is necessary. Theoretical calculation for strain gradient transfer coefficient using four point bending shear lag model is studied and FEM result for strain gradient transfer coefficient agrees well with the theoretical result. The curvature that is tested is from 0.0095m-1 to

0.024m-1 .Experimental results show that the charge outputs of the BST micro-bars showed good linearity with the average strain gradients, with sensitivity of 192 pCm, which is in good agreement with the theoretical estimation by assuming a 30 μm bonding thickness. In addition, the bandwidth of this curvature sensor is investigated as well. This design has good potential application in structural health monitoring for its unique capability for curvature sensing.

8692-22, Session 5

Nondestructive detection of steel rebar corrosion damage using ultrasonic guided waves

Dongsheng Li, Dalian Univ. of Technology (China)

In order to test the corrosion damage of reinforced concrete, the propagation properties of ultrasonic guided waves (UGW) are explored. Numerical methods are employed to calculate the disperse curves. Optimal excitation signal and frequency are selected. According to the reinforced concrete corrosion experiments, stress wave propagation in different conditions is simulated using finite element analysis. The testing result was analyzed through two-dimensional Fourier transform to demonstrate the effect of waveguide dispersion. At last, time domain and frequency domain analysis were used to process received signals. Different corrosion degree UGW energy attenuation was analyzed and a relationship was obtained. This study successful proved that UGW was an effective tool in the nondestructive test the reinforced concrete corrosion damage.

8692-174, Session 5

Acoustic mechanical feedthroughs

Stewart Sherrit, Phil Walkemeyer, Xiaoqi Bao, Yoseph Bar-Cohen, Mircea Badescu, Jet Propulsion Lab. (United States)

Electromagnetic motors can have problems when operating in extreme environments. In addition, if one needs to do mechanical work outside a structure, electrical feedthroughs are required to transport the electric power to drive the motor. In this paper, we will present designs for driving rotary and linear motors by pumping stress waves across a structure or barrier. We accomplish this by designing a piezoelectric actuator on one side of the structure a resonance structure that is matched to the piezoelectric resonance of the actuator on the other side. Typically, piezoelectric motors can be designed with high torques and lower speeds without the need for gears. One can also use other actuation materials such as electrostrictive, or magnetostrictive materials in a benign environment and transmit the power in acoustic form as a stress wave and actuate mechanisms that are external to the benign environment. This technology removes the need to perforate a structure and allows work to be done directly on the other side of a structure without the use of electrical feedthroughs, which can weaken the structure, pipe, or vessel. Acoustic energy is pumped as a stress wave at a set frequency or range of frequencies to produce rotary or linear motion in a structure.

This method of transferring useful mechanical work across solid barriers by pumping acoustic energy through a resonant structure features the ability to transfer work (rotary or linear motion) across pressure or thermal barriers, or in a sterile environment, without generating contaminants. Reflectors in the wall of barriers can be designed to enhance the efficiency of the energy/power transmission. The method features the ability to produce a bi-directional driving mechanism using higher-mode resonances. There are a variety of applications where the presence of a motor is complicated by thermal or chemical environments that would be hostile to the motor components and reduce life and, in some instances, not be feasible. A variety of designs that have been designed, fabricated and tested will be presented.

8692-23, Session 6

An iterative convex optimization procedure for system identification of a space frame bridge

Dapeng Zhu, Georgia Institute of Technology (United States); Xinjun Dong, Georgia Intitute of Technology (United States); Yang Wang, Georgia Institute of Technology (United States)

Structural behavior predicted by finite element models built according to the design drawings is usually different from the behavior of an actual structure in the field, owing to the high complexity of civil structures. To improve the prediction accuracy, finite element (FE) model updating can be conducted base on sensor measurement from the actual structure. The process is known as FE model updating. Numerous algorithms have been developed in the past few decades. However, most of existing algorithms suffer computational challenges. The difficulty comes from the fact that existing algorithms usually attempt to solve non-convex optimization problems. The optimization method suffers convergence difficulty and cannot guarantee global optimum. To address the issue, this paper proposes an iterative convex optimization algorithm for FE model updating. The convex attribute of the optimization problem makes the solution process tractable and highly efficient. For validation of the proposed algorithm, field testing is conducted with a space frame pedestrian bridge on Georgia Tech campus using wireless sensors. The entire bridge is divided into four substructures. Up to 32 channels of dense wireless acceleration data are obtained on one substructure at a time, resulting in over 120 channels of acceleration data collected for the entire bridge. Using the wireless acceleration data, modal characteristics for each substructure are first extracted, and then assembled to obtain the modal characteristics of the entire bridge. Finally, an FE model for the bridge is successfully updated through the iterative convex optimization approach using the experimental modal results.

8692-24, Session 6

Extension of the rotation algorithm for earthquake damage estimation of complex structures

Konstantinos Balafas, Anne S. Kiremidjian, Stanford Univ. (United States)

In a previous paper an algorithm was developed for estimating the slope at locations of ambient vibration measurements along a single column subjected to strong earthquake motion. These slope estimates were used in obtaining permanent drift values for the single column and those were correlated to various levels of damage. The algorithm was illustrated with applications to single column tests performed at the University of Nevada, Reno and the University of California, Berkeley. In this paper, the same columns are first used to simulate slope values along the deformed shape of the columns in order to determine the best estimate of the displacement distribution. This information can then be used to determine the optimal number of sensors needed to provide a reliable permanent drift in a single column. Sensitivity studies are also performed to evaluate the effect of plastic hinge length over or underestimate as this value is usually inferred from empirical equations. The rotation algorithm is then extended to multi-story structures where the slope of both beams and columns is estimated from acceleration measurements. These slope values are then used in the evaluation of interstory drifts in order to correlate them to structural damage. The resulting drift values can then be related to various damage states and can be used for rapid damage assessment immediately following a major earthquake. The main advantage of the proposed approach is that low-cost accelerometers can be used to obtain the information needed for rapid damage assessment.

8692-25, Session 6

Forecasting algorithm for building energy management system

Hae Young Noh, Stanford Univ. (United States) and Carnegie Mellon Univ. (United States); Ram Rajagopal, Stanford Univ. (United States)

This paper introduces a forecasting method for building energy monitoring and management systems that use the measurements from smart meters. Nowadays, more buildings become instrumented with smart meters generating massive data every day, and there is a great need for efficient and reliable analysis methods to extract useful information from them. It is important for utility companies to accurately predict the aggregate energy consumption profile to reliably plan for future energy supply and prevent any crisis. The proposed method involves forecasting individual load profiles on the basis of their measurement history and weather data. It uses a nonparametric Gaussian process to predict the load profiles and their uncertainty bounds with weather information. This method is applied to a set of building energy consumption data collected from the Jerry Yang and Akiko Yamazaki Environment and Energy Building (Y2E2) at Stanford University. It is a three-story building with several laboratories in the basement, a cafe on the first floor, individual offices, lecture rooms, and conference rooms on all three floors and equipped with over 2370 sensors collecting data every one minute. The analysis results show that the measurements are mostly within 95% credible intervals. In addition to using the consumption forecasting for planning future energy supply, it can be combined with other methods to control consumption patterns and diagnose system malfunctioning.

8692-26, Session 6

Sequential detection of progressive damage

Mark Mollineaux, Ram Rajagopal, Stanford Univ. (United States)

Development of a damage diagnosis algorithm, applied to a multi-state progressive damage model, applied to SHM. As a sequential test, it continuously takes in new data samples, and reports a decision (damage has occurred/damage has not occurred) for any subset of damage states, as selected. Multiple definitions for the ``damaged" subset can be processed in parallel.

The efficiency of this algorithm far outstrips the brute-force approach, processing all paths. The gained efficiency in this algorithm is reached by exploiting the Markov structure of the HMM, and also the particular structure of progressive damage. (That is, that a structure cannot become un-damaged without explicit and knowable intervention.) The efficency is improved even further due to the simplification of ``windowing"-- a series of caching probabilities utilized in the algorithm that are unlikely to change when new values come in from a sufficiently removed time step. The algorithm is also generalizable into a case that allows for a less restrictive depiction of what transitions are permissible.

Validation of this algorithm was performed by the application of experimental data of damage states. Many test runs were performed, and used to track the success of this algorithm. It is shown to outperform the naive application (only looking at the last sample, and ignored past data). The simplifications that were introduced were shown to be justifiable, in that the extra data that was excluded through careful caching has almost no effect on the success and failure rate of the algorithm at even modest windowing values.

8692-27, Session 6

Embedded linear classifiers for damage detection in civil infrastructure

Jerome P. Lynch, Courtney Peckens, Univ. of Michigan (United States)

Wireless sensing technologies have recently emerged as a cost-effective and robust method for data collection on a variety of structural monitoring applications. In comparison with their traditional tethered counterparts, wireless sensor systems are low-cost and low-power, allowing for the deployment of dense networks. Additionally, such sensors possess data processing capabilities, thus enabling on-board computations and thereby increasing overall network efficiency by eliminating transmission of raw data. Wireless sensors, however, have unique challenges, such as limited computational capacity and overall energy constraints, which must be considered in the development of monitoring systems. As such, embedded algorithms for wireless sensing networks must be designed to optimize computational efficiency, while minimizing the overall energy consumption across the network. In this study, multiple linear classifier algorithms are embedded on a network of sensors. The computationally intensive tasks of the algorithms are distributed across various sensors, thus maximizing the computational capacity of the network and reducing the overall execution time. Once deployed on a network of sensors, the decomposed algorithms are used to classify damage on a structural system.

8692-28, Session 6

Statistical learning for sensor networks: NPL footbridge case study

Elena N. Barton, National Physical Lab. (United Kingdom)

Sensor networks involve multiple sensors using wireless or wired communications and internet services to provide raw data that is converted to information-based products, e.g monitoring parameters related to the condition of the structure leading to a life-cycle maintenance plan. The interpretation of data obtained from installed or embedded sensors in outdoor structures present new challenges. While traditional measurement systems achieve traceability through the minimisation of environmental influences in controlled laboratories, smart monitoring of assets has to address the issue of environmental changes in situ. This has led to research in development of new statistical learning and data assimilation approaches that combine data and models to provide reliable information about the structure under study.

This paper presents some examples relevant to civil engineering, particularly for structural health monitoring (SHM) applications. The case studies are part of our four year project focused on a footbridge located at National Physical Laboratory (NPL), UK. During this project the 1960s reinforced concrete footbridge was converted to a full-scale SHM demonstrator subjected to damage and repairs. The experimental part of the project will be completed at the end of 2012. We have already considered various statistical methods for analysis of our data and the results of some, such as Gaussian processes, are included here. Although the results are preliminary, we believe that lack of full scale trails in civil engineering makes them useful for wider audience.

8692-29, Session 6

Monitoring of bridge scour using one-class support vector machines

Inho Kim, Rajesh Kumar Neerukatti, Masoud Fard, Aditi Chattopadhyay, Arizona State Univ. (United States)

Bridge scour has been recognized as a major threat of the safety of bridge structures. In the U.S. there are about 3,000 major interstate highway bridges that have been deemed structurally deficient due to scour-triggered deterioration and other damage. Bridge scour happens when soils surrounding bridge piers and abutments are washed out by the flash stream during floods, and accumulation of this process causes collapse of bridges in extreme cases due to the loss of support for bridge foundations. Thus the development of Structural Health Monitoring (SHM) tools is extremely critical for timely surveillance of scour condition. . The scope of this study is to diagnose scour level based on the time-series data from dedicated on-site sensors and communication systems using a kernel based method. An anomaly detection tool will be employed using

one-class Support Vector Machines (SVMs) which utilize the nominal state of the present condition to compare the different conditions that might occur during bridge operation. Various types of pattern recognition algorithms will be utilized to classify different indicators or signatures from the datasets. Field test results will be used to further develop supervised learning models for SVMs for different types of sediment modes. Results will be presented on monitoring of scour for different river bed conditions.

8692-30, Session 7

On the detection of closing delaminations in laminated composite plates using the structural intensity method

Alfredo Lamberti, Fabio Semperlotti, Univ. of Notre Dame (United States)

In recent years, the concept of Nonlinear Structural Intensity (NSI) has been applied to detect fatigue cracks and loose joints in isotropic structures. This paper extends the NSI concept to non-isotropic materials and investigates the possibility to use NSI for the localization of a closing delamination in both orthotropic and anisotropic thin laminated plates. When the delamination is properly excited by a high frequency interrogation signal, the nonlinear contact occurring between the delaminated plies produces nonlinear contact acoustic effects (CAN) associated with the generation of both higher order and fractional harmonics. The closing delamination acts as a mechanism of energy redistribution from the driving frequency to the nonlinear harmonics which clearly appear in the frequency spectrum of the structural response. The intensity associated with the nonlinear harmonics is evaluated using a hybrid approach based on a Finite Element (FE) model and a 13 point finite differencing scheme. The FE model is used to simulate the structural dynamic response while the finite differencing scheme allows estimating the stress distribution from acceleration data. First, the proposed approach is used to investigate the effect of the material orthotropy on the propagation of vibration energy in a thin orthotropic laminated plate. Particular attention is given to analyze the impact that preferential directions of energy propagation have on the ability to interrogate the structure and sense the damage. Successively, the approach is extended to a symmetric anisotropic laminated plate. Numerical simulations are performed to analyze the effect of the stacking sequence on the damage sensitivity.

8692-31, Session 7

Phased-array beamsteering in composite laminates for guide-wave structural health monitoring

Peter Osterc, Daewon Kim, Embry-Riddle Aeronautical Univ. (United States); Byungseok Yoo, Techno-Sciences Inc. (United States)

With ever more extensive use of composites in various industry fields, especially mechanical and aerospace structures, damage detection and evaluation is becoming increasingly important. There is a lack of structural health monitoring (SHM) systems currently applicable to composites. Guided Lamb waves are a promising area of research due to their ability to propagate large distances with little loss of amplitude. In this study, a guided wave phased array beamsteering approach is applied to composite laminates. Standard beamforming delay and sum algorithms developed for isotropic structures generally assume omnidirectional point sources. This assumption makes them not directly applicable to composite laminates due to variations in guided wave properties with angle of propagation which results from inherent anisotropy. As a consequence, dispersion curves vary with propagation direction and standard wave modes do not exist, but are often coupled. Furthermore, the amplitude of guided waves in composites varies with direction as well.

Dispersion curves for composite laminates can be derived from 3D elasticity theory. By evaluating dispersion curves at every possible propagation direction, characteristic curves can be derived, namely velocity, slowness and wave curves, which are no longer simple circular shapes as in isotropic materials. The amplitude variation with propagation direction can be obtained by evaluating displacements obtained from 3D elasticity. Using amplitude variation and wave curves, the wave front due to a single excitation can be described as a function of the angle of propagation and distance from origin. Using this approach, a generic delay and sum beamforming algorithm for composite laminates can be developed for any desired wave mode.

8692-32, Session 7

Analytically modeling the piezoresistivity of CNT composites with low-filler aggregation

Tyler Tallman, Kon-Well Wang, Univ. of Michigan (United States)

Distributed networks of carbon nanotubes (CNT) impart piezoresistive properties to otherwise insulating polymer based composites, and these networks can be exploited as integrated sensors for structural damage detection. However, accurately relating changes in resistance to the mechanical damage state remains a challenge. A common method of modeling high aspect ratio networks of rod like fillers involves placing the fillers within a domain via Monte Carlo techniques and treating the fillers as rigid inclusions within a compliant matrix. Equivalent resistor networks are then formed through and between the fillers to assess the resistance before and after deformation. This method, while physically insightful, is computationally unpalatable on all but the smallest domains due to the extreme number of fillers needed to form a percolated network. In this research, we circumvent this limitation by developing an analytical model of predicting resistance change due to strain which accounts for changes to filler volume fraction, inter-filler spacing, and filler percolation probability as a function of the strain state and the filler constituents. The accuracy of the model is verified by comparison to the experimental and analytical results in existing literatures.

8692-33, Session 8

Numerical and experimental characterizations of low-frequency MEMS AE sensors

Hossain Saboonchi, Didem Ozevin, Univ. of Illinois at Chicago (United States)

In this paper, new MEMS Acoustic Emission (AE) sensors are introduced. The transduction principle of the sensors is capacitance due to gap change. The sensors are numerically modeled using COMSOL Multiphysics software in order to estimate the resonant frequencies and capacitance values, and manufactured using MetalMUMPS process. The process includes thick metal layer (20 um) made of nickel for freely vibration layer and polysilicon layer as the stationary layer. The metal layer provides a relatively heavy mass so that the spring constant can be designed high for low frequency sensor designs in order to increase the collapse voltage level (proportional to the stiffness), which increases the sensor sensitivity. An insulator layer is deposited between stationary layer and freely vibration layer, which significantly reduces the potential of stiction as a failure mode. As conventional AE sensors made of piezoelectric materials cannot be designed for low frequencies (<300 kHz) with miniature size, the MEMS sensor frequencies are tuned to 50 kHz and 200 kHz. The each sensor contained several parallel-connected cells with an overall size of approximately 250 um x 500 um. The electromechanical characterizations are performed using high precision impedance analyzer and compared with the numerical results, which indicate a good fit. The initial mechanical characterization tests in atmospheric pressure are conducted using pencil lead break simulations. The proper sensor design reduces the squeeze film damping so that it does not require any vacuum packaging. The MEMS sensor responses are compared with similar frequency piezoelectric AE sensors.

8692-34, Session 8

Active stiffness modulation of fins using macrofiber composite

Ashok K. Kancharala, Michael K. Philen, Virginia Polytechnic Institute and State Univ. (United States)

A review of the recent studies on the role of body flexibility in propulsion show that fish have a remarkable ability to control or modulate the stiffness of the fin for optimized propulsive performance. The Self–propelled speed (SPS) generated by the fish greatly depends on the stiffness of the fin along with the other parameters. The optimized stiffness for efficiency varies with operating parameters. For example, the optimized stiffness for a fin operating at 1Hz is different than the fin operating at 2Hz. The fins with a particular stiffness might be efficient for a certain range of parameters but they work inefficiently for other parameters. This necessitates the active stiffness modulation for optimized propulsive efficiency based on various operating parameters.

In this work, the active stiffness modulation is implemented using Macro Fiber Composite (MFC's) which uses d33 effect. The advantage of MFC's is their high performance and flexibility over the conventional PZT patches. Two MFC's attached on either side of the fin actively control the stiffness of the fin. A detailed investigation would be required on how active stiffness modulation changes or controls the thrust and efficiency. For this investigation, a coupled computational model which incorporates the piezoelectric constitutive model with fluid structure interaction will be developed. Fluid structure interaction of the fin will be modeled considering unsteady slender wing theory coupled with the nonlinear Euler-Bernoulli beam theory. The developed computational model will be used to predict the SPS and efficiency with parameters such as heaving and pitching amplitude, oscillation frequency, flexibility of the fin and the voltage applied to the MFC's. Based on the simulations, the advantages of active stiffness modulation will be reported. An experimental comparison will be made to validate the results produced by the computational model.

8692-35, Session 8

Tunable fiber ring laser absorption spectroscopic sensors for gas detection

Shijie Zheng, Yinian Zhu, Sridhar Krishnaswamy, Northwestern Univ. Ctr. for Quality Engineering (United States)

Fiber-optic gas sensing techniques are commonly based on the recognition of a wide range of chemical species from characteristic absorption, fluorescence or Raman-scattering spectra. By tuning over the vibrational absorption lines of species in the path of laser beam, tunable diode laser gas sensors measure signal spectroscopic intensity, gas concentration and other properties. However they have limitations of bulk architecture, small change of signal on top of large background, and low sensitivity of direct absorption. Here we report the fabrication and optical measurements of tunable Er-doped fiber ring laser absorption spectroscopic sensor featuring a gas cell that is a segment of photonic crystal fiber (PCF) with long-period grating (LPG) inscribed. The laser beam is coupled into cladding of PCF by the LPG where the gas in air holes absorbs light. Light travels along the PCF and reflects at the end of the fiber where a silver mirror is coated at the facet end. Light propagates back within cladding, passes through the gas one more time thus increasing the interaction length, and is finally recoupled into fiber core for intensity measurement. The proposed fiber gas sensors show excellent sensitivity and selectivity, and are not affected by temperature or humidity changes. The sensors using a PCF-LPG gas cell are simple to fabricate, cost-effective, and are deployed for a variety applications not possible in conventional optical fiber, such as environmental monitoring and structural health monitoring.

8692-36, Session 8

On the sensing of magnetorheological elastomers

Nima Ghafoorianfar , Faramarz Gordaninejad, Xiaojie Wang, Univ. of Nevada, Reno (United States)

Theoretical and experimental studies are performed to understand the behavior of magnetorheological elastomers (MREs) by establishing relationships between the mechanical deformation and electrical property changes under applied magnetic fields. The strain and electrical resistivity of aligned MRE samples with a controlled constant temperature are measured, simultaneously for different magnetic fields. A theoretical study is carried out using a finite element analysis to understand MRE's deformation subjected to a magnetic field. The coupled magnetic and elastic fields' equations are employed to determine the magnetic attraction force between the particles. In this work, combined sensing of magnetic fields and mechanical compression loads have been studied through the electrical resistivity behavior of MREs. In addition, magnetostriction is used along with magnetoresistance to determine the piezoresistivity effect of MREs under such combined conditions.

8692-37, Session 9

Simulation analysis and experimental performance of a radar sensor network for distributed bridge monitoring

Shanyue Guan, Jennifer A. Rice, Univ. of Florida (United States); Changzhi Li, Changzhan Gu, Texas Tech Univ. (United States)

Wireless sensor networks (WSNs) are a promising structural health monitoring (SHM) technology for the evaluation of infrastructure, especially bridges. WSNs are more convenient to install and much cheaper than traditional structural measurement and monitoring methods. Commonly used sensors for vibration-based SHM, such as accelerometers, work well for higher-frequency measurements; however, it is often difficult to acquire satisfactory results when they are applied on long-span bridges with very low modal frequencies. In this paper we will present a multiple input multiple output (MIMO) wireless radar sensor network capable of measuring lower-frequency vibration and static deflection. An integrated simulation model that combines a multi degree-of-freedom structural model with a realistic model of the radar sensor network is introduced and used to characterize and predict the network's functionality in different measurement conditions. In addition, a series of laboratory experiments, including on a seven-story steel building model and a scaled steel truss bridge, have also been performed for comparison with the simulation model. Finally, challenges associated with achieving accurate measurements from the radar network in a range of testing environments are discussed.

8692-38, Session 9

Significance of sensor quality on structural health monitoring results

Siavash Dorvash, Shamim N. Pakzad, Lehigh Univ. (United States)

Advancements in sensing technology have improved the practice of structural health monitoring in different aspects. One of the distinguished developments, introduced to the monitoring systems, is deployment of wireless technology for data communication in a sensing network. While researchers have shown the effective role of wireless sensor networks in improving the affordability of structural monitoring systems, their possible impact on the reliability and accuracy of the results is still a research question. Some challenges in the design of wireless sensor units, such as the trade-off between the functionality and the power consumption, and also attempts for minimizing the cost, have caused limitations in their architecture which do not necessarily exist in the design of wired systems. On the other hand, depending on the subsequent application of the results achieved from the sensing and monitoring, the accuracy of measurements and the uncertainty in the results can be very important. Therefore, it is necessary to carefully investigate the impact of sensor quality on monitoring results. As an effort towards understanding the significance of sensor quality on the results of structural monitoring, this paper presents and validates parameters which can be used to investigate the influence of measurement noise on modal parameter identification.

8692-39, Session 9

Smart sensor nodes for vibration measurement of large civil infrastructure

Jong-Jae Lee, Yong-Soo Park, Sejong Univ. (Korea, Republic of); Ung-Jin Na, Ministry of Land, Transport and Maritime Affairs (Korea, Republic of); Won-Tae Lee, Chang-Geun Lee, Korea Expressway Corp. (Korea, Republic of)

Dynamic characteristics of large civil infrastructures have been monitored for safe operation and efficnent maintenance of the structures. To measure vibration data, the conventional system uses cables which cause very expensive costs and inconvenience for installation. Therefore, various wireless sensor nodes have been developed to replace the conventional wired system. However, there remain lots of issues to be resolved such as power supply, package loss, data security, etc. In this study, smart distributed sensor node (SDSN) was developed to measure vibration data. The SDSN is basically timely synchronized one-channel data acquisition system. It consists of its local time clock with high accuracy and SD memory card for local data storage. To ensure time syronization between each SDSN, the Kalman filter algorithm was utilized. Laboratoy tests were carried to verify the performance of the developed SDSN compared with conventional wired sensors. Several application examples for large civil infrastructure were also suggested.

8692-40, Session 9

Full-scale monitoring of in-service highway bridge using wireless hybrid sensor

Shinae Jang, Sushil Daha, Jingcheng Li, Univ. of Connecticut (United States)

With the rapid development of electrical circuits, Micro electromechanical system (MEMS) and network technology, wireless smart sensor networks (WSSN) have shown significant potential for replacing existing wired SHM systems due to their cost effectiveness and versatility. A few structural systems have been monitored using WSSN measuring acceleration, temperature, wind speed, humidity; however, a multi-scale sensing device which has the capability to measure the displacement has not been yet developed. In the previous paper, a new high-accuracy displacement sensing system was developed combining a high resolution analog displacement sensor and MEMS-based wireless microprocessor platform. Also, the wireless sensor was calibrated in the laboratory to get the high precision displacement data from analog sensor, and its performance was validated to measure simulated thermal expansion of a laboratory bridge structure. This paper expands the validation of the developed system on full-scale experiments to measure both static and dynamic displacement of expansion joints, temperature, and vibration of an in-service highway bridge. A brief visual investigation of bridges, comparison between theoretical and measured thermal expansion are also provided. The developed system showed the capability to measure the displacement with accuracy of 0.00027 inch.

8692-179, Session 9

Design and initial validation of a wireless control system based on WSNs in civil engineering

Yan Yu, Xu Wang, Luyu Li, Jinping Ou, Dalian Univ. of Technology (China)

At present, cantilever structure used widely in civil structures, will produce continuous vibration by external force due to their low damping characteristic, which leads to a serious impact on the working performance and service time. Therefore, it is very important to control the vibration of these structures. The active vibration control is the primary means of controlling the vibration with high precision and strong adaptive ability. Nowadays, there are many researches about using piezoelectric materials in the structural vibration control. They can achieve so cheap, reliable braking and sensing method which is lossless of the structure, that they have a broad application space. They are used for structural vibration control in a lot of civil engineering research currently. In traditional sensor applications, information exchange with the monitoring center or a computer system through wires. If wireless sensor network technology is used, cabling links is not needed, thus the cost are greatly reduced, the civil structures are not damaged whenever it is installed or maintained.

Based on the above advantages, a wireless control system proposal is proposed and validated through preliminary tests. The system includes cantilever, PVDF as sensors, signal conditioning circuit, an A/D acquisition board, control arithmetic unit, a D/A output board, a power amplifier, piezoelectric bimorph as actuators. Use a PC as the control arithmetic unit and compile PD control algorithm. PVDF collects the parameters of vibration, sends them to the PC after A/D conversion, PC calculates and outputs the control values according to the control algorithm, power amplifier amplifies the output signals to drive the piezoelectric bimorph for the purpose of vibration control. Experimental result proves that the structural vibration duration reduces to 1/6 of the uncontrolled, it verifies the feasibility of the system. Next plan is to replace the PC with a DSP as the core control unit of the system, and add wireless modules to realize the wireless control of system.

8692-41, Session 10

Gen-2 RFID compatible, zero down-time, programmable mechanical strain-monitors and mechanical impact detectors

Shantanu Chakrabartty, Kenji Aono, Tao Feng, Michigan State Univ. (United States)

A key challenge for structural health monitoring (SHM) sensors embedded inside civil structures is that the electronics need to operate continuously such that mechanical events of interest can be detected and appropriately analyzed. Continuous operation however requires a continuous source of energy which cannot be guaranteed using conventional energy scavenging techniques. The paper describes a hybrid energy scavenging SHM sensor which experiences zero down-time in monitoring mechanical events of interest. At the core the proposed sensor is an analog flash memory technology that can be precisely programmed at nano-watt and pico-watt power levels. This facilitates self-powered, non-volatile data logging of the mechanical events of interest by scavenging energy directly from the mechanical events itself. Remote retrieval of the stored data is achieved using a commercial off-the-shelf Gen-2 radio-frequency identification (RFID) reader which periodically reads an electronic product code (EPC) that encapsulates the sensor data. The Gen-2 interface also facilitates in simultaneous remote access to multiple sensors and also facilitates in determining the range and orientation of the sensor. The architecture of the sensor is based on a token-ring topology which enables the sensor channels to be dynamically added or deleted through software control.

8692-42, Session 10

Micro-aerial vehicle type wall-climbing robot mechanism for structural health monitoring

Jae-Uk Shin, Donghoon Kim, Jong-Heon Kim, Hyun Myung, KAIST (Korea, Republic of)

The inspection and maintenance of large structures is labor-intensive and costly due to its high risk. To solve the problem, the use of wall-climbing robot is widely considered. Infrastructure-based wall-climbing robots to maintain a facade or outer wall of building have high payload and safety. However, the infrastructure for the robot should be installed on the target structure and the maintenance infrastructure isn't preferred by the architects since it can injure the exterior of the structure. These are the reasons of why the infra-based wall-climbing robot is not preferred. To overcome the aforementioned problems, the wall-climbing robot which does not utilize additional infrastructure is gaining attention. However, most of the technologies are in the laboratory level since the payload, safety, and maneuverability are not satisfactory. For this reason, micro aerial vehicle type wall-climbing robot is considered in this paper. It is a flyable wall-climbing robot based on a quadrotor. The basic platform is a widely used aerial vehicle robot using four rotors to make a thrust for flying. This wall-climbing robot can stick to a vertical wall using the thrust. After sticking to the wall, it can move with four wheels installed on the robot. As a result, it has high maneuverability and safety since it can restore the position to the wall even if it is detached from the wall by unexpected disturbance while climbing the wall. The feasibility of the main concept was verified through simulations and experiments using a prototype.

8692-43, Session 10

Large-area graphene-based thin films and their application as strain sensors for structural health monitoring

Gautam Naik, Northwestern Univ. (United States); Adarsh Kaniyoor, Sundara Ramaprabhu, Indian Institute of Technology Madras (India); Sridhar Krishnaswamy, Northwestern Univ. (United States)

In the present study, we propose a novel method to fabricate large-area graphene-based thin films, and their implementation as strain sensors for structural health monitoring. Large area (~12.5 sq.in) graphene oxide (GO) thin films were fabricated by vacuum filtration of GO solution synthesized by the modified Hummers' method. A device similar to a laminator was manufactured, with heating elements to reach temperatures of 300 °C. The GO thin film was "laminated" between polymer sheets, resulting in the reduction of GO, thereby increasing its conductivity by almost 5 orders of magnitude. The fabricated reduced GO thin films were characterized using powder x-ray diffraction, scanning electron microscopy, Raman spectroscopy, Fourier-transform infrared spectroscopy and x-ray photoelectron spectroscopy. This method offers a new way of fabricating conductive large-area graphene thin films. The use of fabricated thin films for strain sensing is also demonstrated.

8692-44, Session 10

Microparticle transport and concentration with surface acoustic waves

Irving J. Oppenheim, Erin R. Dauson, David W. Greve, Kelvin B. Gregory, Carnegie Mellon Univ. (United States)

Surface acoustic waves generated on SAW devices can move microparticles, suspended in a fluid to nodes or antinodes. That behavior is of interest because the transport, concentration, and separation of microparticles (including bacteria) has scientific and industrial significance. We describe the design, fabrication, testing, and analysis of lithium niobate SAW devices and microfluidic channels with which we have studied microparticle movement.

We present results obtained with lithium niobate SAW devices operating at 6.7, 10, and 20 MHz, corresponding to wavelengths of roughly 600, 400, and 200 micrometers. Whereas earlier work used two interdigital transducers (IDTs) opposing one another to generate the standing waves, we show that a single IDT can generate standing waves with reflections from a parallel boundary, an approach that simplifies the electromechanical design.

Microfluidic channels are fabricated from polydimethylsiloxane (PDMS, silicone). The wave field in the fluid depends on PDMS material properties, especially damping, but the pertinent literature suggests considerable uncertainty in those properties. We report measurements of system response in the presence and absence of the microfluidic channel, which we combine with finite element simulation modeling to extract estimates of the damping. We report our experimental observations and measurements of microparticle movement, involving particles ranging from 5 to 35 micrometers in diameter, and discuss comparisons to available predictions. We conclude with a discussion of possible secondary separation mechanisms to direct particles of interest to intended trajectories.

8692-45, Session 10

Cochlea-inspired sensing node for structural control applications

Courtney Peckens, Jerome P. Lynch, Univ. of Michigan (United States)

While sensing technologies for structural monitoring and control have made significant advances over the last several decades, there is still room for improvement in terms of computational efficiency, as well as overall energy consumption. The biological nervous system can offer a potential solution to address theses current deficiencies found in such engineered systems. The nervous system is capable of sensing and aggregating information about the external environment through very crude processing units, or neurons. These neurons effectively communicate in an extremely condensed format by encoding information into binary electrical spike trains, thereby reducing the amount of raw information flow throughout the network. As such, the overall network is capable of making complex decisions instantaneously, thus enabling real-time sensing and actuation. Due to its unique signal processing capabilities, the mammalian cochlea, and its interaction with the biological nervous system, is of particular interest for civil infrastructure systems. The cochlea uses a novel method of place theory and frequency decomposition, thereby allowing for rapid signal processing within the nervous system. In this study, a low-power sensing node is proposed that draws inspiration from the mechanisms used by the cochlea and biological nervous system. As such, the sensor is able to perceive and transmit a compressed representation of the external stimulus with minimal distortion. Each sensor represents a basic building block, with function similar to the neuron, and can form a network with other sensors for sophisticated decision-making. The proposed sensor is validated through the control of a single degree of freedom structure.

8692-46, Session 11

An electromagnetic energy harvester using asynchronously vibrating cantilevers with phase shift

Jinkyoo Park, Kincho H. Law, Stanford Univ. (United States)

In most vibration-based energy harvesters, the natural frequency of the vibrating component is matched to the most probable excitation frequency of the target inertial frame to maximize power generation. This reliance on the resonance inevitably induces a robustness issue. For example, power production significantly drops when the excitation

frequency is even slightly off from the tuned natural frequency of the harvester. To overcome this limitation, this paper proposes a novel concept of a vibration-based electromagnetic energy harvester in which both the magnet and the coil are attached to vibrating cantilevers whose natural frequencies are separated with the optimal chosen frequency band. When the excitation frequency is outside of the frequency band, only either the magnet or the coil cantilever vibrates while the other functions as an inertial frame. When the excitation frequency falls in the middle of the frequency band, the power level remains almost constant since the two cantilevers vibrate with a phase difference. In addition, the new harvester generates much higher power than a conventional inertial-frame-based harvester, especially when the electrical damping is high. The improvements in both robustness and power level are validated by both numerical simulations and prototype experiments. Finally, a field test on an actual bridge was conducted and showed that robustness and power level improved on a real target civil structure.

8692-47, Session 11

Uncertainty quantification of a corrosion-enabled energy harvester for low-power sensing applications

Scott A. Ouellette, Michael D. Todd, Univ. of California, San Diego (United States)

New developments in novel energy harvesting schemes for structural health monitoring sensor networks have progressed in concert with advancements in low-power electronic devices and components. Energy harvesting from galvanic corrosion is one such scheme that has shown to be a viable solution for powering sensing platforms for marine infrastructure. However, as is the case with this energy harvester, the power output is current limited as a result of a high terminal resistance that increases with time. In addition, the output voltage is non-stationary, and is a function of several environmental parameters and the applied resistive load. Variability in the power source requires a robust conditioning circuit design to produce a regulated power supply to the sensing and computing electronics.

This paper experimentally investigates the non-stationary power characteristics of a galvanic corrosion energy harvester; and uncertainty quantification (UQ) is performed on the measured power characteristics for two experimental specimens subject to resistive load sweeps. The effects on designing a low-power sensor node are considered, and the uncertainty characteristics are applied to a low-power boost converter by means of a Monte Carlo simulation. Lastly, the total energy harvester capacity (measured in mA-Hr) is approximated from the data and is compared to a conventional battery.

8692-48, Session 12

Vibration control simulations and experiments using piezoelectric transducers on wind turbine blades at UC San Diego

Jeffery D. Tippmann, Francesco Lanza di Scalea, Univ. of California, San Diego (United States)

The extension of vibration control to wind turbine blade structures using piezoelectric transducers and periodic structures is investigated through experimental tests and numerical simulations. Both vibration and guided wave theory are used for studying the performance of the piezoelectric transducers on the wind turbine blade structure. The Macro Fiber Composite (MFC) transducer is specifically used in experimental tests because of its wide application range to flexible composite structures. The transducers are connected to a shunt circuit for suppressing certain frequency bands of vibration. The theory of periodic structures is also taken into account with regard to the placement of the transducers on the structure.

The experimental tests utilize both simple cantilevered beam configurations and a full-scale 9-m research wind turbine blade. Numerical simulations of the wind turbine blade are used to study the optimal placement of the transducers on the blade skin. Both traditional finite element and advanced isogeometric models that have been built are used for numerical simulations. In some of the numerical simulations, the shunt circuit is additionally studied by taking into account the electrical-mechanical interface within the simulation. The combination of the experimental and numerical results provide a new look at the feasibility of vibration control in wind turbine blades using piezoelectric transducers.

8692-49, Session 12

Modified ERA analysis for modeling nonstationary rotational structural dynamics in wind turbines

Antonio Velazquez, R. Andrew Swartz, Michigan Technological Univ. (United States)

Wind energy is becoming increasingly important worldwide as an alternative renewable energy source and wind turbines have become a particularly vital component in the world's mixed energy portfolio. Economical, maintenance, and operative factors are critical issues when dealing with such large slender structures, especially in the case of remote offshore wind farms. Health monitoring systems are today very promising technologies to assure reliability and good performance of the overall structure, typically supported by identification techniques constructed through data-driven analysis in either the frequency or time domains. In many cases, frequency response functions have proven to be difficult to calculate repeatable in an autonomous fashion when dealing with models of higher order or those having overlapped frequency content. Instead, time-domain techniques have shown powerful advantages from a practical point of view and are more suitable to differentiate closely-related modes. Often, time-varying effects are often neglected or dismissed when dealing with the stochastic dynamics of wind turbines, spinning multi-body type structures. A more complex scenario is constituted when dealing with a periodic mechanism responsible for the vibration draft of the rotor-blade system from one side, and the wind tower substructure from the other. Transformations of the cyclic effects on the vibration data can be applied to decouple inertia effects from rotating-generated forces that are non-stationary in nature. After applying transformations, structural identification can be carried out by stationary techniques via data-correlated eigensystem realizations. A periodic non-stationary subspace identification technique is presented in this paper adopting a modified Eigensystem Realization Algorithm (ERA) via cyclo-stationary principles, phenomena produced by periodical-motion systems embedded in stochastic wind fields such as wind-turbine rotor blades. Structural response is assumed under non-stationary ambient excitation and white (broad band) noise computed in an operative range bandwidth. ERA analysis is driven by correlation-function matrices from the stationary ambient response aiming to reduce noise effects. Singular value decomposition (SVD) and eigenvalue analysis are computed in a last stage to get frequencies and mode shapes. The proposed methodology is compared against two well established non-stationary models: (1) NExT (natural excitation technique), and (2) extended Ibrahim time-domain methods. Proposed assumptions are carefully weighted to account for the uncertainty of the environment the wind turbines are subjected to. Finally, comments and observations are thrown on how this subspace realization technique can be extended for modal-parameter identification using ambient vibration data exclusively.

8692-50, Session 12

Propagation error minimization method for multiple structural displacement monitoring system

Haemin Jeon, Jae-Uk Shin, Hyun Myung, KAIST (Korea, Republic of)

In the previous study, visually servoed paired structured light system (ViSP) which is composed of two sides facing with each other, each with one or two lasers, a 2-DOF manipulator, a camera, and a screen has been proposed. The system estimates 6-DOF relative displacement between two sides by calculating the positions of the projected laser beams on the screens and rotation angles of the manipulators. To apply the system to massive civil structures such as long-span bridges or high-rise buildings, the whole area is divided into multiple partitions and each ViSP module is placed in each partition in a cascaded manner. In other words, the movement of the entire structure can be monitored by multiplying the estimated displacements from multiple ViSP modules. In the multiplication, however, there is a major problem that the displacement estimation error is propagated throughout the multiple modules. To solve the problem, propagation error minimization method (PEMM) which uses the Newton-Raphson formulation inspired by the error back-propagation algorithm is proposed. In this method, the propagation error at the last module is calculated and then the estimated displacement from ViSP at each partition is updated in reverse order by using the proposed PEMM method. To verify the performance of the proposed method, various simulations and experimental tests have been performed. The results show that the propagation error is reduced significantly.

8692-119, Session PTues

Identification of structural parameters based on symbolic time series analysis and differential evolution strategy

Rongshuai Li, Akira Mita, Jin Zhou, Keio Univ. (Japan)

This new method of identifying structural parameters, called “Symbolization-based Differential Evolution Strategy” (SDES), merges the advantages of Symbolic Time Series Analysis (STSA) and Differential Evolution (DE). Data symbolization in SDES alleviates the effects of harmful noise. SDES was numerically compared with Particle Swarm Optimization (PSO) and DE on raw acceleration data. These simulations revealed that SDES provided better estimates of structural parameters when the data was contaminated by noise. We applied SDES to experimental data to assess its feasibility in realistic problems. SDES performed much better than PSO and DE on raw acceleration data. The simulations and experiments show that SDES is a powerful tool for identifying unknown parameters of structural systems even when the data is contaminated with relatively large amounts of noise.

8692-120, Session PTues

Multi-objective differential evolution strategy for structural system identification considering parametric uncertainties

Jin Zhou, Akira Mita, Rongshuai Li, Keio Univ. (Japan)

The proposed method merges the advantages of multi-objective differential evolution optimization algorithm for non-domination selection strategy and probability density evolution method for considering parametric uncertainty. The primary superiority of the proposed method lies in that it can deal with uncertainty parameter estimation problems. Simulation results for identifying the parameters of a multiple degree of freedom (MDOF) linear structural system under conditions including limited output signals, noise-polluted measurement data and no prior knowledge of damping or stiffness, are presented to demonstrate the feasibility and effectiveness of the proposed method.

8692-121, Session PTues

Low-frequency/high-sensitivity triaxial monolithic sensor

Fabrizio Barone, Fausto Acernese, Rosangela Canonico, Univ. degli Studi di Salerno (Italy); Rosario De Rosa, Univ. degli Studi di Napoli Federico II (Italy); Gerardo Giordano, Rocco Romano, Univ. degli Studi di Salerno (Italy)

This paper describes a new mechanical implementation of a monolithic triaxial inertial sensor, configurable as seismometer and as accelerometer. The sensor is compact, light, scalable, tunable (horizontal frequency < 100 mHz; vertical frequency < 1 Hz), with large band (10^-7 Hz - 10 Hz), high quality factor (Q > 1500 in air) instrument and good immunity to environmental noises, guaranteed by an integrated laser optical readout. The measured sensitivity curve is in very good agreement with the theoretical ones (10^-12 m/sqrt(Hz) in the band (0.1 - 10 Hz). Typical applications are in the field of earthquake engineering, geophysics, and in all applications requiring large band-low frequency performances coupled with high sensitivities.

8692-122, Session PTues

Large-band seismic characterization of the INFN Gran Sasso National Laboratory

Fabrizio Barone, Fausto Acernese, Rosangela Canonico, Univ. degli Studi di Salerno (Italy); Rosario De Rosa, Univ. degli Studi di Napoli Federico II (Italy); Gerardo Giordano, Rocco Romano, Univ. degli Studi di Salerno (Italy)

In this paper we present and discuss the scientific data recorded by the mechanical monolithic horizontal seismic sensors installed in the Gran Sasso National Laboratory of the INFN. These sensors, developed at the University of Salerno, are placed, within thermally insulating enclosures, onto concrete slabs connected to the bedrock, and behind a sound-proofing wall. The main goal of this experiment is the seismic characterization of the site in the frequency band 10^-7 - 10 Hz.

8692-123, Session PTues

Mechanical monolithic tiltmeter for low-frequency measurements

Fabrizio Barone, Fausto Acernese, Rosangela Canonico, Univ. degli Studi di Salerno (Italy); Rosario De Rosa, Univ. degli Studi di Napoli Federico II (Italy); Gerardo Giordano, Rocco Romano, Univ. degli Studi di Salerno (Italy)

The paper describes a tilt meter sensor for geophysical applications, based on Folded Pendulum (FP) mechanical sensor. Both the theoretical model and the experimental results of a tunable mechanical monolithic FP tilt meter prototype are presented and discussed. Some of the most important characteristics, like the measured resolution of about 0.1 nrad at 100 mHz, are detailed. Among the scientific results, earth tilt tides have been already observed with this monolithic FP tilt meter prototype.

8692-124, Session PTues

Beat phenomenon analysis of concrete beam with piezoelectric sensors

Lin-Sheng Huo, Xu Li, Hongnan Li, Dalian Univ. of Technology (China)

The free vibration of undercritically-damped system would be decayed

exponentially. However, when conducting the free vibration test with piezoelectric ceramic sensors, instead of an exponential decay, the vibration tends to decrease or increase periodically, which is characterized as the classical beat phenomenon. The focus of this paper is to give a better understanding of beat phenomenon in the free vibration test of a concrete beam with piezoelectric ceramic sensors from the view of mathematics. The cause of beat phenomenon from piezoelectric ceramic sensors embedded in the concrete beam is illustrated and the influence factors of beat phenomenon are discussed. The results show that the beat phenomenon from piezoelectric ceramic sensors in the column is caused by the coupled responses with similar model frequencies in different directions. The influence factors of beat phenomenon due to damping effect, impact direction, sensor position and sectional dimension are discussed. As the damping ratios increase, the amplitude of beat signal will die out in an exponential decay. The system response with unequal damping ratios in different modes will be decayed into the single mode with lower undercritical damping. Meanwhile, the damping has a tiny influence on the beat frequency of system response. With the variation of impact direction, the amplitudes of beat signal both in the time and frequency domain are changed, which makes it difficult to evaluate the structural frequency and can be characterized as a principle to determine the impact direction. In addition, the amplitude of beat signal will be also changed as the position of sensors altered. The beat frequency will get more with the greater difference of sectional dimension.

8692-125, Session PTues

Semi-active control of stay cables using nonlinear friction damper

Huiping WANG, Limin SUN, Tongji Univ. (China)

Stay cables of long span cable-stayed bridges are easy to vibrate under wind or wind/rain loads owning to their very low inherent damping. To install cable dampers near to the anchorages of cable has become a common practice for cable vibration control of cable-stayed bridge structures. The performance of passive linear viscous dampers has been widely studied. However, even the optimal passive device can only add a small amount of damping to the cable when attached a reasonable distance from the cable anchorage. This paper investigates the potential for improved damping using semi-active devices based on nonlinear frictional type of dampers. The equations of motion of a cable with a friction damper were derived using an assumed modes approach and the analytical solution for the motion equations was obtained. The results show that the friction damper evokes linearly decaying of free vibrations of the cable as long as the damper does not lock the cable. The modal damping ratio of cable with the friction damper is strongly amplitude dependent. Based on the characteristics of friction damper, the authors proposed a semi-active control strategy for cable control with dampers. The damper force has to be adjusted in proportion to the cable amplitude at damper position. The response of a cable with passive and semi-active dampers is studied. The response with a semi-active damper is found to be dramatically reduced compared to the optimal passive linear viscous damper, thus demonstrating the potential benefits using a semi-active damper for absorbing cable vibratory energy.

8692-126, Session PTues

Assessment and evaluation of damage detection methods based on modal frequency change

Hien HoThu, Akira Mita, Keio Univ. (Japan)

Research and development of Structural Health Monitoring (SHM) has been regarded as a very important research field for evaluating and maintaining structural integrity of a building. The main parts of SHM in civil engineering are damage detection and localization, which are essential monitoring zones for structures after major events such as earthquake or strong winds. In many previous researches, various damage detection methods are developed. However most of them require complete information of the structure to achieve reasonable accuracy of the damage detection, which means too many sensors are required to be installed into a building. For most of buildings, expensive and complicated SHM system is not a good application. To overcome these problems, a method using the support vector machine to detect local damages and their extent in a building with limited number of sensors was proposed by Akira Mita and Hiromi Hagiwara. As the method does not require modal shapes, typically only two vibration sensors are enough for detecting input and output signals to obtain the modals frequencies. This paper will propose the using of the squared modal frequencies, which were achieved by reviewing the above method. The proposed damage assessment method will be checked with numerical simulation examples of five-story shear structures and five-story steel model through shake-table tests. The damage of structure can be assumed by reducing of stiffness on each floor. The purpose of this study is to identify, localize and evaluate the magnitude of the real damage in multi-story structure by the shifts of natural frequencies.

8692-127, Session PTues

Structural damage identification based on substructure sensitivity and l1 sparse regularization

Shumei Zhou, Yuequan Bao, Hui Li, Harbin Institute of Technology (China)

Sparsity constraints are now very popular to regularize inverse problems in the field of applied mathematics. Structural damage identification is a typical inverse problem of structural dynamics and structural damage also is a spatial sparse phenomenon, i.e., structural damage occurs, only part of elements or substructures are damaged. In this paper, a structural damage identification method based on the substructure-based sensitivity analysis and the sparse regularization is proposed. By substructure sensitivity analysis, the relation between structural damage stiffness parameter variation and change of modal parameters are established as linear equations. Considering the structural damage sparsity conditions, to identify the location and extent of damages by minimize the l1 norm optimization problem. The numerical example of the truss structure with considering measurement noise, incomplete of measurements and multi-damage cases are carried out. The effects of number of sensor and layout to the identification results are also investigated. The results indicated that the damage locations and extents can be effectively identified by the proposed method. Additionally, the sensor location can be random arrangement, which has great significance to the sensor placement of the actual structural health monitoring because robust structural damage identification also can be obtained even a few of sensor are failure.

8692-128, Session PTues

Automated detection and classification of cracks on concrete bridge decks

Prateek Prasanna, Kristin J. Dana, Nenad Gucunski, Basily Basily, Rutgers, The State Univ. of New Jersey (United States)

The reliability of structural health monitoring of concrete bridges is highly dependent on the efficiency of detection of surface cracks. Frequent tests are conducted in order to determine the degree of deterioration. Moreover, assessment of surface condition of bridge decks is exteremly crucial for reasons of safety. Over the years, visual inspection has been the primary mode of such testing . These methods , apart from being cost and time-ineffiecient, are very labor-intensive as well when the bridges span a longer length. Such methods heavily depend on the experience of the specialist. It can also tend to be inaccurate. Failure of detection of these initial cracks might lead to decrease in longevity of bridge and sometimes collapse. This paper presents the use of image procesing and pattern recognition techniques in assessment of cracks

on a concrete bridge deck. Special emphasis is laid on the classification system developed using Histogram of Oriented Gradients.

This project concentrates on building a crack-detection system that can take into account the irregularity and randomness of cracks and can be successfully integrated with a robot in order to reduce the currently pursued manual process. This paper also discusses the designing of a 'mobile vision cart' for deck-imaging purpose and the subsequent path-planning for the entire process to ensure complete coverage. The obtained results are compared against the ground truth and the accuracy of the proposed system is determined.

8692-129, Session PTues

Application of hall element as multimodal sensing device for artificial skin

Jun-ichiro Yuji, Kumamoto National College of Technology (Japan)

In order to identify features of the touched object, realizing the artificial skin senses like the human fingertip is required. Many kinds of multimodal tactile sensors have been developed for robotic fingers and hands in recent years. However, since the most multimodal tactile sensors consist of some individual sensing elements for each purpose, the kinds of sensor increase with the number of the skin sensation.

In this paper, we reports on tactile sensing methods to apply Hall effect elements, which are generally used as magnetic sensors, to the artificial skin as multimodal sensing devices of contact force and temperature. This tactile sensor consists of Hall elements and magnets that are embedded in an elastic silicone rubber as the artificial skin. Here, contact force is detected by distance change of a Hall element and a magnet, and temperature is also detected using the temperature dependency of a Hall element.

The temperature dependency of a Hall element changes with the Hall material and the drive circuit to detect the Hall output voltage. Therefore, we show three kinds of tactile sensors fabricated by the combination of two Hall elements, that is, GaAs Hall element and InSb Hall element, and two drive circuits, that is, constant voltage drive and constant current drive. Since it is possible to detect contact force and temperature by obtaining two kinds of Hall output voltage, these methods are effective for fabrication of a multimodal tactile sensor.

8692-130, Session PTues

Data analysis for long-term structural health monitoring on a continuous rigid frame bridge

Lei Wang, Harbin Institute 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 brag 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 stain 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 parameters 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.

8692-131, Session PTues

Multigas optical fiber sensing system

Weiqi Wang, Tianyu Zhang, Jilin Univ. (China); David Y. Li, L.C. Pegasus Corp. (United States)

Methane, carbon monoxide, and ammonia are three harmful gases that frequently lead to fatal accidents. Much attention has focused on how to detect these gases at the simultaneously. Absorption of light radiation in the near-infrared spectra is widely used to detect the existence and the concentration of gaseous specimen for its simplicity and high sensitivity to the environmental conditions of the absorbing species.

This paper introduces a multi-gas optical fiber sensing system, which can detect the concentration of multiple gases (including CH4, CO, NH3? in one system rapidly. The system is composed by four parts. The self-designed laser light source section can output light of different wavelengths depending on the specific gas to be measured. Another important part is the gas cell. In order to enable accurate determination of the concentration of different gases, we designed a unique white cell which could make the laser pass different length of the optical path in different gases. The processing circuit and data processing software are the other two parts in this system. This system has achieved relatively high sensitivity (better than about 100 ppm for three gases). The response time of the system is less than 6 seconds.

Extensive tests have been carried out. It is shown that the performance of the optical fiber sensor system is generally superior to the conventional system. The Multi-gas Optical Fiber Sensing System will be used for gas safety monitoring in the many areas.

8692-132, Session PTues

Femtosecond laser irradiation enhanced room temperature tin oxide nanostructure gas sensor

Haizhou Ren, Haibin Huo, Mengyan Shen, Marina Ruths, Hongwei Sun, Univ. of Massachusetts Lowell (United States)

Tin oxide (SnO2) thin film gas sensors that function at room temperature have been fabricated on nanostructured substrates. After femtosecond laser irradiation of the sensing surface of the SnO2, the sensitivity to gases, for example, ammonia, increased noticeably. The dependence of the sensitivity on the number of laser pulses has been investigated. It is believed that the femtosecond laser pulses generate defects in a thin layer on the SnO2 sensor surface. These defects may result in a potential energy well creating surface bound states for electrons to move on the surface, which could increase the sensitivity to gases.

8692-133, Session PTues

Simulation and experiment for large-scale space structure

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The future space structures are relatively large, flimsy, and lightweight. As a result, they are more easily affected or distortion by space environments compared to other space structures. This study examines the structural integrity of a large scale space structure, To maintain the required accuracy of the space structure under orbital temperature changes, the space structures will utilize an active control system, consisting of boundary control actuators and an electrostatic figure control system with a real time closed loop feedback. An experimental system is established to verify the control mechanism with photogrammetric measurement technique and Bragg fiber grating (FBG) sensor technique. The shape control experiments are finished by measuring and analyzing small amplitude distortion of the structure based on the active components made of shape memory alloy (SMA) and shape memory polymer composite (SMPC) material. Then, simulations are finished by NASTRAN finite element software with active effect which is considered to be deformation applied on the analytical model. The amplitude of distortion is obtained by the simulations. Both the experimental and numerical solution show that the amplitude of accuracy are developed which proves the feasibility of shape control using shape memory materials and this investigation explores the feasibility of utilizing an active cable based control system of shape memory materials to reduce global distortion due to thermal loading. It is found that through proper assemble of cable lengths and attachment points, significant thermal distortion reduction is achieved. Specifically, radial distortion due to on-orbit thermal loading .

8692-134, Session PTues

Depth-sensor design and fabrication process using silver-paste printing method

Hyeunseok Choi, Korea Institute of Industrial Technology (Korea, Republic of)

We carried out acid treatment on SWCNT to make homogeneous dispersion in silver-CNT mixed paste ink for the screen-printing process.

Mixing ratio and Dispersion condition make different sensor performance in total resistance, joule heating ratio, pressure sensitive, life time and printing quality. Because SWCNTs make network bridges between the silver nano particles, the resistance of pattern can be decreased. Also sensitivity is increased because SWCNT network structure changed by applied mechanical pressure and electrical resistance is changed. The synthesized ink was measured by 4point probe method.

We finally fabricated the pressure sensor with 1.5% wt SWCNT to silver paste. The sensor pattern printed on PI(Polyimide) film. PI film has been used widely in printed electronics product by flexible PCB and flat cable, because PI film known thermal stability, good chemical resistance, and excellent mechanical properties. The patterned PI film with silver-CNT is encapsulated in waterproof part.

The developed pressure sensor was verified by measuring resistance under various pressure conditions. We used a pressure controlled water tank to test waterproof performance of the sensor and characteristic as depth sensor for the underwater robot.

8692-135, Session PTues

Performance criteria for dynamic window systems utilizing nanostructured behaviors for energy harvesting and environmental comfort

Peter R. H. Stark, Anna H. Dyson, Brandon C. Andow, Bess Krietemeyer, Rensselaer Polytechnic Institute (United States)

Contemporary buildings continue to utilize predominantly glazed envelope systems, despite difficulties with thermal regulation, energy use and visual comfort. The need for window systems to respond to changes in the environment while meeting variable demands for building energy use and occupant comfort has led to considerable investment in advancing dynamic window technologies. Although these technologies demonstrate cost warranting improvements in building energy performance, they face challenges with visible clarity, color variability and response time. The material dependent limitations of advanced glazing technologies have initiated a search for new thin film solutions, with new device possibilities emerging across many fields. Idealized window performance has traditionally been defined as the dynamic control of transmittance, glare, solar gain and daylighting at any time to manage energy, comfort and view. However, emerging material systems point towards other physical phenomena for achieving transparency modulation, demanding a broader reinterpretation of advanced glazing end goals. Building upon the already complex set of requirements for high-performance glazing, we prescribe additional system functions ranging from nano-structural behaviors to an ecological scale, introducing aspects of aesthetic variability, interactivity, sun tracking, spectral selectivity, energy collection, variable solar heat gain coefficients, material lifecycle and glass-integrated sensing. In order to develop new material possibilities for next generation dynamic glazing, a set of prescriptive performance criteria is presented to satisfy an idealized architectural behavior.

8692-136, Session PTues

Structural modal identification using data sets with missing observations

Thomas J. Matarazzo, Shamim N. Pakzad, Lehigh Univ. (United States)

System identification algorithms currently require a full data set, i.e. no missing observations, to estimate the natural vibration properties of a structural system. These algorithms are often based on parameters estimated from a state space or ARMA model. There are circumstances in which a Missing Data Problem can arise during data collection; therefore, it is important to adjust these algorithms to facilitate Structural Modal Identification. Despite having missing observations, ARMA parameters can be estimated from a time series; subsequently, structural modal properties can be identified. This paper will focus on the search for a missingness threshold which can be used to assess the probability of extracting useful structural modal properties from a given data set with missing observations. This assessment will be based on the accuracy of modal estimates for data sets with varying magnitudes and patterns of missingness. It is clear that missingness can only reduce the accuracy of modal estimates however, it is important to establish the associated scale and behavior of the reduction. An example is presented to illustrate the main concepts of this approach.

8692-137, Session PTues

Experimental investigation of annealed ionic polymer transducers in sensing

Bilge Kocer, Ursula Zangrilli, Lisa D. Mauck Weiland, Univ. of Pittsburgh (United States)

Ionic polymer transducers (IPTs) are fabricated from ionomers sandwiched between conductive electrodes. IPTs act as actuators by deforming in response to an input voltage. They also exhibit sensing behavior yielding a current when exposed to various forms of deformation. IPT performance depends on many variables including the stiffness of the polymer which evolves with the level of semicrystallinity within the polymer. It is observed via tension tests that annealing influences the stiffness of the polymer. In this paper, the goal is to determine the effects of annealing on ionic polymer sensors. For this purpose, several IPTs are created via the Direct Assembly Process from both annealed and as-received Nafion samples and tested in bending. For both types of IPTS, generated currents due to step displacement are measured through an amplifying electric circuit and compared. In this work, high surface area RuO_2 is used as the metallic powder in the electrode while the transducers used in the experiments are Li^+ exchanged and solvated with 1-ethyl-3-methylimidazolium trifluoromethanesulfonate (EmI-Tf) ionic liquid.

8692-138, Session PTues

The Community Seismic Network and Quake-Catcher Network: enabling structural health monitoring through instrumentation by community participants

Monica D. Kohler, Thomas H. Heaton, Ming Hei Cheng, California Institute of Technology (United States)

A new type of seismic network is in development that takes advantage of community volunteers to install low-cost accelerometers in houses and buildings. The Community Seismic Network and Quake-Catcher Network are examples of this, in which observational-based structural monitoring is carried out using records from one to tens of stations in a single building. We have deployed about one hundred accelerometers in a number of buildings ranging between five and 22 stories in the Los Angeles region. In addition to a USB-connected device which connects to the host's computer, we have developed a stand-alone sensor-plug-computer device that directly connects to the internet via Ethernet or wifi. In the case of the Community Seismic Network, the sensors report both continuous data and anomalies in local acceleration to a Cloud computing service consisting of data centers geographically distributed across the continent. Visualization models of the instrumented buildings' dynamic linear response have been constructed using Google SketchUp and an associated plug-in to matlab with recorded shaking data. When data are available from only one to a very limited number of accelerometers in high rises, the buildings are represented as simple shear beam or prismatic Timoshenko beam models with soil-structure interaction. Small-magnitude earthquake records are used to identify the first set of horizontal vibrational frequencies. These frequencies are then used to compute the response on every floor of the building, constrained by the observed data. These tools are resulting in networking standards that will enable data sharing among entire communities, facility managers, and emergency response groups.

8692-139, Session PTues

Automated computer vision-based detection of exposed transverse reinforcement for post-earthquake safety assessments

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Current procedures in post-earthquake safety and structural assessment are performed by a triage team of structural engineers or certified inspectors. These procedures are inherently time-consuming and qualitative. Spalling has been accepted as an important indicator of significant damage to structural elements during an earthquake, and thus provides a sound springboard for a model in computer vision-based automated assessment procedures as is proposed in this research. Thus, a novel method that automatically detects regions of spalling on reinforced concrete columns and measures their properties in image data is desired. With respect to these efforts, the properties of spalled regions are determined based largely on the extent of exposure of reinforcement. Thus, this work focuses primarily on the efforts to detect the exposure of transverse reinforcement on reinforced concrete frame members. According to this method, the region of spalling is first isolated by way of a local entropy-based thresholding algorithm. Following this, the regions of exposed reinforcement (transverse and longitudinal) are identified by thresholding in the CMYK channels. Then the Hough Transform is used to detect horizontal edges within the regions contained in each of respective CMYK channel thresholded images. Then, all of the edges are combined, near-collinear lines are merged and the result is output as a region of transverse reinforcement exposed on the element surface. The method was tested on a database of damaged RC column images collected after the 2010 Haiti Earthquake, and comparison of the results with manual detection indicate the validity of the method.

8692-140, Session PTues

Active mass damper system employing time delay control algorithm for vibration mitigation of building structure

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The feasibility of an active mass damper (AMD) system employing the time delay control (TDC) algorithm, which is one of the robust and adaptive control algorithms, for effectively suppressing the wind-induced vibration of a building structure is investigated. The TDC algorithm has several attractive features such as the simplicity and the excellent robustness to unknown system dynamics and disturbance. Based on the characteristics of the algorithm, it has the potential to be an effective control system for mitigating excessive vibration of civil engineering structures such as buildings, bridges and towers. However, it has not been used for structural response reduction yet. In order to verify the effectiveness of the proposed active control method combining an AMD system with the TDC algorithm, its stability analysis is first performed. And then, numerical simulations and lab-scale tests are carried out.

8692-141, Session PTues

Dynamic strain measurement for early damage detection of structures via long-gage optical fibers

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The performance of modal macro strain-based damage detection using dynamic measurement with long-gage strain sensors in low-level vibrations is limited by its deficiency in accurately analyzing of low signal-to-noise-ratio signals and inability in high frequency information identification of non-stationary signals. Recent advances in Pulse-Pre-Pump Brillouin Optical Time Domain Analysis (PPP-BOTDA) based fiber optic sensing techniques have improved the global and local performances of large scale structures in damage detecting and strain monitoring. However, the PPP-BOTDA based sensing technique requires a low sampling rate to ensure the measuring accuracy. This low sampling rate limited the application of PPP-BOTDA based sensing technique in dynamic strain measurements. This paper introduces an improvement of PPP-BOTDA based high sampling rate measurement, and proposed a wavelet-based signal analysis method to reduce the influence of noises and measuring errors in short and long time scale. The validation of the proposed method of real-time measured low level dynamic strains through optical fiber sensors shows the denoised signals achieve the requirement of early damage detections. The high frequency modal information of a low level dynamic signal is easily influenced by stochastic noises, the wavelet-based de-noising method are suitable to deal with the real-time measured signals and can reliably detect damage through noised continuous dynamic signals via distributed long-gage optical fiber sensors. Finally, the effectiveness of the proposed method on a high sampling rate PPP-BOTDA measured train-induced vibration of an excited bridge is verified.

8692-142, Session PTues

Fault detection using magneto-inductive waves with WVD-based time-frequency representation

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Time-frequency representations (TFRs) have been demonstrated effective for characterizing dispersive waves. Multiple time and frequency analysis methods are developed for identifying the time-varying characteristics of dispersive waves. The Wigner-Ville distribution (WVD) method satisfies

many desirable time-frequency properties such as better temporal and frequency resolution, and free of smearing effect by a windowing function. This paper investigates the use of Wigner-Ville distribution in interpreting magneto-inductive waves and the application of passive magneto-inductive waveguide to monitor defect in infrastructure systems.

The Wigner-Ville distribution method is applied on reflected MI waves to locate where the reflection occurs. A simulated onset of corrosion in concrete is studied using this technique. A passive MI waveguide is built with an array of capacitively loaded metallic rectangular spiral loops printed on PCB board and characterized by dispersion relationship and group velocity of MI waves. The onset of corrosion increases the impedance of a resonator circuit along the MI waveguide and makes reflected waves take place at the point. With WVD-based time-frequency representation of received reflected waves, the propagation distance is estimated by multiplying arrival time and group velocity of MI waves. This is then used to determine the location of defect. The one-port time-domain experimental results show WVD method can effectively provide the frequency content as a function of time for MI waves and estimate the travel distance. The onset of defect is correctly located along the passive MI waveguide. This implies great potential of MI waves for fault detection in structural health monitoring.

8692-143, Session PTues

Operational modal identification of a long span cable-stayed bridge with wireless sensors

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For health monitoring of a long span cable-stayed bridge, modal parameters and tensions of cable stays are the most important parameters to assess the condition of bridge structure under operation. Yamen cable stay bridge with main span of 328m , which located in Jiangmen city cross Pearl River, was open to traffic in 2002. A modal test and cable vibration test of the bridge was performed based on Imote2 wireless smart sensors under ambient excitation and a three dimensional FEM of Yamen bridge was established. The modal parameters of the bridge and the cable tensions of selected cable stays were identified using a improved multiple reference DOFs stabilization diagram algorithm based on ERA. By setting different reference DOFs in each group of data, NExT-ERA was used to identify modal parameters. Damping ratio, Consistent Mode Indicator from Observability (CMI_O) and Modal Assurance Criterion (MAC) was used as threshold to identify the most accuracy modal parameters. Lower order frequencies and modes of the bridge were estimated by quadratic fit method, and cable tension was estimated by two different methods. The measured results showed that there are no significant differences for the identified frequencies of the bridge and the cable tensions compared with those of the bridge at the completion. Based on the analysis of deck and cable vibration, it is evident that the vertical vibration of the bridge deck is tightly coupled with the cable vibrations within the frequency range of 0~3Hz.

8692-144, Session PTues

Optimal placement of smart sensors in CFS structures under blast loading using hybrid FEM-GA technique

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Blasts can produce, in a very short time, an overload much greater than the design load of a building. The blast explosion nearby or within structures causes catastrophic damage to the building both externally and internally. Hence, they have to be protected from the blast effects. This study intends to model a Cold-Formed Steel (CFS) building using Finite Element Method (FEM) in which material properties of the model are defined according to results of performed laboratory test. Then accelerograph record of a standard blast was applied to the model. Furthermore, various Optimal Sensor Placement (OSP) algorithms were used and Genetic Algorithm (GA) was selected to act as the solution of the optimization formulation in the selection of the best sensor placement according to the blast loading response of the system. In this research a novel numerical algorithm was proposed for OSP procedure which utilizes the exact value of the structural response under blast excitation. Results show that with a proper OSP method for Structural Health Monitoring (SHM) can detect weak points of CFS structures in different parts efficiently.

8692-145, Session PTues

Real-time health monitoring on impact identification of composite structures with distributed built-in sensor network

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Wear and tear resulting from certain mechanical impact events threats to the safety and reliability of aerospace structures, and affects aerospace structures' integrity over the course of their operational lifetime. Especially for composite structures, damage due to impact events may not be visible to surface inspection but still can cause significant loss of structural integrity. Therefore, special techniques and equipment are required to inspect this kind of damage, such as x-ray, radiography, or ultrasonic scan, all of which are costly, labor-intensive, and time-consuming for a large aerospace structure.

Therefore, an investigation was performed to develop a real-time health monitoring system for the identification and prediction of the location and force history of foreign object impact on composite structures with distributed built-in piezoceramic sensors. The smart health monitoring system is composed of the two main subsystems: a measurement subsystem and an identification subsystem. The measurement subsystem with distributed built-in sensor network was used to collect and preprocess sensor data, and then the identification subsystem was implemented to reconstruct the force history and determine impact locations with the acquired prefiltered sensor data. The identification subsystem consists of a system model & model structure and an inverse model operator (IMO) and a response comparator. The identification subsystem was created to identify the impact locations and force history reconstruction on composite structures without the need for the information about actual mechanical properties, geometries and boundary conditions of a structure, and without building a specific neural network with exhaustive training such as neural-network techniques, also without the need of constructing a full-scale accurate structural model. A novel dynamic mechanical model based time-series model structure approach (the combination of Wavelet based SFE and ARXMs) is used into the identification subsystem, which the entire impact identification procedure is much faster than that of the classical model-based techniques. The smart health monitoring system was tested with more various impact situations, for all of the cases considered, good agreement was found between predicted and actual force history and location, and the estimation errors fell well within the prespecified limit.

8692-146, Session PTues

Semi-active vibration control with harmonically varying damping (application to serial TDOF system and filtering using the Stuart-Landau Equation)

Satoshi Hirohata, Daisuke Iba, Kyoto Institute of Technology

(Japan)

This paper demonstrates a new semi-active vibration control method with harmonically varying damping on a serial two-degree-of freedom system. We applied the method to vibration mitigation of a single-degree-of-freedom structure and a parallel-coupled structure with sinusoidal base excitation having two frequencies, before. In these studies, an ideal variable damper was used in conjunction with the secondary sinusoidal disturbance vibration to reduce the response due to the primary vibration. In other words, another resonance can be generated by the modulated component caused by the variable damping device and the secondary base excitation. The additional resonance was adjusted to be out of phase with the primary response, and the response of the structure was effectively reduced as a result of the generated damping force. However, no such study considering the serial multi-degree-of-freedom system has been conducted. In this paper, the proposed semi-active control law is applied to the serial multi-degree-of-freedom system, i.e. the structures with the seismic isolation layer. To more specifically, the primary mode response of the structure is controlled by the effect between harmonically varying damping and the higher-order mode response of the structure. In addition, because the proposed control law requires the phase of the each mode response of the structure, a new filter using nonlinear oscillators, Stuart-Landau equation, is also proposed. The filter is taken advantage of the synchronization properties of the nonlinear oscillators. As a result of the advantage, the oscillators can separate each vibration mode of the structure, and estimate the each phase.

8692-147, Session PTues

Design and development of piezo based on board alignment hexapod system

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High resolution Camera systems consist of large size high definition telescope. In general the telescope systems consist of large size primary mirror along with other mirrors called secondary mirror and tertiary mirror located at a long distance from the primary mirror. The dimensional stability requirement for relative positioning amongst each other is of the order or 1 micron between mirrors in terms of linear displacement and 1 arc second in terms of tilts amongst the mirrors. With finest possible material properties of metering structure like co-efficient of thermal expansion, it is very difficult to ensure the required dimensional stability. This is mainly due to thermal, structural and zero gravity environmental impacts on the structure.

This can be overcome satisfactorily by keeping provision of onboard alignment capability. To correct the misalignment of the relative positions of critical optical components, active positioning system based on actuators is required which can be commanded onboard for achieving optimum performance of camera systems.

Smart material like piezoelectric material whose physical properties can be changed in a controlled manner by changing electric fields is a suitable choice for this application. Piezoelectric material is one of the smart materials which experiences increase in size when applied with an electrical field.

A miniaturize Hexapod is designed and developed using the piezo actuators. It provides submicron level accuracy, high stiffness and backlash free operation which is most essential for onboard telescope alignment. The work involves design and analysis of virtual ball joint, derivation of hysteresis loop and voltage-displacement transfer function for piezoelectric actuator, realization of hexapod, development of algorithm to drive actuator for achieving desired DOF, characterization of a hexapod system for all 6 DOF, derivation of error function of each DOF and implementation of it to the computer algorithm to achieve desired accuracy.

Work is also done to identify the ways to obtain the values for each degrees of freedom, so that accordingly by forward integration the actuators can be given command.

8692-148, Session PTues

A piezoelectric-wafer-stack vibration energy harvester for wireless sensor networks

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Over the past few decades, wireless sensor networks have been widely used in civil structure health monitoring application. Currently, most wireless sensor networks are battery-powered and it is very costly for maintenance because of the requirement for continuous battery replacements. In order to solve this problem, this paper presents a novel piezoelectric vibration energy harvester to convert the structural vibration into usable electrical energy for powering the wireless sensor networks. Unlike the normal cantilever beam structure, the piezoelectric harvester shown in this paper is based on the wafer-stack configuration which is appropriated for large force vibration conditions, and can be embedded in civil structures and convert the large structural vibration force directly into electrical energy. The longitudinal mode of the piezoelectric-wafer-stack was developed firstly to illustrate the force-to-voltage relationship of piezoelectric materials and to find the inter-medium force that will be used to convert vibration energy into electrical energy. Then, two electromechanical models (without and with a rectified circuit), considering both the mechanical and electrical factors of the harvester, were built to characterize the harvested electrical power across the external load. Exact closed-form expressions of the electromechanical models have been given to analyze the maximum harvested power and the optimal resistance. Finally, a shake table experimental testing was conducted to evaluate the feasibility of the presented piezoelectric-wafer-stack harvester under standard sinusoidal loadings. Test results show that the harvester can generate a maximum 45mW AC and 16mW DC electrical power for sinusoidal loading with amplitude of 40mm and frequency of 2Hz, and the harvested electrical power is proportional to the exciting vibration strength.

8692-150, Session PTues

Nonlinear behavior of coupling beams with novel shape-memory alloy dampers under lateral loads

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For the conventional frame-shear wall system, severely damage in coupling beams results in high repair cost post earthquake and even in some cases it is difficult to repair the coupling beams. In order to solve this problem, a novel passive SMA damper exploiting pseudoelasticity of austenite SMA material was proposed in this study. The dampers are installed in the middle of coupling beams. Three key design parameters of SMA dampers are defined: (1) the ratio of dampers' yielding force to coupling beam's ultimate shear force (YFR); (2) the ratio of dampers' yielding deformation to net span of coupling beam (YDR); (3) the ratio of nominal stiffness of SMA dampers to flexural stiffness factor of coupling beam (SR). To get rational values of these parameters, numerical simulation was conducted investigating nonlinear behavior of floor-level coupling beam subassemblies with SMA dampers under monotonic and cyclic loading. Three conclusions can be obtained: (1) for cases of the same YFR, the maximum deformation and damage of coupling beams are slightly magnified with YDR increasing; (2) for cases of the same YDR, coupling beam's deformation is concentrated in dampers, and residual deformation and the damage of coupling beams are reduced with YFR decreasing; (3) when YFR are in the range of 0.6 to 0.8, the dampers almost simultaneously yield with yielding of longitudinal rebar in coupling beams, and the coupling beams have good self-centering ability. The damage of coupling beams is relatively small.

8692-151, Session PTues

High-temperature measurement using Cu-plating fiber Bragg grating for metal smart structure applications

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The commonly used coating for fiber Bragg gratings (FBGs), with Acrylate as its main component, is not able to endure high temperature and is used only under 100°C. With polyimide coating it can measure temperature up to 300°C. However, the relationship between the FBG's central wavelength shift and temperature variation is not linear by quadratic, once the measured temperature is above 100°C, which restricts FBG's application in measuring high temperature. To improve FBG's temperature characteristics, we covered FBG's surface with copper uniformly by way of electroless Cu-plating, and carried out high temperature experiments to validate the feasibility of high temperature measurement and obtained good results.

Our high-temperature experiments for electroless Cu-plating FBG indicate that Cu-plating FBG can measure high-temperature up to (even beyond) 300°C, and it has high linearity, accuracy and repeatability. In a certain range, FBG's thermal expansion coefficient increases with increase in the Cu-plating thickness, so we can obtain specific Cu-plating FBG's temperature sensitivity by controlling the plating layer's thickness. The temperature sensitivity of FBG with Cu-plating can be improved by more than three times with no less than 300 um thick coating by electroless and electrical Cu-plating. Such Cu-plating FBG can be soldered onto metal structures to get good bonding with the structure. As a result, the Cu-plating FBG sensors soldered with metal structure can get good protection, and can be bonded with metal structure perfectly to constitute metal smart structure with high-temperature monitoring. It will pave a new way for fiber smart metal structures and materials.

8692-152, Session PTues

Monitoring the deformation of the SMP-based active morphing structure using fiber Bragg gratings

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We theoretically and experimentally demonstrate a technique monitoring the deformation process of the active morphing shape-memory polymers (SMPs) structure by using the embedded fiber Bragg gratings (FBGs) as the vector bending sensors. The finite element model (FEM) was developed to model the strain distribution induced by deployable deformation and optimize the design of experiment. In the experiment, a SMP plate as a simply model was fabricated to validate experimentally using the thermal-responsive epoxy based SMP materials. Two FBGs sensors which were place in orthogonal were embedded at the upper and lower surfaces of the SMP plate separately. The sample was tested under various static conditions to determine the response characteristics of the proposed embedded sensors. When the SMP model undergoes different degree bending deformity or different bending radius, the resonance wavelength of the FBG will has red-shift according to the tensile stress gradient along the FBG. Static six angles bending tests showed good agreement between values measured by embedded strain grating and those predicted by FEM. Such a sensing system can effectively reduce the cross-sensitivity between strain and temperature during the curing and deformation process through temperature compensate.

8692-153, Session PTues

Brush wear and dust accumulation fiber-optic sensor system for synchronous compensators online monitoring

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An electro-optical sensor system for monitoring synchronous compensators in the electrical distribution network is presented. The fiber-optic sensor system is based on two main technologies: optical bend loss sensors for monitoring the brush wear and free-space optics to determine the dust accumulation from brush wear. Both techniques are characterized to monitor the parameters by means of simple optical power readings. In order to avoid optical power fluctuations in the fiber optics link from interrogation system to the synchronous compensators, bend-loss insensitive fibers are used. The low-cost interrogation system consists on one laser, optical splitters and 80 photodetectors to independently monitor each one of the synchronous compensators' s brushes. This set up ensure an ease installation and avoid cascaded fault that a serial configuration could originates, thus increasing reliability of the sensor system.

The technique of optical fiber bending loss principle can also be used in other situations, such as structural heath monitoring of large building and complex structures. The low cost displacement sensor proposed can be easily adapted to respond to several situations, including larger displacements, by a properly packaging fitting. The sensor is said a low-cost one when compared with FBG displacement sensor counterparts for low precision application, were no micrometric or submicrometric measurement is required.

In fact, in these cases, FBG displacement sensors have a cost of hundreds of dollars in contrast with a few dollars cost of the proposed sensor.

8692-154, Session PTues

Design of self-contained sensor for monitoring of deep-sea offshore platform

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Offshore platform, which is the base of the production and living in the sea, is the most important infrastructure for developing oil and gas resources. At present, there are almost 6500 offshore platforms servicing in the 53 countries' sea areas around the world, creating great wealth for the world. In general, offshore platforms may work for 20 years, however, offshore platforms are expensive, complex, bulky, and so many of them are on extended active duty. Because of offshore platforms servicing in the harsh marine environment for a long time, changes in the marine environment have a great impact on the offshore platforms. Besides, with the impact and erosion of seawater, and material aging, the offshore platform is possible to be in unexpected situations when a badly sudden situation happens. Therefore, it is of great significance to monitor the marine environment and offshore platforms. The self-contained sensor for deep-sea offshore platform with its unique design, can not only effectively extend the working time of the sensor with the capability of converting vibration energy to electrical energy, but also simultaneously collect the data of acceleration, inclination, temperature and humidity of the deep sea, so that we can achieve the purpose of monitoring offshore platforms through analyzing the collected data, this design plays an important role in monitoring the offshore platforms.

The self-contained sensor for monitoring of deep-sea offshore platform includes sensing unit, data collecting and storage unit, the energy supply unit. The sensing unit with multi-variables, consists of an accelerometer LIS344ALH, an inclinometer SCA103T and a temperature and humidity sensor STH11; the data collecting and storage unit includes the

MSP430 low-power MCU, large capacity memory, clock circuit and the communication interface, the communication interface includes USB interface, serial ports and wireless interface; in addition, the energy supply unit, converting vibration to electrical energy to power the overall system, includes the electromagnetic generator, voltage multiplier circuit and a super capacitor which can withstand virtually unlimited number of charge-discharge cycles. When the seawater impacts on offshore platforms to produce vibration, electromagnetic generator converts vibration to electrical energy, its output(~ 1 V 50 Hz AC) is stepped up and rectified by a voltage multiplier circuit, and the energy is stored in a super capacitor. It is controlled by the MSP430 that monitors the voltage level on the super capacitor. The super capacitor charges the Li-ion battery when the voltage on the super capacitor reaches a threshold, then the whole process of energy supply is completed. The self-contained sensor for deep-sea offshore platform has good application prospects and practical value with small size, low power, being easy to install, converting vibration energy to supply power and high detection accuracy.

8692-155, Session PTues

Battery-less wireless acoustic emission sensor based on piezoelectric wafer active sensor

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The sensing of Acoustic Emission signals usually requires specially design piezoelectric transducer and complicate signal preconditioning. Moreover, the large bandwidth of AE signal makes wireless AE transmission using conventional wireless sensor nodes extremely difficult. This paper presents a battery-less wireless AE sensing system based on a low cost and low profile piezoelectric wafer active sensor (PWAS). A low power amplifier is designed to amplify the AE signal as well as matching the high impedance of the PWAS to the 50 ohm input impedance of the wireless transponder. A solar harvesting unit consisting of a Schmitt trigger and a voltage booster is designed to power the low-power amplifier. A wireless transponder is constructed from a dual polarization antenna and a frequency mixer. One polarization of the antenna receives the interrogation AE sensor, which serves as the carrier signal that converts the analog AE signal to a radio frequency signal using the passive frequency mixer. A sensor interrogation unit implemented on a printed circuit board was used to recover the wirelessly transmitted signal using homodyne receiver configuration. The battery-less wireless AE sensing system is characterized using pencil lead break experiment. The design, implementation, and characterization of the wireless AE sensing system are discussed.

8692-156, Session PTues

Incorporating gyroscopic effects in low-order spinning finite element models for wind-turbine structural dynamics

Antonio Velazquez, R. Andrew Swartz, Michigan Technological Univ. (United States)

Renewable energy sources have been the fastest growing installed production technologies developed in the past decade to replace fossil-fuel sources. Capturing wind energy in a more efficient manner has resulted in the development of more sophisticated technologies, especially for horizontal axis wind turbines (HAWTs). To promote efficiency, traditional finite element methods have been used extensively in the past to characterize the aerodynamics of these multi-body systems. Nevertheless, the modeling of complex geometries, moving components, and wind-structure interactions has demanded huge computational resources while still desiring faster computation times at lower cost and avoiding tradeoffs in reliability and numerical accuracy. Given their aero-elastic behavior, tapered-swept blades offer the potential to optimize energy capture and decrease fatigue loads. Instead, the computational cost and the effort invested to reproduce dependable aerodynamics of the complex-shape beams, using traditional FE methods, can be prohibitive. A condensed spinning finite element method (SFE) is presented in this study aimed to alleviate this issue by means of modeling wind-turbine rotor blades with tapered-swept cross-section variations of "nt" order all along the span. This study focuses on the case of yaw effects expressed within the described skew-symmetric gyroscopic matrix to achieve modal analysis with complex-number eigenfrequencies. By means of dynamic mass, gyroscopic, and stiffness matrix condensation (order reduction), numerical analysis is carried out for several prototypes with different tapered, swept, and twisted intensities, and for a practical range of spinning velocities at different rotational angles. Time-varying modal analysis and its collateral effects for, either amplification or reduction of the structural response, such as tip displacements, overturning moments and base shears, is investigated. Numerical examples are provided for wind turbines of order low orders. Simultaneously, execution times are computed as a function of number of nodes and number modes required to satisfy convergence. Condensed SFE approach is benchmarked with standard computer-aided wind-turbine FE model formulated for rotational dynamics via ANSYS commercial software. The proposed framework is projected to be particularly suitable for the characterization of large systems at low computation cost. In the same way, results demonstrate that condensed SFE is adequate for model updating and validation using experimental data via "online" search algorithms (e.g. Simulated Annealing). The proposed method offers therefore the potential to be implemented in embedded wireless sensors with intense operational throughputs and high data sampling rates.

8692-157, Session PTues

Development of cyber-based autonomous structural integrity assessment system for building structures

Masahiro Kurata, Kohei Fujita, Xiaohua Li, Tomoya Yamazaki, Kyoto Univ. (Japan)

When large-scale building structures are subjected to a severe earthquake, making a judgment call on whether to continue normal activities in buildings or to evacuate involves many uncertain factors and subjectivity in decision-making processes. For the use of post-earthquake damage screening, a practical structural health monitoring (SHM) system must be designed to automatically identify the degree of damage in primary structural components in a prompt manner. Nevertheless, the scheme of conventional SHM systems monitoring the global behavior of buildings is not well designed for this type of application. This paper presents a cyber-based SHM system specifically designed for autonomous structural integrity assessment of building structures that is based on the detection of local structural damage. In the system, a dense array of multiple-type sensors installed to building structures (i.e., dynamic stain sensors, accelerometers and gyro sensors) is networked using Narada wireless modules. The large amount of data acquired by the sensing network are stored and automatically processed to extract damage feature using an associated cyberinfrastructure. The cyberinfrastructure is structured by a relational database and local damage detection applications, and presents structure's status in a web-viewer. The developed system is evaluated through a series of exercises for detecting damage in a 1/3.75-scaled 5-story steel testbed frame, which can replicate damage (i.e., yielding and fractures) in beams and columns. In exercises, shake table tests are conducted for the testbed frame using ambient loading and minor earthquakes, and an damage detection algorithm based on the changes in internal force distribution is verified.

8692-158, Session PTues

Strength gain pattern analysis for real-time concrete curing process monitoring using an embedded PZT-steel plate probe

Ju-Won Kim, Changgil Lee, Eun-Seok Shin, Seunghee Park, Sungkyunkwan Univ. (Korea, Republic of)

In recent years, it is strongly required to evaluate the strength development during the curing process of concrete structures to ensure the good quality of high performance concrete during the construction. Especially, monitoring the pattern of the curing strength gain at early-age concrete structures is very important to reduce the construction time and cost because it can provide the exact information for the decision to progress to the next phase safely. In this context, this research proposes an embedded PZT-steel plate probe-based nondestructive curing strength gain monitoring method that can be utilized even for the early-age concrete structures. This approach used an embedded steel plate-type sensor probe, fabricated by bonding PZT sensors onto a steel plate. To measure the high frequency dynamic response of the steel plate-type sensor probe from the early-age concrete, the proposed sensor probe was inserted at the same time with concrete placement. While the concrete is cured, the high frequency response signals from the PZT-steel plate probe were measured continuously at a regular interval, and it was observed that both the resonant frequencies' component and/or the guided waves' velocity are varied according to the concrete curing process. Finally, specific equations to estimate the strength of the concrete were derived using regression analysis based on some specific pattern analysis.

8692-159, Session PTues

Percussive augmenter of rotary drills (PARoD)

Mircea Badescu, Jennifer Hasenoehrl, Yoseph Bar-Cohen, Stewart Sherrit, Xiaoqi Bao, Patrick N. Ostlund, Jack B. Aldrich, Jet Propulsion Lab. (United States)

Increasingly, NASA exploration mission objectives include sample acquisition tasks for in-situ analysis or for potential sample return to Earth. To address the requirements for samplers that could be operated at the conditions of the various bodies in the solar system, a piezoelectric actuated percussive sampling device was developed that requires low preload (as low as 10N) which is important for operation at low gravity. This device can be made as light as 400g, can be operated using low average power, and can drill rocks as hard as basalt. Significant improvement of the penetration rate was achieved by augmenting the hammering action by rotation and use of a fluted bit to provide effective cuttings removal. Generally, hammering is effective in fracturing drilled media while rotation of fluted bits is effective in cuttings removal. To benefit from these two actions, a novel configuration of a percussive mechanism was developed to produce an augmenter of rotary drills. The device was called Percussive Augmenter of Rotary Drills (PARoD). A breadboard PARoD was developed with a 6.4 mm (0.25 in) diameter bit and was demonstrated to increase the drilling rate of rotation alone by 1.5 to over 10 times. The test results of this configuration were published in a previous configuration. Further, a large PARoD breadboard with a 50.8 mm (2.0in) diameter bit was developed and tested. This paper presents the design, analysis and test results of the large diameter bit percussive augmenter.

8692-160, Session PTues

A novel rotational stiffness monitoring method of structure foundation

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The foundation rotation under earthquake will affect the failure modes of building structures. Due to the complexity of Soil-Structural Interaction (SSI), it is difficult to accurately determine the rotational stiffness of foundations. Therefore, the monitoring of rotation stiffness of foundations under earthquake is very important for exploring the mechanism of foundation rotation. This paper puts forward a novel monitoring method of the rotational stiffness of foundations of RC building structures, by using MEMS inclinometer to measure the rotation process and using distributed piezoelectric smart aggregate(SA) array to measure the sectional bending moment. Firstly, the selected MEMS inclinometer is calibrated and its frequency response range is determined. Then, a one-story frame model shake table test was conducted to verify the feasibility of this monitoring method. The frame model is supported by four spring bearings with rotational stiffness predetermined to simulate the building foundations. The frame model is subjected to one-direction horizontal cyclic excitation and earthquake records exerted by shake table. During the excitation the strains at the bottom of the column of the frame are measured for calculating the sectional bending moment and the rotation of the spring bearing are measured through MEMS inclinometer. The rotational stiffness determined from the monitoring signal is compared with the designed value with excitation of different frequency characteristics. From the preliminary test, it can be concluded that proposed monitoring method is heavily influenced by the frequency range of the MEMS inclinometer, and under the low-frequency dominant excitations the monitoring method shows considerate accuracy.

8692-161, Session PTues

A novel partial correlation noise model for damage identification

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The sources and mechanism of various noises are discussed in details and the physical significance and application scope of traditional uncorrelated noise model are analyzed in the paper. Based on these discussions, various noises are further classified into two groups: system fundamental noise and environmental noise. The first group of noises is independent of measured signal and the second is closely correlated to the amplitude and phase of measured signal through interacting with environmental interferences. A partial correlation noise model is thus proposed to account for the uncorrelated system fundamental noise and correlated environmental noise, which is the major contribution of the paper. Variation ratios and signal to noise ratios of simulated accelerations with traditional uncorrelated noise model and the partial correlation noise model developed in the paper are compared. Furthermore, the influences of both models on the identification of mode shapes and damages of a beam are analyzed. It is found that the proposed partial correlation noise model agrees well with engineering practice while the traditional uncorrelated noise model could not effectively simulate system and environmental noises.

8692-162, Session PTues

Shear-mode piezoelectric acoustic emission sensor with a particular geometry design

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The turbulent flow at the leakage points of pressurized pipelines generates continuous acoustic emissions (AE). If pipeline transports fluid in gas state, the elastic waves propagate through pipe structure. The leakage point can be detected and located with the passive sensors mounted on the surface of the pipelines with spacing determined from the attenuation curves and the sensor sensitivity. The discrete sensor spacing can be increased further if the sensors are sensitive to longitudinal waves which are less dispersive than other cylindrical waves. In this paper, a new piezoelectric sensor with a particular geometry, specifically designed for leak detection in pipelines, is introduced. The sensor is polarized in thickness direction; however, through particular cut geometry, the sensor sensitive axis is placed parallel to the pipe structure

to detect in-plane motion. The sensor is designed to have a resonance at 60 kHz. PZT 5A is the material chosen because it has the highest g33 coefficient among the soft piezoelectric materials. Numerical models of the sensor geometry for eigenfrequency and frequency domain analyses are performed using COMSOL multiphysics software. The paper shows the excellent fit of numerical frequency response and experimental impedance measurement of the sensor. The sensor response to detect and locate leak is compared with conventional 60 kHz sensors on a 152 cm long, 11.43 cm diameter steel pipeline built at the laboratory. The sensors' responses are studied for different leak rates. The required sensor spacing using the new sensor design is reported using numerically obtained attenuation curves.

8692-163, Session PTues

An acceleration transducer based on optical fiber Bragg grating with temperature self-compensating function

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Abstract—Along with the maturity and development of Optical Fiber Bragg Grating (OFBG) sensing technology, OFBG sensors with different functions have been widely used in civil engineering. In this paper, a novel OFBG acceleration transducer with a characteristic of temperature self-compensation is developed, which aims at meeting the needs of acceleration measurement in Structure Health Monitoring Systems, especially those based on optical fiber sensing technologies. Considering the environment temperature change which would lead to influences on the test results especially for the long-term structure health monitoring, the structure of novel transducer is designed first, which contains a cantilever structure model with equal strength beam, and a fixed mass at the end of the beam, a pasted two OFBGs array on upper and lower surface axis of beam at the corresponding place. Because of the two OFBG are in the same temperature field, the wavelength variations in both OFBG caused by temperature change is equal. According to the temperature self-compensating principle and acceleration measurement principle discussed in this article, we can achieve the temperature self-compensating function of real acceleration measurement by simply calculating the test results. Besides, it can eliminate the influence of temperature change and get the real wavelength variation only caused by stress. Then the calibration tests are carried, and the results show that, this type of acceleration transducer has high sensitivity and stability and its measuring range can also be changed according to the practical requirements, 10G and 100G are discussed in this paper, which appear high accuracy and sensitivity both. From the research work, we can see that this novel type of acceleration transducer meet the needs of engineering structure acceleration measurement well in different environment conditions.

8692-164, Session PTues

Experimental investigation on the interaction between magnetorheological fluid damper and stay cable

Min Liu, Harbin Institute of Technology (China)

Control-structure interaction (CSI) during structural vibration control system has been investigated in some current literatures. However, the interaction between MR damper and flexible stay cable has not been reported. In this paper, experimental investigation on vibration control is carried out on a stay cable model incorporated with one small size magneto-rheological (MR) fluid damper taking into account the interaction effect of the stay cable and the MR damper. Experiments on the vibration control of the stay cable model attached with the MR damper with different constant current input indicates the obvious interaction between the stay cable and the MR damper. A novel model of MR damper with constant current input coupled with stay cable is proposed to better predict the MR damper's behavior considering the interaction effect between the stay cable and the MR damper. The proposed coupling model is validated by the numerical simulations using the experimental results. For the purpose of some investigations on semi-active vibration control of the stay cable incorporated with the MR damper, a model of MR damper with fluctuating current input coupled with stay cable is developed. Utilizing the proposed model of the MR damper with fluctuating current input coupled with the stay cable, experiments on the semi-active vibration control of the stay cable model incorporated with the MR damper are conducted to investigate the control efficacy and dynamic properties of the semi-active MR dampers attached to the stay cable model. Moreover, the semi-active MR damper can achieve much better mitigation efficacy than the passive MR dampers with different constant current inputs due to negative stiffness provided by the semi-active MR damper.

8692-165, Session PTues

Prediction of scour depth around bridge piers using Gaussian process

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A reliable prognostics framework is essential to prevent catastrophic failure of bridges due to scour, which accounts for almost 60% of bridge failures in the U.S. It is estimated that the annual cost for the maintenance of bridges due to scour is approximately $30 million. Currently available techniques for predicting scour are mostly based on laboratory experiments and do not account for complexities such as the unsteadiness in flow, presence of horseshoe vortices and the remixing of sediment. Also, the methods that are most commonly used for Residual Useful Life (RUL) estimation such as neural network regression are deterministic and do not provide confidence intervals for the prediction. In this paper, we discuss a probabilistic framework for the prediction of scour evolution around bridge piers. We conduct field experiments to account for all the complexities and uncertainties in the data. Support Vector Machine(SVM) classification is used to classify the signals from different kinds of sensors and extract the features that affect the scour depth. The Gaussian process (GP) based prognosis algorithm uses the real-time scour data to predict the future scour depths and thus the RUL of the structure.

8692-166, Session PTues

A piezoelectric-electromagnetic-based energy harvester for railway health monitoring

Jingcheng Li, Shinae Jang, Jiong Tang, Univ. of Connecticut (United States)

Recently, wireless smart sensor network (WSSN) has drawn such attention for railway health monitoring due to the long-term operation and low-maintenance performances. With WSSN, the real-time performance of railway track including the information of displacement, acceleration, temperature, humidity, etc., can be monitored. However, how to supply power to wireless sensor nodes is a big issue. The idea of converting ambient kinetic energy from vibration of railway track induced by passing train to electric energy has made it a possible way for powering the wireless smart sensors. Energy harvester with piezoelectric patch with and without tip mass has been investigated, and compared to mathematical model in our previous research. However, less than 1 mW power was generated by the piezoelectric based energy harvester which is far less than most of the wireless smart sensors need. In this paper, a piezoelectric-electromagnetic based energy harvester was designed and investigated. Here the energy harvesting device consists of a primary piezoelectric patch and an electromagnetic component is added to amplify the power generation from ambient vibration. Field test was also performed to test the feasibility of the device for powering Imote2 which is one the most commonly used wireless smart sensors nowadays.

The experimental results show the capacity of the energy harvester for supplying enough power to Imote2.

8692-167, Session PTues

Online structural health monitoring under operational conditions using wireless smart sensors

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Structural health monitoring has such a great attention during past three decades due to its vast potential to provide sustainability and resilience of our infrastructure. Many researchers have developed numerous algorithms, laboratory-scale consideration, as well as full-scale experiments. Still, monitoring our infrastructure under operational conditions is challenging and the gap between the theoretical development and practical perspectives is considerable. For practical structural health monitoring, a wireless smart sensor network (WSSN) has been a hot issue lately, due to its low cost, easy installation, and versatile usage. Though hardware and basic software framework are well prepared, the online health monitoring strategy using wireless smart sensors are still lacking. In this paper, a user-friendly graphical interface based on Matlab has been developed for Imote2-based wireless hybrid sensor, which combines wireless sensor board and conventional analog sensor channel for multi-scale sensing. This software enables the visualization of measured data as well as safety alarm based on modal property fluctuation. Two laboratory validation on a truss bridge and a building structures are demonstrated using Imote2-based wireless hybrid sensor. Full-scale demonstration of the software and hardware framework is underway.

8692-168, Session PTues

Optimal sensor placement of base-isolated structure subjected to near-field earthquakes using novel TTFD approach

Seyed Kazem Sadat Shokouhi, Azam Dolatshah, Hamid R. Vosoughifar, Islamic Azad Univ. (Iran, Islamic Republic of); Bijan Dowlatshahi, Univ. of Minnesota (United States)

As a consequence of the ground motions during the near-field earthquakes, stronger design and controlling damages of vital structures should be significantly paid attention. Seismic base isolation system is an effective approach for passive protection of structure when an earthquake occurs, because it modifies the structural global response and improves seismic performance. The Base-Isolated (BI) structures against near field earthquakes, due to the vertical component have not proper seismic response. As a conservator; Health Monitoring of BI structures can monitor different elements exposed to stress and strain. In this research, a BI structure was modeled using Finite Element Method (FEM) in which Modal and Nonlinear Time-history Analyses (NTA) were utilized considering the effects of three scaled near-field earthquakes. Furthermore, three various Optimal Sensor Placement (OSP) algorithms were used and Genetic Algorithm (GA) was selected to act as the solution of the optimization formulation. A novel approach was proposed by authors for OSP which was adopted TTFD algorithm. The TTFD method uses time-history analysis results as an exact seismic response despite the common OSP algorithms which utilize modal analysis results. Results show that with a proper OSP method for Structural Health Monitoring (SHM) can detect weak points of BI structures.

8692-169, Session PTues

An operational power management method for the grid containing renewable power systems utilizing short-term weather and load forecastings

Fadhil Aula, Samuel C. Lee, The Univ. of Oklahoma (United States)

This paper addresses the problems associated with power management of the grid containing renewable power systems and proposes a method for enhancing its operational power management. Due to the nature of the renewable energy which provides uncertain and uncontrollable resources, the renewable power systems can only generate irregular power. This irregularity will create problems affecting the grid power management process as well as impacting the parallel operations of conventional power plants of the grid. To demonstrate this power management method for this type of grid, the weather-dependent wind and photovoltaic power systems are chosen to use as an example. This study also deals with another uncertain quantity which is the system load. In this example, the management method is based on adapting short-term weather and load forecastings. The forecasting data give the ability for estimating the load values as well as for knowing all load regions in advance. Furthermore, by setting the loads for baseload power plants and knowing when other plants are needed to increase or decrease their supplies to the grid. This will decrease the irregularity behavior effects of the renewable power systems and at the same time will enhance the smoothing of the power management for the grid. Hence, the purpose of this paper is to demonstrate the use of the weather and load forecastings to achieve the optimum operational power management for the grid containing renewable power systems. An illustrative example of such a power system is presented and verified by simulation.

8692-171, Session PTues

Housing and Development Board (Singapore) structural-health monitoring system for public housing in Singapore: An informed sense of health for building structures

Chor Cheong Fong, Housing & Development Board (Singapore); Joo Ming Lau, Housing & Development Board (Singapore)

Engineers and developers understand the importance of having their buildings in a good health, but how often are the buildings monitored. Structural monitoring of the buildings help to find out if there is underlying conditions even if they look satisfactory. In the pursuit of in-depth knowledge for the long term behaviour of high-rise buildings during their life span from construction to service condition, a building health monitoring system using long-gage fibre optic sensors has been progressively implemented for Singapore's public housing. These sensors were embedded in the ground level columns during the construction to enable the monitoring of the building behaviour since the birth of the structure.

This paper will share the success of Housing & Development Board (HDB), Singapore, large scale structural monitoring of high-rise buildings. To-date, close to 4000 sensors had been installed and another 4000 sensors are due to be completed next year. The HDB experience will include the pilot project in year 2001, and the journey over the subsequent 10 years in structural health monitoring of HDB high-rise buildings. The monitoring system for the international awarded winner project, Pinnacle @ Duxton, will also be shared.

The HDB experience will encompass HDB strategy in developing a monitoring system with an outcome of a reliable data integrated analysis and structural control, which provide a good and informed sense of health for the building structures. It will include key monitoring criteria designed into the structural monitoring system.

8692-172, Session PTues

Dynamic calibration of pressure transducers with an improved shock tube system

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The need for reliable dynamic calibration of pressure transducers is becoming increasingly more important, especially with growing demands for improved performance, increased reliability and efficient energy generation from the aerospace, defense and energy sectors - all while being mindful of low lifecycle cost, minimizing maintenance downtime and reducing any negative impact to the environment.

State of the are piezoelectric (PE) and piezoresistive (PR) silicon MEMS pressure transducers specifically designed for harsh environments are answering the call to provide the necessary measurements for applications such as high temperature gas turbine engine health monitoring (both in-flight and land / marine based aero-derivative), high pressure blast studies / ordnance explosion optimization, low profile wind tunnel testing / flight testing, etc. However, these pressure transducers are only as valuable as the dynamic calibration they possess so that more understanding of the physical measurement can be ascertained by the end-user.

The Shock Tube is an established laboratory tool capable of imparting near instananeous pressure stimulus for the purpose of providing quantifiable dynamic calibration of pressure transducers.

From a performance perspective, a vast amount of empirical data has been collected over fifteen years and used to model more accurately the one-dimensional gas dynamics occurring within a Shock Tube so that the time interval of the reflected shock - the most critical parameter in determining the transfer function for the pressure transducer under test - can be optimized for the largest frequency bandwidth over varying shock amplitudes.

Accordingly, an introduction of an improved Shock Tube system offering both increased performance and ease of user operation is presented.

8692-173, Session PTues

Capacitance sensors for nondestructive moisture determination in bio-fuel materials

Chari V. Kandala, Agricultural Research Service (United States); Naveen Puppala, New Mexico State Univ. (United States)

Moisture content of wood chips, pellets, switch grass powders, and similar organic bio-fuel materials is an important property to be known to determine their utility and energy efficiency at various stages of their processing and storage. Several moisture measuring instruments are available in the market but for most of these instruments some sort of sample preparation is needed that involves sizing, grinding and weighing. The samples in this process are usually destroyed, and the measurement involves considerable time and labor. The standard methods of oven drying and Karl-Fisher also fall in the destructive and laborious category. In this presentation, estimating moisture content (MC) of various bio-fuel materials, from the measurement of capacitance, phase angle, and impedance of a parallel-plate capacitor, holding samples of these materials between them, at frequencies 1 and 5 MHz, is described. The applicability of the method to determine MC of these products in their powder form was also presented. The results obtained with a prototype instrument working on these principles, as shown, indicate the possibility of developing a commercial instrument useful for the bio-fuel industry.

8692-175, Session PTues

Behavior of prestressed sensor-metal plastic joints under static and dynamic load scenarios

Matthias Brenneis, Peter Groche, Institute for Production Engineering and Forming Machines (Germany)

Metal carrying structures often fulfill safety critical functions. A continuous monitoring of these structures lends additional safety, may reduce maintenance costs and can process operational scenarios.

The novel approach presented in this paper is a carrying structure with integrated sensor, which is inserted during the forming of the component. The result is a smart component with a sensor in the main power flow of the structure. Since the assembly basically consists only of a structural material and a sensor and requires no additional joining elements or additional steps, these components can be manufactured economically. The sensor can also be substituted by a smart material with actuator or sensor abilities. The undercuts generated during the forming process and the integration inside the structure lead to a protected installation of the sensor.

Using the example of a sensory connecting element, the forming process for the carrying structure is shown. Within this scope, it is discussed how the sensor is joined under prestress during the forming process. The focus lies on the basic mechanism of the prestress, which enables the integrated sensor to take loads in multiple directions. Subsequently the calibration of the smart component takes place.

Operating scenarios are discussed with reference to measurements. Of particular importance for fasteners in mechanical engineering is the remaining prestress within the connection, which can be detected by the sensory ability of the introduced connecting element. In Addition, the influence of dynamic operating loads on the measured signals is investigated. The experimental studies are accompanied by Finite Element simulations to design the joining task and to explicate the interactions between external loads and the sensor in the main power flow within the carrying structure.

8692-176, Session PTues

Surface characteristics and mechanical properties of high-strength steel wires in corrosive conditions

Shunlong Li, Yang Xu, Hui LI, Harbin Institute of Technology (China)

Cables are always a critical and vulnerable type of structural components in a long-span cable-stayed bridge in normal operation conditions. This paper presents the surface characteristics and mechanical performance of high-strength steel wires in simulated corrosive conditions. Four stress level (0MPa, 300MPa, 400MPa & 500MPa) steel wires were placed under nine different corrosive media erosion periods based on the Salt Spray Test Standards ISO 9227:1990. The geometric feathers of the corroded steel wire surface were illustrated by using fractal dimension analysis. The mechanical performance index including yielding strength, ultimate strength and elastic modulus at different periods and stress levels were tested in detail. The uniform and pitting corrosion depth prediction model, strength degradation prediction model as well as the relationship between strength degradation probability distribution and corrosion crack depth would be established in this study.

8692-177, Session PTues

Design, modeling, and testing of a piezoelectric impact compressive kinetic (PICK) tool for crack-stop hole treatment

Gary Simmons, Ronald M. Barrett, Caroline Bennett, Adolfo Matamoros, Stanley Rolfe, The Univ. of Kansas (United States)

This paper outlines the design, modeling and testing of a new class of tool which is specifically intended for the treatment of crack-stop holes. By integrating a high power stack of piezoelectric elements in a very stiff compression caliper, this Piezoelectric Impact Compressive Kinetic (PICK) tool was used to clamp very tightly on either side of an aluminum

plug which was inserted in a crack-stop hole. Ultrasonic vibrations at high clamping loads applied by the piezoelectric stack dynamically cold worked both the aluminum plug and the inside of the crack stop hole. This paper shows the overall design of the tool, how it is clamped, the layout of the plug, plug expansion and shaping with dynamic impacts and time and how dynamic vibrations were applied. Additionally, finite element modeling of the natural frequencies shows good correlation with experimentally measured values, which were important as the system was driven at various resonance modes during the cold-working process. Several 1/8" steel specimens with 1/8" crack-stop holes were treated ultrasonically with the PICK tool to prove the concept. Dynamic fatigue testing showed that fatigue lives of the specimens could be increased substantially. Micro-Hardness and neutron bombardment testing confirmed high levels of cold working at the edge of the hole, increase in grain density with a regular decay as a function of distance from the hole edge. The paper concludes with power-size trends, design sketches of field equipment and an overall assessment of the significant safety and cost enhancements which can be realized by such a tool.

8692-178, Session PTues

FE simulation of SMA seal for Mars sample return

Xiaoqi Bao, Paulo J. Younse, Pradeep Bhandari, Jet Propulsion Lab. (United States)

Several NASA's rovers and lander have been on Mars and performed successful in-situ exploration. Returning Martian samples to Earth for extensive analysis is in great interest of planetary science community. Current Mars sample return architecture requires leaving the acquired samples on Mars for a couple of years before being retrieved by subsequent mission. Each sample would be sealed securely to keep its integrity. A reliable seal technique that does not affect the integrity of the samples and uses simple low-mass tool is required. The shape memory alloy (SMA) seal technique is a promising candidate. A study of the performances of several primary designs of SMA seal for sample tubes by finite element (FE) simulation will be presented and the measures to reduce temperature rising of the samples will be discussed.

8692-180, Session PTues

Preliminary research on monitoring the durability of concrete structures subjected to sulfate attack with optical fibre Raman spectroscopy

Yun Bai, Univ. College London (United Kingdom); Jing Jing Wang, Trinity College Dublin (Ireland); Yanfei Yue, Univ. College London (United Kingdom); P. A. Muhammed Basheer, Queen's Univ. Belfast (United Kingdom); John J. Boland, Trinity College Dublin (Ireland)

The formation of ettringite and gypsum under sulfate attack together with the carbonation attack and the ingress of chloride have been considered as the most serious deterioration mechanisms of concrete structures. Although Electrical Resistance Sensors and Fibre Optic Chemical Sensors could be used to monitoring the latter two mechanisms in situ, they cannot be used to identify the sulfate attack mechanisms and hence systems for monitoring the sulfate attack is still to be developed. In this paper, a preliminary study was carried out to investigate the feasibility of monitoring the sulfate attack with optical fibre Raman spectroscopy through characterising the ettringite and gypsum formed in cementitious materials under an "optical fibre excitation + spectroscopy objective collection" configuration. Bench-mounted Raman spectroscopy and X-Ray diffraction (XRD) analysis were also used to validate the results obtained from the fibre-objective configuration. The results showed that the four fingerprint bands of gypsum, i.e., two peaks at 1006cm-1 (λ1) and 1135cm-1 (λ3) and two doublets at 414 & 491cm-1 (λ2) and 618 & 669 cm-1 (λ4), can be identified, which were in agreement with the bench-mounted Raman results and those reported in the literature. For ettringite, the λ1 band (995cm-1), λ2 mode (457cm-1) and λ4 band (638cm-1) were also identified. Therefore, based on these preliminary results, there is a good potential of developing an optical fibre Raman spectroscopy-based system for monitoring the deterioration mechanisms of concrete subjected to the sulfate attack.

8692-181, Session PTues

Corrosion detection and evolution monitoring in Reinforced Concrete Structures by the use of Fiber Bragg Grating sensor

Shamyr S. Ali Alvarez, Pierre G. P. Ferdinand, Sylvain Magne, Commissariat à l'Énergie Atomique (France); Ricardo Nogueira, LEPMI UMR 5279 CNRS - Grenoble INP (France)

Corrosion of reinforced bar (rebar) in concrete structures represents a major issue in civil engineering works, being its detection and evolution a challenge for the applied research. In terms of mechanical changes on the rebar surface, corrosion attack depends on several chemical and electrochemical parameters (pH, carbonation, presence of chlorides, presence of microbes, etc.), but mainly appears in two forms. In the first one, the metal oxidation forms rust that increases the internal pressure yielding to the crack of the concrete upper layer (general corrosion). In another typical scenario, corrosion agents locally attack the rebar (pitting corrosion), and iron ions generated are evacuated out of the structure, with no impact on internal strains. In this work, we present a new methodology to corrosion detection in reinforced concrete structures able to detect both kinds of corrosion evolution, based on the direct interface measurement by optical fiber sensor. By combining Fiber Bragg Grating (FBG) sensors with the electrochemical and physical properties of rebar in a simplified pre-strained assembly, a corrosion detector is conceived. Tests in electrolytic solutions and concrete were performed for pitting and general corrosion. The evolution of the FBG wavelength during corrosion tests indicates the feasibility of this technique as solution for remote monitoring, with low cost implementation. The proposed Structural Health Monitoring (SHM) methodology constitutes a direct corrosion measurement potentially useful to implement or improve Condition-Based Maintenance (CBM) program for civil engineering concrete structures.

8692-51, Session 13

Laser lock-in thermography for fatigue crack detection in an uncoated metallic structure

Yunkyu An, Ji Min Kim, Hoon Sohn, KAIST (Korea, Republic of)

This paper presents a noncontact laser lock-in thermography (LLT) technique for surface-breaking fatigue crack detection. LLT utilizes a modulated continuous wave (CW) laser as a heat source for lock-in thermography instead of commonly used flash and halogen lamps. LLT has following merits compared to conventional thermography techniques: (1) the laser heat source can be positioned at a long distance from a target structure thank to its directionality and low energy loss, (2) no special surface coating is necessary to measure thermal waves and (3) a large target structure can be inspected using a scanning laser heat source. The LLT system is developed by integrating and synchronizing a modulated CW laser, galvanometer and infrared camera. Then, a holder exponent-based crack detection algorithm is proposed. A surface-breaking fatigue crack with 5 μm or smaller width on a steel plate is successfully detected using the proposed technique without any special surface treatment.

8692-53, Session 13

High-speed noncontact air-coupled to air-coupled ultrasonic system for internal defects and surface characterization of rails

Stefano Mariani, Thompson V. Nguyen, Robert R. Phillips, Francesco Lanza di Scalea, Univ. of California, San Diego (United States)

As rail freight companies continue to increase the tonnage moved on their rail system, the cost of combating the effects of rolling contact fatigue (RCF) also grows. RCF is the major cause to the formation of head checks, shelling and flaking on the surface of the rail that can potentially lead to internal transverse defects. At the same time, internal defects in rail remain the cause of several derailments.

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 integrity evaluation system. A prototype using an ultrasonic air-coupled signal generation to air-coupled signal detection probing system is under development. In addition to a real-time statistical analysis algorithm, this system requires a specialized filtering approach due to the poor signal-to-noise ratio.

The goals of this project are to develop a rail monitoring system that provides: reliable and high-speed internal rail defect detection, and rail surface characterization.

Results from small scale laboratory tests and large scale tests at the UCSD/FRA Rail Defect Farm using the full non-contact flaw detection system will be presented.

8692-54, Session 13

Thermoelastic stress analysis of fatigue prone details on highway bridges

Steven B. Chase, Univ. of Virginia (United States)

Fatigue cracks in highway bridges continue to be a problem for the aging civil infrastructure in the United States. The situation is likely to become more serious due to ever-increasing numbers and magnitude truck loads combined with insufficient funding for civil infrastructure maintenance and renewal. The primary method employed by bridge inspectors to manage the very large number of steel highway bridges in the United States is visual inspection. This approach has many shortcomings. First, the number of steel highway bridges requiring inspections is very large, 168,000. Second, the number of locations where a fatigue crack might form on a single bridge is also quite large (often in the hundreds). Third, fatigue cracks are difficult to detect by visual inspection alone. The inspector must be within a few feet of the detail and finally, steel bridges represent only a portion of the overall bridge population requiring inspection. There are close to 600,000 bridges requiring biannual inspections. Given the enormity of this inspection task, bridges have been categorized into fracture critical and not fracture critical, with a requirement of a so called fracture critical inspection on fracture critical bridges. Even with this prioritization of bridges for a hands-on inspection, the task remains very difficult. There are still over 18,000 bridges classified as fracture critical. Fatigue cracks can and have formed on bridge that are not fracture critical. There is a pressing need for an inspection method that can improve the reliability of detection of fatigue cracks once they have formed. There is also, perhaps an even more pressing need for a nondestructive inspection method that can help evaluated the potential for fatigue cracks. Additionally, there is a need for a method to assess whether a fatigue retrofit, such as hole drilling, has been effective. Visual inspection alone is not able to meet these needs. One nondestructive evaluation method capable of detecting and assessing fatigue prone details on highway bridges is thermoelastic stress analysis (TSA). This method has been demonstrated to reliably detect fatigue cracks and provide full field information about localized principal stress fields in the laboratory and in manufacturing environments. However, these demonstrations have all utilized very sensitive thermal cameras and imagers with cryogenically cooled detectors. Such instruments are considered too fragile and too expensive to be routinely used for the bridge inspection task. A novel approach, utilizing an uncooled microbolometer based imager, has been demonstrated to capture and provide images of stress concentrations in a laboratory setting. This successful proof of concept has led to a new project supported by the Virginia Department of Transportation to develop an inspection device suitable for field inspections of fatigue prone details of highway bridges.

8692-55, Session 13

Noncontact measurement of guided ultrasonic-wave scattering for fatigue crack characterization

Paul Fromme, Univ. College London (United Kingdom)

Fatigue cracks can develop in aerospace structures at locations of stress concentration such as fasteners. For the safe operation of the aircraft fatigue cracks need to be detected before reaching a critical length. Guided ultrasonic waves offer an efficient method for the detection and characterization of fatigue cracks in large aerospace structures. Noncontact excitation of guided waves was achieved using electromagnetic acoustic transducers (EMAT). The transducers were developed for the specific excitation of the A0 Lamb mode. Based on the induced eddy currents in the plate a simple theoretical model was developed and reasonably good agreement with the measurements was achieved. However, the detection sensitivity for fatigue cracks depends on the location and orientation of the crack relative to the measurement locations. Crack-like defects have a directionality pattern of the scattered field depending on the angle of the incident wave relative to the defect orientation and on the ratio of the characteristic defect size to wavelength. The detailed angular dependency of the guided wave field scattered at crack-like defects in plate structures has been measured using a noncontact laser interferometer. Good agreement with 3D Finite Element simulation predictions was achieved for machined part-through and through-thickness notches. The amplitude of the scattered wave was quantified for a variation of angle of the incident wave relative to the defect orientation, the defect depth, and the ratio of the characteristic defect size to wavelength. These results provide the basis for the defect characterization in aerospace structures using guided wave sensors.

8692-56, Session 13

Visualization of thermally-induced delamination by means of guided-waves processing

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Laser vibrometer allows to register full wavefield in elements of a structure instead of single point measurements acquired by e.g. piezoelectric sensor. In this way new possibilities for Non-destructive Evaluation emerge. This enabled precise registration and visualization of guided waves interacting with various types of damage.

The aim of this paper is to present overview of methods for visualization thermally induced delamination in composite material based on guided wave propagation phenomenon. Investigated methods utilize processing of full wavefield acquired by the Scanning Doppler Laser Vibrometer.

Tested specimens were submitted to short time period high temperature source, which generated thermal degradation. In particular, delamination in material occurred. This procedure simulates some real case scenarios like atmospheric discharge in wind turbine blade.

Various damage visualization techniques were applied to experimental

data to compare its effectiveness in thermally induced delamination detection.

Root mean squared (RMS) value is recently most popular tool for damage localization. Obtained results constitute RMS map, regarded also as damage index, which forms the basis for damage localization.

Another procedure utilizes Three-dimensional Fourier Transform to operate in frequency-wavenumber domain, where the guided waves generated by the transducer are removed. Therefore, only reflected waves remain. The residual wavefield analysis can be used for baseline-free detection and characterization of defects.

Finally, waveimage filtering method proposed by the authors is applied. This technique is based on elimination of wave propagation pattern. This produce signal comprising only information about changes in wave propagation phenomenon and may be used for damage visualization.

8692-57, Session 13

Identification of impurities and strains in granular chains using acoustic solitons

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In this study we show the feasibility of acoustic solitons as a novel information carrier to discern impurities and to assess strains in granular media. For experiments, we assemble a one-dimensional granular chain that is in various levels of compression and includes a heavy impurity in different masses and locations. To investigate the transmission and reflection behavior of acoustic solitons in the region of impurities, we conduct full-field measurements of granular particles' velocities using a laser Doppler vibrometer. Additionally, the temporal force profiles of soliton propagation are recorded by an instrumented sensor particle embedded in the chain. As a result, we find that the travelling time and attenuation of backscattered solitons are highly sensitive to the location and mass of an inserted impurity. We also show that the strain fields in the granular chain can be efficiently measured by calculating the travel time of acoustic solitons reflected from strategically positioned impurities. In principle, this mechanism is similar to the strain sensing method by optical fiber Bragg grating sensors. We also obtain numerical results via a discrete element model and theoretical predictions based on nonlinear wave dynamics and classical contact theory. We find that these numerical and theoretical results are in excellent agreement with the experimental results. This study suggests that highly nonlinear acoustic solitons can be used as an efficient, nondestructive probing tool to identify impurities and localized strain fields in granular architectures.

8692-58, Session 14

Singular value decomposition for novelty detection in ultrasonic pipe monitoring

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Pipes carrying fluids under pressure are critical components in infrastructure and industry. Piezoelectric transducers bonded to the pipe produce guided waves that propagate long distances and illuminate the whole pipe, but it is difficult to recognize the change produced by a scatterer because of the many wave modes. Moreover, in realistic conditions the ultrasonic signals are dramatically affected by the environmental and operational variations. In order to detect a change of interest, it is necessary to first differentiate events caused by damage from those change caused by benign variations.

We conducted field experiments on an industrial-scale pressurized hot water piping system. We collected over 1,000 hours of pitch-catch signals from permanent mounted PZT transducers 16 diameters away. We observed dramatic variations in the ultrasonic signal produced by the operation of the piping system and noise from the environment. Under these conditions, the presence of a grease-coupled scatterer on the pipe cannot be detected by conventional methods because the change produced by the scatterer is too small compared to the other changes.

In this paper, we use Singular Value Decomposition (SVD) to identify the change of interest from the ultrasonic signals. We show that SVD is able to separate the changes caused by different sources. The trends over slow time are captured in the left singular vector matrix, while the corresponding right singular vectors are the physical difference signals caused by the changes. We also develop robust novelty detection schema to automatically identify the sudden changes caused by the scatterer(s).

8692-59, Session 14

Thermomechanical simulation of guided waves in pipes excited by laser pulses

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Ultrasonic guided waves have been widely utilized for the structural health monitoring (SHM) of structural components that have thin members such as plates and pipes. In particular, the noncontact excitation of the pipe surfaces using laser pulses has shown several advantages in experiments by eliminating the bonding process of the dielectric patches on the curved surfaces and complicated interpretation of the temperature effect on the bonding layers. However, the numerical simulation of the methodology requires thermomechanical coupling and large-scale computation. The laser excitation on the surface is modeled in the form of heat flux, and the generated wave forms are investigated. The numerical efficiency of the spatial partitioning by deploying thermomechanical elements and mechanical elements is investigated, and the formation and propagation of the guided waves are studied numerically.

8692-60, Session 14

Monitoring of hot pipes at the power plant Neurath using guided waves

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In order to reduce the CO2-emissions and to increase the energy efficiency, the operating temperatures of power plants will be increased up to 720°C. This demands for novel high-performance steels in the piping systems. Higher temperatures lead to a higher risk of damage and have a direct impact on the structure stability and the deposition structure. Adequately trusted results for the prediction of the residual service life of those high strength steels are not available so far. To overcome these problems the implementation of a online monitoring system in addition to periodic testing is needed.

RWE operates the lignite power plant Neurath. All test and research activities have to be checked regarding their safety and have to be coordinated with the business operation of the plant. An extra bypass was established for this research and made the investigations independent from the power plant operating. In order to protect the actuators and sensors from the heat radiated from the pipe, waveguides were welded to the bypass.

The data was evaluated regarding their dependencies on the environmental influences like temperature and correction algorithms were developed. Furthermore, damages were introduced into the pipe with diameters of 2 mm to 10 mm and successfully detected by the acoustic method.

8692-61, Session 15

Theoretical and experimental study of a time-domain-reflectometry (TDR) probe used for water content measurement of clayrock through their electromagnetic properties

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In this paper, we will discuss some experimental and theoretical results obtained with Time Domain Reflectometry probe. The purpose consists in water content estimation of clayrock, for monitoring of nuclear wastes disposal.

Firstly, we will present some electromagnetic characterization of clayrock. In this context, a coaxial transmission line fixture with a cm size was developed to measure the dielectric properties over the 10 MHz – 1 GHz frequency range. The use of coaxial line requires that the material under test is carefully drilled and machined: a special sample preparation procedure was developed. The effect of water content and saturation degree will be examined throughout the entire working frequency range.

A second step concerns the TDR probe modeling. Theoretical results are obtained through a semi-analytical approach, based on both classical RF lines results and DPSM (Distributed Point Source Method) modeling. A validation of our model has been obtained through a comparison with experimental results in the case of simple material (tap water, distilled water and sand).

In the last part of this paper, theoretical results of the probe response will be obtained including the material properties of clayrock deduced from the first part of the study. The effect of air gap between the TDR probe and clayrock will be examined.

8692-62, Session 15

Micromachined fiber tip pressure sensor with corrugated diaphragm

Yinan Zhang, Amardeep Kaur, Lei Yuan, Hai Xiao, Missouri Univ. of Science and Technology (United States)

Pressure sensors are demanded in various industrial applications, including extremely harsh environments such as turbine engines, power plants and material processing systems. Fiber optic pressure sensors have been developed for years and show reliable performance in such harsh environments. Especially, corrugated diaphragm based pressure sensors have the advantages of high sensitivity, wide bandwidth, high operation temperature, immunity to EMI, etc.

In this paper, a miniature fiber-tip pressure sensor with corrugated diaphragm was designed, fabricated and measured. Finite-element method was used for optimal design of diaphragm structure. Both static and dynamic behaviors of square corrugated diaphragms are analyzed. The simulations show that high performance (i.e., high pressure sensitivity and high resonant frequency) of the diaphragms can be achieved with this structure. The sensor was built by splicing and cutting a small length of hollow core silica tube to lead-in SMF as a sealed Fabry-Perot microcavity, and then splice to a very thin silica diaphragm micro-machined and thinned using femtosecond laser and chemical etching technique. The measurements have shown reasonable agreement with the simulation. The sensor could be potentially used for engine field test, hydrophone and partial discharge detection, etc.

8692-63, Session 15

Assembly-rree embeddable fiber-optic strain and temperature sensor for structural health monitoring

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In this paper, a hybrid assembly-free fiber optic sensor comprising a femto-second (fs) laser fabricated cavity based External Fabry-Perot Interferometer (EFPI) and a CO_2 laser fabricated long-period fiber grating (LPFG) is presented for simultaneous measurement of strain and temperature. The EFPI sensor is fabricated by micromachining a cavity on the tip of a standard single mode fiber (SMF). This cavity is then self-enclosed by fusion splicing another piece of single mode fiber to it creating a fabry-perot interferometer. The LPFG is fabricated using point-by-point CO_2 laser irradiations. The fs-laser and CO_2 laser based fabrication makes the sensors thermally stable to sustain temperatures as high as 650ºC. The EFPI and the LPFG are spliced together to form the hybrid strain and temperature sensor. The sensor can be embedded in Bismaleimide (BMI) composite for simultaneous temperature and strain monitoring, and curing process optimization. The sensor is capable of obtaining precise strain measurements at high temperature thus making it useful for various structural health monitoring applications.

8692-64, Session 15

Vibration control of shell-like structures with optical strain gauges

Simone Cinquemani, Francesco Braghin, Lorenzo Comolli, Gabriele Cazzulani, Ferruccio Resta, Politecnico di Milano (Italy)

Carbon fiber structures are claimed to offer several advantages such as contained mass and high stiffness. However, these structures are characterized by a very low mechanical damping and, therefore, they are easily subjected to potentially dangerous vibratory phenomenon. Active control techniques have been widely developed to suppress vibration and great progresses have been achieved. On the other hand the research on sensors and actuators to be used is still a research field of interest. The paper discusses the opportunity to use piezoelectric actuators (PZT) and Fiber Bragg Grating sensors (FBGs) to realize a smart structure including in itself both the sensing and the actuating devices. Fiber optic strain sensors, such as Fiber Bragg Gratings (FBG), have a great potential in the use in smart structures thanks to their small transversal size and the possibility to make an array of many sensors. They can be embedded in carbon fiber structures and their effect on the structure is nearly negligible. Such a structure is able to measure its state of excitation and to reduce the amplitude of vibration using the embedded actuators.

Different control strategies have been implemented on a test rig consisting on a plate made of carbon fiber using two chains with 15 FBG sensors each and 6 PZT actuators. Control forces are designed to increase the damping of the structures, allowing to increase of damping of the first modes of vibration of about 10 times.

8692-65, Session 16

Damage detection and characterization using fiber optic sensors

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Fiber optic sensors (FOS) have significantly evolved and have reached their market maturity during the last decade. Their widely recognized advantages are high precision, long-term stability, and durability. But in addition to these advantageous performances, FOS technologies allow for affordable instrumentation of large areas of structure enabling global large-scale monitoring based on long-gauge sensors and integrity monitoring based on distributed sensors. These two approaches are particularly suitable for damage detection and characterization, i.e., damage localization and to certain extent quantification and propagation, as illustrated by two applications presented in detail in this paper: post-tensioned concrete bridge and segmented concrete pipeline. Early age cracking was detected, localized and quantified in the concrete deck of a pedestrian bridge using embedded long-gauge FOS. Post-tensioning of deck closed the cracks; however, permanent weakening in a bridge joint occurred due to cracking and it was identified and quantified. Additional cracking due formwork removal was also detected and characterized. The damage was confirmed using embedded distributed FOS and a separate load test of the bridge. Real-size concrete pipeline specimens and surrounding soil were equipped with distributed FOS and exposed to permanent ground displacement in a large-scale testing facility. Two tests were performed on different pipeline specimens. The sensors bonded on the pipeline specimens successfully detected and localized rupture of pipeline joints, while the sensors embedded in the soil were able to detect and localize the failure plane. Comparison with strain-gauges installed on the pipeline and visual inspection after the test confirmed accurate damage detection and characterization.

8692-66, Session 16

Multiple impacts identification techniques in composite structures using FBG sensors

Mijia Yang, Tao Ruan, North Dakota State Univ. (United States)

Fiber Bragg grating (FBG) sensors are widely used in the field of structural health monitoring for its high sensitivity, EM radiation immunity, fatigue resistance, multiplexing process, and long distance measurement capacity. In this paper, a novel algorithm for impact identification was then proposed. Transfer matrix between impact and sensor responses was obtained via experiments. By inversing the transfer matrix, impacts can be located and force history can be reconstructed, precise results were obtained through optimization. Based on the developed model, a 4x4 FBG sensor network was implemented on a composite laminate, and FBG sensors were employed to capture the responses. Besides the single impact, multiple impacts can also recognized by further utilizing superposition technique. Finally, the predicted impact and its locations were compared with the theoretical values. Close match results proved the effectiveness of the proposed method.

8692-67, Session 16

Dynamic signal recovery from fibre Bragg grating sensors using two-wave mixing

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Several methods exist to detect impacts on composite structures by using a fibre Bragg grating (FBG) to measure dynamic strain. A significant challenge for such systems is due to cross-sensitivity with both temperature and static strain. In an aerospace application sensors must be able to detect and distinguish dynamic strain whilst experiencing a temperature range of -60 to 100oC and a static strain range of ±3500microstrain. For a multiplexed sensor array in such an environment strain isolated reference gratings for temperature compensation are not a sufficient solution. This work attempts to address this problem using two wave mixing in erbium doped fibre (EDF) to create a dynamic gain grating insensitive to low bandwidth temperature and strain effects. Light returning from a FBG sensor reflects off the end face of a short piece of EDF forming an interference pattern inside the fibre which generates a temporary gain grating. This temporary grating will readjust to the shifting spectrum of the FBG sensor with a delay of ~1ms. Thus, only higher frequency dynamic strains will produce a change in the overall reflected light intensity. The presence of a gain grating is proven by measuring the change in the percentage of light reflected from the EDF as the intensity of incident light is increased for both the pumped and unpumped cases. Dynamic strain signals were then detected and the frequency response and cut-off frequency determined. The insensitivity to both static strain and temperature was measured and the wavelength multiplexing ability of the technique proven.

8692-68, Session 16

Fiber Bragg grating sensor system network for an adaptive trailing-edge shape monitoring: preliminary finite element evaluation

Monica Ciminello, Antonio Concilio, Ctr. Italiano Ricerche Aerospaziali (Italy)

It is the aim of this paper to present the design of a sensor system network based on fiber Bragg gratings (FBG) for the shape monitoring of an adaptive trailing edge (ATE) device. This research is part of a the project SARISTU (EU-FP7), funded by the European Union inside the VII Framework Programme and focused on smart aircraft structures; in detail, both fuselage and wing elements are dealt with.

The authors were involved with the detection and process of data concerning the in-flight ATE local deformation, necessary to reconstruct the shape produced by the action of a dedicated actuation system. Because the TE is immerged into 3D structural and aerodynamic fields, the sensor system network should have chord- and span-wise features.

The ATE device will be equipped with a shape monitoring system using a widely distributed sensors based on fiber optic (FO) elements. FO elements are herein referred to, mainly with the aim of reducing the number of channels (then expense, complexity, etc.). The simplest thing to think about is in fact to place a single fiber running all over the demonstrator, multiplexed with the necessary number of FBG.

In what follows, a numerical evaluation of the shape reconstruction capabilities is presented. The main challenge is to attain a 3D displacement field, moving from strain info. A FEM of the TE is used for this preliminary evaluation. The shape reconstruction algorithm output, opportunely processed, is preliminarily compared and validated with numerical results.

8692-69, Session 16

Strain and damage monitoring in solar-powered aircraft composite wing using fiber Bragg grating sensors

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A solar powered aircraft is operated by converting solar energy into electrical energy. The wing of the solar powered aircraft requires a wide area to attach a number of solar cells in order to collect a large amount of solar energy. But the structural deformation and damage of the aircraft wing may occur because of bending and torsional loads induced by aerodynamic force during the operation. Therefore, the structural health monitoring of the wing is needed for increasing the operating time of the aircraft. In this study, the strain and damage of a composite wing of a solar powered aircraft were monitored by using fiber optic sensors until failure occurrence. In detail, a static loading test was performed on the composite wing with a length of 3.465m under a solar simulation environment, and the strain and acoustic emission (AE) of fracture signal were monitored by using fiber Bragg grating (FBG) sensors. In the results

of the structural test, the damage occurred at a stringer when 4.5G load was applied to the composite wing, and the strain variations and AE signals were successfully measured by using FBG sensors. As a result, it is verified that the damage occurrence and location could be estimated by analyzing the strain variations and AE signals, and the fiber optic sensor would be a good transducer to monitor the structural status of a solar powered aircraft.

8692-70, Session 17

Unpowered wireless generation and sensing of ultrasound

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Ultrasound inspection is a popular Structural Health Monitoring technique. Even though wireless ultrasound sensing has been published before, wireless ultrasound generation has not been achieved. In this paper, we will present a wireless ultrasound pitch-catch system that demonstrates the wireless generation of ultrasound based on the principle of frequency conversion. For wireless ultrasound generation, the ultrasound generation signal is first mixed with a RF carrier signal to generate an ultrasound-modulated RF signal, which is then transmitted to the ultrasound actuator using an antenna. The ultrasound actuator is equipped with a wireless transponder that receives both the carrier signal and the modulated RF signal and recovers the ultrasound excitation signal using a passive mixer. For wireless sensing, the frequency conversion process is reversed. The ultrasound sensing signal is up-converted to a radio frequency signal by the wireless transponder and recovered at the wireless interrogation unit using a homodyne receiver. To differentiate the ultrasound actuator from the ultrasound sensor, each ultrasound transducer is equipped with a narrowband microwave filter so that it only responds to the carrier frequency that matches the filter's operation band. Detailed description of the wireless system will be presented. The interrogation distance of the wireless system is calculated from a power transmission model that is validated by experiment measurement. A signal processing algorithm is developed to recover the ultrasound sensing signal. The wirelessly acquired ultrasound signal is compared with those acquired using wired connection in both time and frequency domain.

8692-71, Session 17

Assembly of smart adaptronic piezometal composites by use of prefabricated batches of piezoceramic microparts

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Current technologies for smart sheet metal part production base upon adhesive bonding of piezo-patches to the surface. A novel concept and process chain is the assembly of piezoceramic micro parts into local microstructures of metal sheets and subsequent joining by forming. This results in a full functional integration of the piezoceramic in the metal for sensor and actuator purposes. Mechanical coupling is non-positive without elastic interlayers and the electrical coupling is characterized by the metal being the ground electrode of the sensor. The paper describes the design, methods and tolerance management to overcome the challenges for reliable parallel microassembly and joining of prefabricated batches of 20 piezoceramic fibres with dimensions of 0.135 x 0.235 x 11.5 mm^3 and nominal assembly clearances of 0.015 mm. The prefabrication of the batches is achieved by stacking and dicing of piezoceramic plates. Both the principles of sorting and elastic averaging have to be applied for reliable production and joining of the batches. In experiments, tolerances < 0.008 mm where achieved for the position of the piezoceramic fibres within the batch. FE simulations have been performed for dimensioning of the batches in terms of compliance for reliable assembly. Prototypes were assembled and joined by forming achieving functional piezo-metal composites. With the given tolerances of the parts, microstructure and the assembly system statistical tolerance distributions have been calculated by numerical simulations. An assembly yield of > 95% is expected for future scaled up high-volume assembly of piezo-metal composites.

8692-72, Session 17

Guided-wave generation and sensing using d36 piezoelectric elements

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This work presents guided wave generation and sensing in isotropic plates by using d36 type piezoelectric transducers. The d31 mode of conventional Lead zirconate titanate (PZT) has been widely used to excite guided wave in plates, pipes or thin-walled structures, and receive wave signals propagating in the structures. Especially in the thin plate-like structures, different types of plate waves, such as Lamb waves with symmetric modes and antisymmetric modes, and shear horizontal waves, are generated by the excitation of PZT actuators. In some cases, after reflection or scattering, combination of different types of waves requires more complex signal processing techniques. The d36 mode of piezoelectric transducers however induces shear deformation in the plane normal to its polarization direction. In the plate, this results in more significant shear horizontal waves whose amplitudes are much more significant than those from Lamb waves. In this paper, mechanical model of the transducers and analysis of shear horizontal waves' generation are presented at first. Finite element analysis is employed to explore displacement response of the plate. Moreover, for the d36-based actuator, voltage responses of both conventional and d36 sensors are obtained. Different transducers size and shape, and input frequencies are also investigated. Results indicate this type of transducers has potential for providing quantitative estimation of damage in structural health monitoring.

8692-73, Session 17

Design of alternative sensors for NDE/SHM applications based on highly nonlinear solitary waves

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In this paper, we describe the designs and the relative experiments of novel transducers utilized for the generation and detection of highly nonlinear solitary waves (HNSWs). In recent years these waves have been proposed for the NDE/SHM of structural materials and structural elements such as concrete and aluminum lap-joints bonded by high-strength epoxy. Conventionally these transducers contain a chain of spherical particles and the waves are measured by means of thin piezoelectric material embedded in between two half-particles. The final product is usually identified as a sensor bead. Although sensor beads can measure the propagation of HNSWs effectively, their manufacturing may require high level of precision. In this paper we propose two alternative designs. In the first, we investigated the use of cylindrical piezoelectric material in lieu of the sensor bead. In the second design we propose to exploit the magnetostrictive phenomenon to detect HNSWs. For both transducers' designs a series of experiments were conducted and the results were compared to the results obtained by a conventional HNSW transducer. As the results in good agreement, this study may pave the road to broader applications of HNSWs for NDE and SHM.

8692-74, Session 17

Analytical assessment of in-plane and out-of-plane electromechanical impedance spectroscopy (EMIS) of piezoelectric wafer active sensor

Tuncay Kamas, Bin Lin, Victor Giurgiutiu, Univ. of South Carolina (United States)

This paper discusses theoretical analysis of electro-mechanical impedance spectroscopy (EMIS) of piezoelectric wafer active sensor (PWAS). Both free and constrained PWAS EMIS models are developed for in-plane (lengthwise) and out-of plane (thickness wise) mode. The paper starts with the general piezoelectric constitutive equations that express the linear relation between stress, strain, electric field and electric displacement. This is followed by the PWAS EMIS models with two assumptions: 1) constant electric displacement in thickness direction (D3); 2) constant electric field in thickness direction (E3). The effects of these assumptions on the free PWAS in-plane and out-of-plane EMIS models are studied and compared. For a constrained PWAS bonded to a structure, the same assumptions are applied to determine the EMIS. The effects of internal damping of PWAS and structure are considered in the analytical EMIS models. The analytical EMIS models are verified by Coupled Field Finite Element Method (CF-FEM) simulations and by experimental measurements. The extent of the agreement between the analytical and experimental EMIS results is discussed. The paper ends with summary, conclusions, and suggestions for future work.

8692-75, Session 18

Development of smart seismic bridge bearing using fiber optic Bragg grating sensors

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After a bridge was completed, a faulting at supporting point may occur because of the un-expected loads to bridge bearing. Serviceability of bridges could be impaired by the faulting which had caused structural damage. Therefore, it is needed for a smart bridge bearing which can observe the supporting points continuously. Some of bridge bearings have been developed for measuring vertical load and vertical displacement by installing sensors in the bearing. However in those systems, it is not easy to be replaced with new sensors when repairs are needed. In this study, the smart bridge bearing of which sensors can be replaced has been de-veloped to overcome such a problem.

In this study, strain signals were used for measuring both vertical displacements and loads. FBG sensors(fiber optic Bragg-grating sensors) preventing electronic noise due to mediating light, which enable the simplification of the measuring cable due to multiple measurements and are easy to place due to lightweight and small, has been used for measurement of the strain signals.

Smart bridge bearings based on FBG sensors consist of EQS(Eradi Quake System) which has been commercially used for seismic bridge bearings. Experiments and dead load test were carried out to prove applicability of the smart bridge bearing based on FBG sensors that can measure vertical displacements and loads. B-WIM system by using smart bridge bearings based on FBG sensors is supposed to be developed as further work of this study.

8692-76, Session 18

Analysis of monitoring data from cable-stayed bridge using sensor fusion techniques

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Here we illustrate an application of Bayesian logic to monitoring data analysis and structural condition state inference. The case study is a 260 m long cable-stayed bridge spanning the Adige River 10 km north of the town of Trento, Italy. This is a statically indeterminate structure, having a composite steel-concrete deck, supported by 12 stay cables. Structural redundancy, possible relaxation losses and an as-built condition differing from design, suggest that long-term load redistribution between cables can be expected. To monitor load redistribution, the owner decided to install a monitoring system which combines built-on-site elastomagnetic and fiber-optic sensors. Fiber-optic strain gauges are FBG-based and allow measurement of changes in deformation with accuracy of the order of a few microstrains with respect to the value at installation. The elastomagnetic sensors detect changes in magnetic permeability of the cable which are in turn directly correlated to the cable stress. In this note, we illustrate the calibration procedure for the sensing systems and the outcome of the first year of continuous monitoring. We use a multi-sensor data fusion approach to identify the cable stress redistribution with the required accuracy and for probabilistic inference of any cable relaxation. The data processing algorithm uses Bayesian logic to combine prior knowledge with information from the various sensing systems and with the results of visual inspection. With real-life examples, we highlight how the extent of prior knowledge can alter the final engineering perception of the current state of the bridge.

8692-77, Session 18

Real-time bridge scour monitoring with magneto-inductive field coupling

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Scour was responsible for most of the U.S. bridges that collapsed during the past 40 years. The maximum scour depth is the most critical parameter in bridge design and maintenance. Due to scouring and refilling of river-bed deposits, existing technologies face a challenge in measuring the maximum scour depth during a strong flood. In this study, a new methodology is proposed for real time scour monitoring of bridges. Smart rocks with embedded electronics are deployed around the foundation of a bridge as field agents. With wireless communications, these sensors can send their position change information to a nearby mobile station. This paper will be focused on the design, characterization, and performance validation of active sensors. The active sensors use 3-axis accelerometers/ magnetometers with a magneto-inductive communication system. In addition, each sensor includes an ID, a timer, and a battery level indicator. A smart rock system enables the monitoring of the most critical scour condition and time by logging and analyzing sliding, rolling, tilting, and heading of the spatially distributed sensors.

These on-board sensors provide the smart rock capability of sensing scour related conditions such as depth, location, and orientation of the rock. In order to transmit the sensed data to the base station, all the active components of the smart rock are mounted on a printed circuit board (PCB) in addition to the required wireless modules such as a transmitter/receiver antenna, battery, real-time clock and calendar module, sleep/wake-up module, on-board receiver and transmitter circuit. The comprehensive embodiments enable the active smart rock to be recognized, commanded, and communicated wirelessly and specifically, regarding the ID, battery status, orientation, acceleration, pressure, and/or other scour related data. In addition, with the on-board timer, a smart rock is in low power consumption sleep mode and can be woken up and the communication between the smart rock and base station/center can be operated at select times as demanded (for example, every hour, day, month, or year). The smart rock PCB can be enclosed into a water-proof (sealed) shell for the purpose of underwater protection. An example of embodiment inside a 2.5 in. diameter spherical shell was used in various

small-scale laboratory tests to demonstrate the active sensor concept. For practical application of bridge scour monitoring, the protected or sealed smart rock PCB can be further embedded into the artificial rocks to integrate with the scour mitigation. The on-bridge base station includes large antenna, power amplifier, controller board, and a computer with Matlab graphical user interface (GUI).

8692-78, Session 18

Automated wireless monitoring system for cable tension using smart sensors

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Cables are critical load carrying members of cable-stayed bridges; monitoring tension forces of the cables provides valuable information for SHM of the cable-stayed bridges. Monitoring systems for the cable tension can be efficiently realized using wireless smart sensors in conjunction with vibration-based cable tension estimation approaches. This study develops an automated cable tension monitoring system using MEMSIC's Imote2 smart sensors. An embedded data processing strategy is implemented on the Imote2-based wireless sensor network to calculate cable tensions using a vibration-based method, significantly reducing the wireless data transmission and associated power consumption. The autonomous operation of the monitoring system is achieved by AutoMonitor, a high-level coordinator application provided by the Illinois SHM Project Services Toolsuite. The monitoring system also features power harvesting enabled by solar panels attached to each sensor node and AutoMonitor for charging control. The proposed wireless system has been deployed on the Jindo Bridge, a cable-stayed bridge located in South Korea. Tension forces are autonomously monitored for 12 cables in the east, land side of the bridge, proving the validity and potential of the presented tension monitoring system for real-world applications.

8692-79, Session 18

Structural health monitoring of a steel stringer bridge with long-gauge FBG sensors

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The Federal Highway Administration (FHWA) Long-term Bridge Performance (LTBP) Program initiated an International Bridge Study (IBS) by selecting a steel stringer bridge in northern New Jersey as a benchmark structure to formulate and demonstrate best practice guidelines for health monitoring of bridges. As a part of this program, the authors applied the LG-FBG (Long Gauge Fiber Bragg Grating) sensors as area sensors to monitor this benchmark bridge. This papers aims at illustrating the LG-FBG related state-of-the-art technologies by taking the benchmark bridge as the test bed. (1) The concept of the LG-FBG sensors for area sensing is first presented. Most fiber optic sensors measure point strain, which only suit for local monitoring. In contrast, the developed LG-FBG area sensor has a long gauge (e.g., 1~2 meters) and can be connected each other to make a sensor array, which makes it possible to measure not only local strain but also distributed strain throughout the full at least the most important areas of a structure. (2) Spectral analyses of the macro strain time histories from the developed area sensors are performed to identify structural frequencies, and the results are compared with those from recorded accelerations. (3) Neutral axis positions of the girders of the investigated bridge are determinated from the recorded macro strain time histories, and the results are compared with those from static truck tests. (4) An innovative modal macro-strain (MMS) based damage index is applied for damage detection of the steel stringer bridge. Both field test data and finite element simulation data of the benchmark bridge are used to verify the effectiveness of the MMS based damage index for structural damage detection.

8692-80, Session 19

Visualization technique for fatigue cracks at steel structures integrating a scanning laser source with piezoelectric sensors

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In this research, a noncontact nondestructive testing (NDT) method is proposed to detect the fatigue crack and to identify the location of the damage. To achieve this goal, Lamb wave propagation of a plate-like structure is analyzed, which is induced by scanning laser source actuation system. A ND: YAG pulsed laser system is used to generate Lamb wave exerted at the multiple points of the plate and a piezoelectric sensor is installed to measure the structural responses. Multiple time signals measured by the piezoelectric sensor are aligned along the vertical and horizontal axes corresponding to laser impinging points so that 3 dimensional data can be constructed. Then, the 3 dimensional data is sliced along the time axis to visualize the wave propagation. The scattering of Lamb wave due to the damage can be described in the wave propagation image and hence the damage can be localized and quantified. Damage-sensitive features, which are reflected wave from the damage, are clearly extracted by wave-number filtering based on the 3 dimensional Fourier transform of the visualized data. Additional features are extracted by observing different scales of wavelet coefficients so that the time of flight (TOF) of Lamb wave modes can be clearly separated. Steel plates with fatigue cracks are investigated to verify the effectiveness and the robustness of the proposed NDT approach.

8692-81, Session 19

Implementation of a wireless image motion estimation method for two-dimensional crack monitoring

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Deterioration of concrete structures is usually accompanied by the formation and propagation of cracks. Excessively wide and deep cracking can lead to corrosion of reinforcement and inevitably affect the durability of the structures. There are currently a few sensors for crack monitoring application. They however cannot be applied extensively in civil engineering infrastructures due to labor-intensiveness for cabling. They are also limited in one dimensional crack monitoring.

In this paper, a wireless image-based sensor for two-dimensional (2D) crack propagation monitoring is reported. This sensor contains an optical navigation sensor board (ADNS-9500) which is incorporated into the Imote2 IPR2400 platform. To monitor crack propagation, the Imote2 sends a signal to the ADNS-9500 to switch on the built-in laser and camera collecting images reflected from a surface. The captured images are processed by some image motion estimation methods to obtain the 2D relative displacement between images. Four motion estimation methods have been studied: Lucas & Kanade Optical flow [1], Thomas Brox Optical flow [2], Normalized cross correlation and Phase correlation [3].

A series of numerical simulation and experimental tests are being conducted to study the tracking performance under different surfaces and motion estimation methods. Temporarily the results show that Thomas Brox method is the most effective method. Under Thomas Brox method, the crack sensor shows excellent results to track the crack motion up to 0.001mm accuracy under a certain propagation speed range and a particular surface.

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[3] Zitaova, B. and Flusser, J. (2003). "Image registration methods: a survey, Image and Vision Computing, 11, 977-1000

8692-82, Session 19

Accurate and fast in-plane displacement measurement method for large-scale structures by utilizing repeated pattern

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Imaging based nondestructive monitoring systems are critical for evaluation of large-scale infrastructures. In this study, an accurate and fast in-plane displacement measurement method based imaging technique is developed for the purpose of health monitoring of large-scale infrastructures such as high building, long bridge, etc. The build-in repeated patterns on infrastructure facade, such as tile, checker, and brick wall pattern is proposed to measure the in-plane displacement distribution accurately. By performing the down-sampling and intensity interpolation image processing to the captured single image before and after deformations, multiple phase-shifted moiré fringe can be obtained simultaneously. The phase distribution of the moiré fringe is calculated using the phase shifting method and discrete Fourier transform technique. In this method, both the fundamental and high frequency components are considered to analyze the repeated patterns. The in-plane displacement distribution can be obtained from the phase differences of the moiré fringe before and after deformations. Compared with conventional displacement methods and sensors, the main advantages of the developed method are high-resolution, accurate, fast, low-cost, and easy to implement. The principle of the proposed in-plane displacement measurement is presented. The effectiveness of our method is confirmed by computer simulation and primary experimental results. Experimental results showed that a sub-millimeter displacement could be successfully detected against the field of view with meter-scale.

8692-83, Session 19

Use of advanced noncontact instrumentation for exploring structural behavior

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As experimental capabilities at large-scale structural labs develop, there is a growing need for advancement in instrumentation that yields data which can be readily processed and analyzed to reveal actual complex structural responses. A wide array of conventional displacement sensors can be used in combination in order to achieve a relatively comprehensive set of data for analysis of behavior. Non-contact instrumentation allows for a different methodology for obtaining local and global responses of experimental specimens. The use of non-contact methods, namely the application of the Krypton measurement system, is introduced in this paper. This system is capable of measuring three-dimensional displacements based on specimen coordinates. Through a large array of Light Emitting Diodes (LEDs) installed on a specimen, both local displacements and global behavior can be measured by the Krypton system.

An example is provided utilizing data obtained on the complex response of reinforced concrete bridge piers subjected to combined loading. The measured data from the mesh of LEDs applied to this specimen directly correlates to six degree-of-freedom displacements, strains and curvatures over the structural dimensions. The same data can also be used to indirectly assess stresses at the local level of resolution dependent on the size of the mesh, as well as overall global behavior of the structure. Detailed discussion is provided on the proposed methods used to analyze the data for a hybrid simulation of a four-span curved bridge. Results provided by the analysis using these methods are compared to photos and traditional instrumentation applied to the specimens.

8692-84, Session 19

The use of digital image correlation for nondestructive and multiscale damage quantification

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This talk validates the use of Digital Image Correlation (DIC) as a noncontact nondestructive testing and evaluation (NDT&E) technique by presenting results pertinent to damage of several material systems at different length scales of interest. At the microstructural level compact tension aluminum alloy specimens were tested under Mode I loading conditions with a field of view small enough to observe the onset of crack growth of the fatigue pre-crack, while observing directly the material's grain structure. The results permitted the quantification of the strain accumulation around the tip of the pre-crack and the prediction of crack initiation, while the monitoring strategy allowed the computation of the relevant crack opening displacement as a function of crack growth. At the mesoscale level, damage quantification in fiber reinforced composites subject to both tensile and fatigue loading conditions was achieved by using the DIC as part of a novel integrated NDT approach combining both acoustic and thermal methods. DIC in these experiments provided spatially resolved and high accuracy strain measurements capable to track the formation of damage "hot spots" that corresponded to the sites of visible final fracture, while it further allowed the correlation of mechanical parameters to thermal and acoustic features. Finally, at the macrostructural level DIC measurements were also performed and compared to traditional displacement gages mounted on a steel deck model subject to both static and dynamic loads, as well as on masonry structures to evaluate the strength of hollow and grouted concrete walls.

8692-85, Session 20

Estimation of defect parameters in transversally anisotropic materials using infrared thermography

Arun Manohar, Jeffery D. Tippmann, Francesco Lanza di Scalea, Univ. of California, San Diego (United States)

Estimation of defect size and depth in composite structures is a relevant problem as the aerospace and wind energy industries are increasingly using composites. The determination of defect depth and size is important in order to perform repairs and assess the integrity of the structure. The problem has been previously studied using simple 1D heat conduction models. Unfortunately, 1D heat conduction based models are generally inadequate in predicting heat flow around defects, especially in composites. In this study, a novel heat conduction model is proposed to model heat flow around defects accounting for 2D heat conduction in transversally anisotropic materials. The proposed approach is used to quantitatively determine the defect depth and size. The validity of the model is established using experiments performed on a CFRP specimen with simulated delaminations present at different depths.

8692-86, Session 20

Entangled CNTs active layer for noncontact nondestructive evaluation in composite laminates and enhanced impact properties

Fulvio Pinto, J. O'Byrne, Davide Mattia, Michele Meo, Univ. of Bath (United Kingdom)

During the past decade there has been an increasing use of composite materials in aerospace applications due to their low density and high mechanical properties. As a result, complex parts are nowadays manufactured using composite materials, reducing the total weight of the structures and therefore lowering fuel consumption and CO2 emissions.

However, even though carbon fibre-reinforced composites (CFRP) structures are able to withstand high stresses, they are characterised by weak interfacial strength between laminas and can be seriously damaged from impact of foreign objects. This kind of loads can lead to various types of damages such as microcracks, delamination and barely visible impact damages (BVID) that can compromise the structural integrity of the entire composite part.

This work investigates experimentally the possibility to increase the composite impact properties by embedding a sponge-like structure made with carbon nanotubes (CNT) between the composite plies. CNTs are grown by a chemical vapour deposition (CVD) process, via thermal catalytic decomposition of hydrocarbons (e.g. toluene or xylene) in the presence of a metal catalyst obtained by the decomposition of an organometallic compound, such as ferrocene. Using a novel manufacturing technique it is possible to create the CNTs sponge directly on a pre-impregnated CFRP ply, characterised by very long entangled nanotubes uniformly distributed all over the structure. The presence of the entangled CNTs sponge increases the energy absorption rate of the material resulting in enhanced impact properties.

Moreover, the electrical conductivity of the CNTs sponge layer can be exploited as an active layer for in situ non-destructive damage evaluation. Indeed, transmitting low amperage current in the active layer, an ohmic thermal flow is induced within the material and diffuses through the thickness towards the external surface. Analysing the emitted thermal waves from the sample with an IR Camera, the presence of internal damages can be detected monitoring the potential variation in the apparent temperature.

8692-87, Session 20

A vision-based approach for obtaining the time-varying displacement field of vibrating systems

Mohammad Reza Jahanshahi, Yulu Chen, Sami F. Masri, The Univ. of Southern California (United States)

This study presents the results of an extensive analytical and experimental investigation to develop, calibrate, implement, and evaluate the feasibility of a novel vision-based approach for measuring the absolute displacement time history at numerous locations of vibrating dynamic systems that leads to the extraction of the associated time-varying displacement field. The measurements were obtained using a combination of a camera and a cost-effective depth sensor. Calibration of the vision system was conducted to match the RGB pixels with the corresponding depth values, and to compensate for the lens distortion. It is shown that the proposed approach can potentially be used as an economical and robust solution for obtaining the evolving displacement field in realistic civil, mechanical, and aerospace structural systems undergoing time-varying complex three-dimensional deformations.

8692-88, Session 20

Development of a stereo camera system for road surface assessment

Di Su, Tomonori Nagayama, Yozo Fujino, The Univ. of Tokyo (Japan)

Currently pavement condition assessment mainly relies on the manual approaches. Trained investigators survey the condition of the road surface and detect the deficiency by visual inspection. Obviously this procedure is very time consuming and inefficient. Furthermore, the reliability of results is limited since it is determined by the subjective judgment of investigators Special pavement condition survey vehicle could obtain the precise condition of the road surface. However its inspection cost is too high to let it be a routine monitoring means. Consequently, the development of efficient and accurate assessment techniques for road surface is an urgent need to diagnose the condition of the deteriorating road surface.

In recent year, stereo vision is a widely researched and implemented monitoring approach in object recognition field. This paper introduces the development of a stereo camera system for road surface assessment. In this study, first the static photos taken by a calibrated stereo camera system are utilized to reconstruct the three-dimensional coordinates of targets in the pavement. Subsequently to align the various coordinates obtained from different view meshes, one modified Iterative Closet Point method is proposed by affording the appropriate initial conditions and image correlation method. Several field tests have been carried out to evaluate the capabilities of this system. After succeeding to align all the measured coordinates, this system can offer not only the accurate information of local deficiency such as the patching, crack or pothole, but also global fluctuation in a long distance range of the road surface.

8692-89, Session 20

Excitation of stress waves in concrete using a focused electric spark source

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The recently developed air-coupled sensing methods have greatly improved NDT test speed of concrete structures. A microphone has been used to measure leaky surface wave and impact-echo signals radiated from concrete surface. However, an air-coupled source is needed to enable a fully non-contact test system. Because of large thickness (typically > 100 mm) of concrete structural members and high acoustic impedance mismatch between concrete and air, the commercially available air-coupled transducers cannot be directly used for NDT of concrete.

In this study, we propose a simple spark source system by combining an electrical spark generator with an ellipsoidal reflector to generate elastic waves in concrete. The sparks source located at the inner focus of the reflector will be reflected and converged to the outer focus of the reflector, which is be aligned on the testing surface. The system is able to provide consistent excitation with broad bandwidth. Rayleigh wave and impact-echo modes have been successfully generated in a concrete specimen by the air-coupled spark source in the lab experiment. A fully non-contact air-coupled system has also been validated by combining the spark source and air-coupled sensors.

8692-90, Session 20

Evaluation of vision-based corrosion detection algorithms for noncontact condition assessment of structures

Mohammad Reza Jahanshahi, Sami F. Masri, The Univ. of Southern California (United States)

Corrosion is an important phenomenon that can lead to catastrophic consequences if neglected. This study evaluates the effects of several parameters that can influence the performance of color wavelet-based texture analysis algorithms for detecting corrosion in structural systems. In addition, an approach is proposed that utilizes the depth perception for corrosion detection. This novel approach enhances the reliability of the corrosion detection algorithm. The incorporation of depth perception with the texture classification algorithms is part of the contribution of this study. Several parametric studies are presented to evaluate the performance and reliability of the investigated approaches.

8692-91, Session 20

Identification of source location by using compressive approach

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In this paper, a new approach to identify the source location is proposed by exploiting the compressive sensing theory, which indicates that sparse or compressible signals can be recovered using just a few measurement. A square grid configuration plate with some piezoelectric actuator and sensor is used to verify the proposed approach. The grid is used to sweep across the plate to identify the location of source. Piezoelectric actuator placed on the plate is used to excite waves, and the signals of waves received at some sensors. The sensor locations are known, however, the source location need not be known. The candidate source locations are suitably chosen grid on the surface of plate. Sensing matrix which is related to the locations of source and sensor can be calculated at each sensor. Then, the proposed approach used the received signal strengths to locate the source by minimizing the ?1-norm of the sparse matrix in the discrete spatial domain based on the concept of compressive sensing (CS). The simulations and experimental studies show the proposed method achieves a high level of localization accuracy.

8692-92, Session 21

Integration of structural health monitoring in the design-cycle and reduction of weight

Mulugeta A. Haile, Anindya Ghoshal, U.S. Army Research Lab. (United States)

Many aerospace structures are designed and built much stronger than needed to allow for uncertainty. Uncertainty is ubiquitous in materials and loads data, and the operational environment of a component is not fully predictable. The conventional way of dealing with uncertainty is to use conservative design parameters in the design stage and to apply a safety factor. Such design, however, entails a high weight penalty. Structural Health Monitoring (SHM) sensor systems such as ultrasonic, eddy current, and acoustic emission, have gained much interest in the aerospace community as potentially enabling technologies for reducing inspection and maintenance costs while maintaining flight safety of aging structures. Many of these systems have the potential to provide on-board damage detection, state awareness of structural health, and usage monitoring. Currently, SHM is primarily viewed as a means for detecting damage to support inspection and maintenance activities. While such use has a great potential to reduce maintenance cost and downtime, SHM can also be incorporated in the design cycle to reduce the overall weight of critical aerospace structures. The goal of this research is to develop a design framework where SHM is integrated in the design stage so that the final structure has a lower weight. By continuously monitoring the condition of a load carrying member via integrated SHM sensors, we show that one can significantly reduce usage uncertainty and safety factors without affecting the design life. To validate the weight saving advantage of the SHM-based approach, we compare our result with a standard reliability-based design.

8692-93, Session 21

Temperature-compensated strain measurement of full-scale small aircraft wing structure using low-cost FBG interrogator

Jin-Hyuk Kim, Yeongwan Lee, Yoon-Young Kim, Chun-Gon Kim, KAIST (Korea, Republic of)

Recently, health and usage monitoring systems(HUMS) are being studied to monitor a real-time condition of aircrafts during flight. HUMSs can prevent aircraft accidents and reduce inspection time and cost. A fiber Bragg grating(FBG) sensor is widely used for aircraft HUMSs with many advantages such as light weight, small size, easy-multiplexing, and EMI immunity. However, commercial FBG interrogators are too expensive to apply for small aircrafts. Generally the cost of conventional FBG interrogators is over $20,000. Therefore, cost-effective FBG interrogation systems need to be developed for small aircraft HUMSs. In this study, cost-effective low speed FBG interrogator was applied to full-scale small aircraft wing structure to examine the operational applicability of the low speed FBG interrogator to the monitoring of small aircrafts. The cost of the developed low speed FBG interrogator was about $10,000, which is an affordable price for a small aircraft. 10 FBG strain sensors and 1 FBG temperature sensor were installed on the surface of the full-scale wing structure. The load was applied to the tip of the wing structure, and the low speed interrogator detected the change in the center wavelength of the FBG sensors at the sampling rate of 5Hz. To assess the applicability of low-cost FBG interrogator to full-scale small aircraft wing structure, a temperature-compensated strain measurement algorithm was verified experimentally under various loading conditions of the wing structure with temperature variations.

8692-94, Session 21

Fiber-optic system for deflection and damage detection in morphing wing structures

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The motivation behind the development of morphing wings is biologically inspired by the flight capabilities of birds that are able to achieve a wide dynamic range missions through large shape changes to their wings. There are several examples in aircraft industry where morphing wing approach is already tested with good results in terms of tune-able aerodynamic properties. The basic platforms are morphing wings equipped with active elements such as piezoelectric transducers. Within the EC Clean Sky - Smart Fixed Wing Aircraft initiative concepts for actuating morphing wing structures are under development.

For a complete integrated system including the actuation and the closed loop control unit a concept of a hybrid deflection and damage monitoring system based on fiber optic sensors was developed. The used sensors are based on the low coherence interferometry performed by an “all-in-fibre” configuration of Michelson type. The fibre optic sensors are used to capture the slow varying strain caused by the deflection due to actuation and the quick varying strain caused by the emission of acoustic signals from the onset and growth of damages. The optical signal will be converted to electrical by means of an optoelectronic device and split by different filters to discriminate between the signal part containing the information about the deflection and the transient signals arising from the acoustic emission event. The filtered signal will be acquired and post processed using a commercially AE system. Within this paper the authors present the concept, analyses and first experimental results of the mentioned system.

8692-95, Session 22

A regenerative damper with MR fluids working between gear transmissions

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Magnetorheological (MR) dampers are used for semi-active vibration control of various dynamic systems. Existing MR dampers are usually cylinder-piston based design, which may limit the shapes and imply constraints to the implementation of related parts and devices. In this paper, we propose a novel MR damper design with MR fluids working between gear transmissions to provide required damping force. A prototype of the regenerative damper with MR fluids working between gear transmissions was designed, fabricated, and tested. This MR damper has the capability of power generation and velocity sensing. It combines the advantages of energy harvesting - reusing wasted energy, MR damping - controllable damping force, and sensing - providing dynamic information for controlling system dynamics. This multifunctional integration would bring great benefits such as energy saving, flexible shape as well as possibility of size and weight reduction. In this paper, experimental studies on damping force and power generation were performed. The velocity-sensing capability was also experimentally validated.

8692-96, Session 22

Auto-Gopher: a wireline deep sampler driven by piezoelectric percussive actuator and EM rotary motor

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The ability to penetrate subsurfaces and perform sample acquisition at depth of meters is critical for future NASA in-situ exploration missions to bodies in the solar system, including Mars and Europa. A corer/sampler was developed with the goal of acquiring pristine samples by reaching depths on Mars beyond the oxidized and sterilized zone. To developed rotary-hammering coring drill, called Auto-Gopher, employs a piezoelectric actuated percussive mechanism for breaking formations and an electric motor rotates the bit to remove the powdered cuttings. This sampler is a wireline mechanism that can be fed into and retrieved from the drilled hole using a winch and a cable. It includes an inchworm anchoring mechanism allowing the drill advancement and weight on bit control without twisting the reeling and power cables. The penetration rate is being optimized by simultaneously activating the percussive and rotary motions of the Auto-Gopher. The percussive mechanism is based on the Ultrasonic/Sonic Drill/Corer (USDC) mechanism that is driven by piezoelectric stack and that was demonstrated to require low axial preload. The design and fabrication of this device were presented in previous publications. This paper presents the results of laboratory and field tests and lessons learned from this development.

8692-97, Session 22

Laser displacement sensor to monitor the layup process of composite laminate production

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Flaws still occur during the layup process of prepreg laminates due to human errors, failing equipment, faulty materials and failing detection systems. When quality control is performed by non-destructive testing techniques after curing, these flaws are already irreversibly embedded in the laminate. This paper presents the laser displacement sensor technique applied during the layup process of prepreg laminates to detect flaws. The aim of this research is to apply the laser displacement technique to detect typical flaws during the layup process with a high accuracy and to design a laser displacement technique as part of an industrial in-situ layup process monitoring system.

Foil or other enclosures between the layers, incorrect number of layers, the orientation of the fibres, fibre wrinkling and incorrect overlap are dominant flaws during the process of layup. These flaws have been modelled to assess the performance of in-situ monitoring during the layup process of prepreg laminates. In the experimental phase a 2D laser displacement sensor is used for flaw detection with a resolution of 1 µm in Z-axis and 20 µm in X-axis, with a maximum interrogation speed of 62.5 kHz. These specifications result in a design for a monitoring system, which is able to scan prepreg laminates specimens with 3.8 m^2 per minute and is able to detect a minimal flaw size of 0.4 mm^2. Therefore this research builds upon previous research in detecting not only numbers of prepreg layers, but all dominant flaws in composite production, including the successful detection of 50 µm thick foil remaining between the layers.

8692-98, Session 22

Self-powered wireless vibration-sensing module for machining monitoring

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We report an attachable kinetic-energy-harvesters powered wireless vibration-sensing module for milling monitoring. The module consists of a kinetic energy harvester, MEMS accelerometer, and wireless sensing module. The harvester is a coil-less magnetic-actuated piezoelectric-beams energy harvester. Several small permanent magnets are attached to the end of the piezoelectric beams fixed on the frame attached on the machine while few big permanent magnets are attached on the spindle of the machine. During machining, the big magnets rotate with the spindle and subsequently generate a periodic magnetic-repulsive force between the big and small magnets. The periodic magnetic force actuates/deforms the piezoelectric beams accordingly. This generates an electrical output due to the piezoelectric effect. Through utilizing an energy-storage/rectification circuit, the harvested energy is capable of steadily powering both the MEMS accelerometer and wireless sensing module. Through integrating the energy harvester, MEMS accelerometer, and wireless sensing module, a self-powered wireless vibration-sensing module is achieved. The test result of the module used to monitor the milling process shows the module successfully senses the vibration during milling. Through analyzing the vibration data, a criterion is established for simulating the milling process and operating sequence. For more details, please see the uploaded file (two-page abstract).

8692-99, Session 23

Decoupling of multiple-input systems and time-domain system identification of civil engineering structures

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Civil engineering structures are often subjected to multi-directional loadings such as earthquakes, which induce complex structural responses in which the contributions from the multiple inputs are

highly coupled, leading to Multiple Input, Multiple Output (MIMO) system identification problems. Compared with Single Input, Multiple Output (SIMO) system identification, MIMO problems are more computationally complex and error-prone. To convert a MIMO problem into SIMO problems, the outputs need to be decoupled by extracting the contribution from desired input signals to the outputs. In this paper, a QR Decomposition-based decoupling method is adopted and its performance is examined. Three factors which affect the accuracy of the decoupling result, including the memory length, the input correlation, and the system damping, are investigated. This method is then applied to the seismic measurements of the Meloland Road Overcrossing (MRO) Bridge to decouple the outputs in the vertical direction. Meanwhile, a system identification method which combines the ARX and ERA methods is proposed, which utilizes the noise mode indicators in ERA to identify genuine modes from the fitted ARX model. The ARX-ERA method is then applied in SIMO system identifications to identify the modal properties of the MRO Bridge with the decoupled output signals.

8692-100, Session 23

A novel model-free data processing technique for ad hoc analysis in monitoring for heterogeneous infrastructure networks

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The development of data processing algorithms that enhance pattern detectability for civil infrastructure systems exposed to the environment is critical in various monitoring applications for construction, operation, maintenance, and hazard detection. For example, precise detection of snow/ ice forming on road pavement surface is essential for transportation safety. Another example is monitoring for precipitation effects on structural safety of retaining walls. Ad hoc analysis of streamed data involves processing complicated non-stationary nonlinear multi-physics behaviors of coupled interactions between civil systems and various surrounding factors. Therefore, the modeling of these coupled interactions is usually very difficult. In addition, monitoring cost can be too expensive and sometimes impossible to measure all significant factors.

Auto Modulating Pattern Detection Algorithm (AMP) is a novel data processing algorithm to enhance the standard EMD-HHT methods to detect a “small” but important intermittent event of interest that is usually masked by “dominant” environmental disturbances in various monitoring applications. With the AMP, higher detectability can be achieved by: (1) amplifying the frequency amplitude of the pattern-changing event in time-frequency plot, (2) reducing the baseline frequency fluctuation in the time-frequency plot, and (3) increasing the temporal resolution of the energy-time-frequency domain signal. This study shows AMP is applicable to various monitoring applications in operation and maintenance, such as monitoring structural safety for retaining walls and monitoring meteorological hazards on road pavement surface under field conditions.

8692-101, Session 23

Error bounds for curvature-based structural damage-detection approaches

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Estimating accurate curvature information is very important in many structural systems. The estimated curvature shapes can be used for active shape control, health monitoring, and condition assessment. The availability of advanced strain sensors such as Fiber Optic Strain Sensors (FOSS) makes the estimation of the curvature shapes from the strain data relatively straightforward. However, in many practical engineering cases the strain data is not available and the curvature information should be obtained from the displacement measurements. This study investigates the viability of using the measured deformation to estimate the corresponding curvature shape, particularly for damage detection and quantification purposes. A computational model of a swept aluminum plate of span (L) is created using FEMAP. Several induced artificial damage cases are created and analyzed using the finite element analysis (FEA) package NASTRAN. Various mesh sizes are considered and nodes (sensors) are placed at resolutions ranging from (L/50) to (L/400) along the span of the plate. Artificial noise is added to the FEA output to simulate a realistic experimental condition. The displacement data is then used to obtain the corresponding curvature shapes using numerical differentiation tools available in MATLAB. The results are then compared to the curvature output obtained from the finite element models (FEM). Based on the performed analyses, an error bound is established that defines the minimum sensor spacing (sensor resolution) required to accurately estimate the curvature from the displacement data, as well as to detect, locate, and quantify structural damages using the estimated curvature values.

8692-102, Session 23

Health assessment of structures in presence of nonlinearity: novel approaches

Achintya Haldar, Abdullah Al-Hussein, Ajoy Kumar Das, The Univ. of Arizona (United States)

Two time-domain system identification (SI)-based structural health assessment (SHA) procedures using Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF) will be presented and compared. Structures will be represented by finite elements. Both methods assess structural health by tracking changes in the stiffness properties of the elements as they degrade. The unique properties of them are that they are capable of assessing structural health using only limited number of noise-contaminated acceleration time histories measured only at small part of a structure completely ignoring the information on excitation. Both methods can identify a structure in the presence of nonlinearity in the response information. However, the authors believe that there may be a limitation of level of nonlinearities EKF-based method can handle. If this threshold, unknown at this stage, is exceeded, then UKF-based method must be used. Both procedures need to be implemented in two stages. In the first stage, based on the response measurements, substructure(s) are identified. Using the information from the first stage, the whole structure is identified in the second stage. Although acceleration time histories will be measured, they need to be successively integrated to obtain the corresponding velocity and displacement time histories. Since acceleration time histories, even measured by smart sensors, are expected to be noise-contaminated, the generations of velocity and displacement time histories are not trivial. An Advanced Digital Integration Technique will be proposed for this purpose. The paper will summarized some of the related works completed by the research team at the University of Arizona.

8692-103, Session 23

Adaptive structural damage identification using residual error analysis

Qiang Yin, Nanjing Univ. of Science and Technology (China)

An objective of a structural health monitoring system is to identify the state of the structure and to detect the damage when it occurs. When a structural element is damaged, such as cracking, the stiffness of the damaged element is reduced. Hence it is important to develop data analysis techniques capable of detecting the parametric changes of structural elements during a severe event.

In this paper, a residual error analysis based online adaptive tracking technique is proposed to identify the changes of parametric values of the damaged element online. The presented technique is based on a newly proposed data analysis method referred to as the quadratic sum squares error (QSSE) combined by using a residual error analysis based online adaptive tracking technique which utilizes the statistic distributing of the outlier, i.e., the damage index, to track the structural damage online. The capability and accuracy of the proposed approach in tracking the variations of structural parameters due to the structural damages will be demonstrated by: (i) numerical simulations using both linear and nonlinear structures, and (ii) available experimental data obtained form experimental tests using a small-scale three-story building model. To simulate structural damage during the test, a stiffness element device is used to reduce the stiffness of some stories. Different damage scenarios have been simulated and tested. Both the simulation results and experimental data indicate that the proposed approach is capable of: (i) identifying structural parameters, (ii) tracking the changes of parameters leading to the detection of structural damages.

8692-104, Session 24

Evaluation method for a controller of active mass damper using central pattern generator

Junichi Hongu, Daisuke Iba, Morimasa Nakamura, Ichiro Moriwaki, Kyoto Institute of Technology (Japan)

This paper shows an evaluation method for a CPG controller designed for an active mass damper. Neural oscillators composing the CPG have nonlinear and entrainment properties. Therefore, the proposed controller has possibility to exhibit the characteristic of robustness, when the structural parameters, i.e. stiffness or damping, are changed by earthquakes and the like. Our earlier studies have proposed the new controller and ascertained the efficacy of vibration suppression. The designed controller has the CPG part and a PD controller part. The ideal desired phase relation between the structure and the AMD is clarified from the energetically viewpoint. The CPG part generates the phase relation by using the outputs from the structure and the AMD, and the AMD is positioned by the PD controller which uses the output from the CPG. However, there has been no study to evaluate the controller's above-mentioned properties. For tuning into practical application, the reliability and robustness along with the controller's performance must be analyzed. Last year, the phase reduction theory was tried to appraise the synchronization between the structure and the CPG and it gave us the synchronization region. But, because the CPG has a phase difference called a phase rocking "point" between the structure and the CPG during the synchronization, the information from the synchronization region providing the phase rocking "area" was insufficient to evaluate the systems. In this paper, focusing on the phase rocking "point" within the region to have the active mass damper's system dissipate energy of the structure.

8692-105, Session 24

Averaging sensors technique for active vibration control applications

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Fiber Bragg Gratings (FBG) sensors have a great potential in active vibration control of smart structures thanks to their small transversal size and the possibility to make an array of many sensors. They can be embedded in carbon fiber structures and their effect is nearly negligible.

The paper deals with the opportunity to reduce vibration in structures by using distributed sensors embedded in carbon fiber structures through the so called sensors-averaging technique.

This method provides a properly weighted average of the outputs of a distributed array of sensors generating spatial filters on a broad range of undesired resonance modes without adversely affecting phase and amplitude. This approach combines the positive sides of decentralized control techniques as the control forces applied to the system are independent of one another, while, as for the centralized controls it has the possibility to exploit the information from all the sensors.

The ability to easily manage this information allows to synthesize an efficient modal controller. Furthermore it enables to easily evaluate the stability of the control, the effects of spillover and the consequent effectiveness in reducing vibration. Theoretical aspects are supported by experimental applications on a large flexible system composed of a thin cantilever beam with 30 longitudinal FBG sensors and 6 piezoelectric actuators (PZT).

Control forces are designed to increase the damping of the structures, allowing to increase of damping of the first modes of vibration of about 10 times.

8692-106, Session 24

Low-frequency control strategy for seismic attenuation of inertial platforms and mechanical suspensions

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In this paper we present the results of a theoretical and experimental study aimed to demonstrate both the feasibility and the advantages of a large band low frequency control strategy based on the application of open loop monolithic folded pendula with optical readout as very low noise/ high sensitive sensors in the control of inertial platforms and multistage suspensions (seismic attenuators). In fact, the characteristics of compactness and robustness of this class of sensors, together with high sensitivity (< 10^-10 m/sqrt(Hz)), large measurement band (10^-7 - 100 Hz), resonance frequency tunability (70 mHz - 1 Hz, high sensitive integrated laser optical readout (e.g. optical lever, laser interferometer) and very good immunity to environmental noises make them very effective for the improvement of the performances of these devices.

The experimental results, obtained in the band 0.01 – 10 Hz, demonstrate both that open loop monolithic pendulum sensors are enough sensitive and have a sufficient dynamics to be very effective within the control system. Moreover, their full scalability allows an easy integration and positioning on the different stages of multistage mechanical suspensions (seismic attenuators) and inertial platforms.

These results demonstrate the feasibility of the proposed new control strategy in the low frequency region, that minimizes the use of control electronics, priviledging the use of optical and mechanical devices instead, and a reduced sensitivity to environmental noises.

Finally, other possible and direct applications are presented and discussed (platforms and mechanical structure control and stabilization, buildings controls, etc.) together with the planned further developments and improvements of this control strategy.

8692-107, Session 24

Effect of in-structure damping uncertainty on semi-active control performance: a modeling perspective

Arun Puthanpurayil, Paul Reynold, Donald S. Nyawako, The Univ. of Sheffield (United Kingdom)

System parameters in the mathematical model of a vibrating structure include mass, damping and stiffness; out of which mass and stiffness could be defined as a function of the system geometry, whereas damping involves more of an observed phenomenon. Despite having a large literature on the subject, the underlying physics is only known in a phenomenological ad-hoc manner, making damping an overall mystery

in the general dynamic analysis of structures. A major reason of this could be the fact that there is no single universally accepted model for damping. Common practice is to use the classical viscous damping model originated by Rayleigh, through his famous 'Rayleigh dissipation function',with a preconceived damping ratio, irrespective of the purpose or type of analysis involved.

In this paper an investigation is initiated into the effect of this uncertainty on the modeling and application of Magneto-Rheological (MR) dampers to control the human induced vibration in structures. Global classical viscous and non-viscous damping models along with enhanced elemental damping models (Spatial hysteresis and Time hysteresis) are studied. Finite element implementation of the damper incorporated structure is developed with damper specific hysteresis loops. Nonlinear time integration simulations are carried out using revised Newmark constant average acceleration method for a pre-conceived control law. Real time physical testing of the prototype is carried out and the responses are compared. The comparisons outline the effect of the choice of in-structure damping models on the realistic analytical predictions of the optimized performance of MR damper incorporated structure.

8692-108, Session 24

Vibration control of piezoelectric FGM plate using finite element method

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The advances in composite technology have lead to the increasing application of piezolaminated structure due to their sensing and actuating property also these structures have self-diagnostic and self-controlling capability. These structures can be able to control the shape, size, vibration and stability of the structural systems because of their direct and converse piezoelectric effects. Particularly the distributed piezoelectric sensor layer monitors the structural shape deformation due to the direct effect and the distributed actuator layer controls the deflection through the converse piezoelectric effect. Research on smart composite structures with integrated piezoelectric sensors and actuators have been investigated extensively. The laminated composite structures are faces major delamination problem because of abrupt change in material properties, extreme environmental conditions, weakness of interfaces of layers placed between two adjacent laminates of composite structures. Such problems are overcome by using the FGM's. Because functionally graded materials are the microscopically inhomogeneous composite materials which exhibit smooth and continuous change of material properties along the thickness direction.

This paper investigates the vibration control analysis of functionally graded (FG) plate integrated with piezoelectric actuator and sensor at top and bottom face. The material properties of the FG plates are assumed to be graded along the thickness direction according to simple power-law distribution in terms of the volume fraction of the constituents, while the poison's ratio is assumed to be constant. The plate is simply supported at all edges. The finite element model is based on higher order shear deformation theory and degenerated shell element. The displacement component of the present model is expanded in Taylor's series in terms of thickness co-ordinate. The Hamilton principle is used to derive the equation of the motion for the piezolaminated FGM plate. The vibration control analysis of simply supported piezoelectric FG plate is carried out to present the effect of power law index and gain values. The present analysis is carried out on newly introduced FGM material which is mixture of aluminum and stainless steel. Stainless steel is high strength material but it can rust in extreme cases and Aluminum doesn't rust but it is low strength material.This new FGM will definitely help to construction as well as metal industry.

8692-109, Session 25

A study of re-usable electromechanical impedance methods for structural health monitoring of concrete structures

Sam Na, Haeng-Ki Lee, KAIST (Korea, Republic of)

Up to date, various studies have been conducted using electro-mechanical impedance (EMI) method on concrete, including monitoring the strength development or to find damage in the structure. Since EMI method utilizes a single piezoelectric material to be used as an actuator and a sensor simultaneously, the method has major advantages compared to other non-destructive testing methods. However the method requires a piezoelectric material to be permanently attached or embedded into a structure. Thus when monitoring multiple structures, the method may become quite expensive. In this study, various re-usable EMI methods conducted by several researchers are overviewed. The idea of re-usable EMI method is still relatively new, resulting in the reduction of monitoring costs since the same piezoelectric material is used as many times as possible, while ensuring better repeatability and reliability in measurements.

8692-110, Session 25

Characterization of in-situ triboluminescent optical Fiber (ITOF) sensor for real-time damage monitoring in cementitious composites

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The in-situ triboluminescent optical fiber (ITOF) sensor is designed to mimic the sensory neurons of the human nervous system and to provide real time damage (crack) monitoring in engineering structures such as concrete bridges. The sensor has potential to provide wireless, in-situ, real time and distributed damage monitoring in aging and overloaded civil infrastructure systems. For enhanced sensor performance, 3 point bend tests were performed on the sensor to gain insights into its behavior under flexural loading. Our result shows that the Triboluminescent (TL) responses from the sensor increased with increase in the failure stress. The sensor also demonstrated capability to monitor hidden and internal cracks that that may not be perceived with conventional surface-mounted SHM systems. Dynamic mechanical analysis result indicates that the sensor has a strain limit that exceeds 0.6%. Consequently, the sensor coating can remain undamaged when a concrete structure cracks at a strain limit of about 0.015%. Raman spectroscopy indicates that the triboluminescent crystals retain their chemical properties and structure after fabrication. Triboluminescent multifunctional cementitious composite (TMCC) incorporating the ITOF sensor were fabricated and the damage sensing behavior also characterized under flexural loading. Field Emission Scanning Electron Microscope (FESEM), Energy Dispersive Spectroscopy (EDS), Dynamic Mechanical Analyzer (DMA) and Raman Spectroscopy were applied to characterize the smart structures.

8692-111, Session 25

Identification of impact force using embedded PZT sensors: experimental verification of identification accuracy

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This paper describes an experimental verification on the identification accuracy of impact force and impact position during ship-bridge collision making use of embedded PZT sensors. A 1:10 reinforced concrete model of bridge pier with a total of 22 embedded PZT sensors is fabricated for this study. The ship-collided-to-bridge impact force is simulated by dragging a hammer with adjustable weight and hanging height and swinging the hung hammer to strike the structure. Based on the measured impact force from a force sensor deployed at the head of the hammer and the measured voltage outputs of the PZT sensors embedded into the tested structure under various impact scenarios (different impact positions, impact amplitudes and attack angles), relationships between the impact force and the output voltage of embedded PZT sensors at different locations are established. Then a method for identifying the impact force and impact position is proposed based on the mean and variance analyses of the estimated impact forces using the established relationships. The identification of impact force and impact position is carried out by using the proposed method and experimental data, the identification accuracy is verified by comparing the identified impact force and the directly measured impact force by the force sensor. The experimental verification results show that the proposed method is competent to satisfactorily identify the impact force and impact position when an appropriate number of PZT sensors are embedded to provide voltage outputs.

8692-112, Session 25

Smart multifunctional cement mortar containing graphite nanoplatelet

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The piezoresistivity-based strain sensing ability of cementitious composites containing graphite nanoplatelet (GNP), which is a nanoscale carbon-based material, is being investigated. GNP offers the advantages of excellent mechanical and electrical properties at a very low cost. Cement mortar with 10, 15 and 20% of GNP (by mass of cement) were cyclically loaded in compression at 5 strain levels with an interval of 200 micro-strains between them. The electrical resistance of the specimens was measured by both the two-probe and four-probe methods using direct current during the cyclic loading. At the same strain level, the electrical resistance of specimens containing higher amount of GNP is lower due to the higher electrical conductivity of GNP compared to the constituents in the mortar matrix including water. The percolation threshold was found to be between 10 and 15% of GNP. At the same GNP content, the resistance decreased with increasing compressive strain amplitude due to the shortened distance and overlaying between conductive GNP. Two-probe method produced much higher gage factor due to the influence of contact resistance between electrode and cement mortar which contributes to a larger drop in resistance due to better contact under compression. Gage factor, an indication of the sensitivity of electrical resistance to its strain, increased with higher GNP content (up to 10 for mortar with 20% GNP with 4-probe method) but decreased with higher strain amplitude.

8692-113, Session 25

A scouring sensor by using the electrical properties of carbon nanotube-filled cement-based composite

Huigang Xiao, Guanjin Wang, Harbin Institute of Technology (China)

A cement based scouring sensor filled with CNTs is studied in this paper for monitoring the scouring state of the hydraulic structures. First, CNT filled cement-based composites were prepared by using the CNTs in the amount of 0.5%, 1%, 1.5%, 2% and 2.5% to the weight of cement. To investigate the electrical properties of the material filled with different amount of CNTs, the resistivity of the composite and the electrical conductivity mechanism were studied . The effect of the alignment of CNTs induced by external magnetic field (generated by a set of Helmholtz coils) during curing procedure on the electrical properties of the composite was then studied in this paper. The experimental results showed that the electrical properties of the composites became to anisotropic because of the alignment of CNT under magnetic field. Second, the effect of moisture on the electrical performance of the composite was studied. A increase of resistivity upon measuring time because of polarization was observed, and the polarization effect increased upon moisture. To eliminate the adverse effect of polarization on the resistivity measurement, a self-compensation method was proposed in this paper by using separated electrode. Finally, The quantitative relationship between the scouring depth and the resistance were established and tested under aridity and saturated condition. By comparison of the sensitivity of the composite with different scouring electrode arrangements, the stability of the reference electrode and system errors, the optimal scheme of the electrode arrangement was obtaiend.

8692-114, Session 26

Road condition evaluation using the vibration response of ordinary vehicles and synchronously recorded movies

Tomonori Nagayama, The Univ. of Tokyo (Japan); Yuuki Shimada, Univ. of Tokyo (Japan); Yozo Fujino, The Univ. of Tokyo (Japan)

Frequent and quantitative assessment of road condition is important as the maintenance of the road infrastructure needs to be performed with a limited budget. Vehicle Intelligent Monitoring System (VIMS) has been developed to estimate an index of road ride comfort (International Roughness Index; IRI) by obtaining the acceleration responses of ordinary vehicles together with GPS position data. VIMS converts the vertical acceleration of the measurement vehicle to acceleration RMS of the sprung mass of the standard Quarter Car model, and then to IRI using an approximate expression. By driving over a hump of a known profile and comparing the responses with Quarter Car simulation responses, a variety of vehicles can be calibrated. By driving a course with multiple driving speeds, the difference in driving speed can also be calibrated. Furthermore, by interpolating vehicle characteristics obtained at several driving speeds, VIMS has been extended to variable drive speed conditions. The measurement results can be exported to the google earth to comprehend road condition in a geographical view and to other data base systems. In addition, smartphones which can record motions, GPS data, and movies synchronously are utilized to further analyze the road surface condition. Road sections with large IRI values are extracted and corresponding smartphone data sets are analyzed. The movie file and 6-DOF motion records reveal the detail of rough road conditions.

8692-115, Session 26

Compressive sampling based approach for identification of moving loads distribution on cable-stayed bridges

Yuequan Bao, Hui Li, Fujian Zhang, Harbin Institute of Technology (China); Jinping Ou, Dalian Univ. of Technology (China) and Harbin Institute of Technology (China)

In the paper, a moving loads distribution identification method for cable-stayed bridges based on compressive sampling (CS) technique is proposed. CS is a technique for obtaining sparse signal representations to underdetermined linear measurement equations. In this paper, CS is employed to localize moving loads of cable-stayed bridges by limit cable force measurements. First, a vehicle-bridge model for cable-stayed bridges is presented. Then the relationship between the cable force and moving loads is constructed based on the influence lines. With the hypothesis of sparsity distribution of vehicles on bridge deck (which

is practical for long-span bridges), the moving loads are identified by minimizing the 'l2-norm of the difference between the observed and simulated cable forces caused by moving vehicles penalized by the 'l1-norm' of the moving load vector. The resultant minimization problem is convex and can be solved efficiently. A numerical example of a real cable-stayed bridge is carried out to verify the proposed method. The robustness and accuracy of the identification approach with limit cable force measurement for multi-vehicle spatial localization are validated.

8692-116, Session 26

Road profile estimation of city roads using DTPS

Qi Wang, Northeastern Univ. (United States); Gregory J. McDaniel, Boston Univ. (United States); Ming L. Wang, Northeastern Univ. (United States)

This work presents a non-destructive and non-contact acoustic sensing approach for measuring road profile/vertical road height with vehicles running at normal speed without stopping traffic. This approach uses an instantaneous dynamic tire pressure sensor (DTPS) that can measure dynamic response of the tire-road interaction and increases the efficiency of currently used road profile measuring systems with vehicle body-mounted profilers and axle-mounted accelerometers. A data analysis algorithm developed in our previous work was used to remove axle motion and to find the transfer function between dynamic tire pressure change and the road profile. Field tests in the city of Brockton, Massachusetts have been performed to compute road profile and test the real time road height algorithm. Numerical and experimental studies of the Brockton test show that road profiles can be computed with a vertical resolution of 0.01inch for most road features, and with a horizontal special resolution of 5 inches along the line of travel direction, which is only restricted by the contact length of the tire. Comparisons between road profiles and the Pavement Condition Index (PCI) for the city of Brockton have been investigated. The average road height found using this approach aligns closely with known PCI values and agree qualitatively with images taken by an onboard high speed camera for different road conditions.

8692-117, Session 26

Structural health monitoring of bridges in Kentucky

Issam E. Harik, Abheetha Peiris, Univ. of Kentucky (United States)

Structural Health Monitoring of a number of bridges in Kentucky has proven to be an economical and effective method for extending the life of bridges and for providing the tools for immediate response and decision making. Three bridges are highlighted in this paper. The first bridge is on I?65 in Louisville where instrumentation that continuously monitors the bridge, permitted the design of an economical retrofit. The second bridge is on I?64 over US 60 where instrumentation continuously monitors the bridge for possible impact on the girders resulting from over the height limit trucks. The third bridge is on US 41 North over the Ohio River where instrumentation has been placed on the bridge piers to monitor for barge impact. For the I?64 and US 41 bridges, and in the case of an incident, selected personnel are notified via text messages on their cell phones along with e?mail messages. The messages identify the type of incident and its severity, and list the web site where the incident can be viewed along with data from the instrumentation on the bridge. Decisions can be made in minutes in regard to the course of action.

8692-118, Session 26

Time-frequency methods for structural health monitoring of deepwater risers subjected to vortex-induced vibrations

Satish Nagarajaiah, Rice Univ. (United States); Srinivasan Gopalakrishnan, Indian Institute of Science (India); Chaojun Huang, Peng Sung, Rice Univ. (United States)

In this paper, a new approach, based on wave propagation and wavelet techniques, for monitoring the structural health of risers used for production in deep-water floating platforms, in depths in excess of 3000m, is presented. PZT patches are used as single transmitter and multi-receiver. Lamb waves are generated by the single transmitter, and received by multi-receivers along the wave propagation path along the riser/pipe longitudinal direction (with and without damage). Spectral analysis of the wave propagation test data using wavelets is performed; the results show that in the range different time-frequency characteristics are captured effectively by wavelet algorithms. The influences of multiple cracks in the riser/pipe on the wave propagation are studied. A damage detection method for riser/pipe is proposed and tested. The damage detection method developed provides information about the estimated crack location(s) and the possible extent of crack. Wavelet based signal analysis can be combined with existing localized damage detection techniques—such as magnetic flux leakage (MFL)—for enhanced study and detection of cracks/damage in deepwater risers.

8693-1, Session 1

A locally-exact strain-to-displacement approach for shape reconstruction of slender objects using fiber Bragg gratings *(Invited Paper)*

Michael D. Todd, Univ. of California, San Diego (United States); Christopher J. Stull, Los Alamos National Lab. (United States)

This paper presents a new approach for determining three-dimensional global displacement (for arbitrarily-sized deformation) of thin rod- or tether-like structures from a limited set of scalar strain measurements. The approach is rooted in Cosserat rod theory with a material-adapted reference frame and a localized linearization approach that facilitates an exact local basis function set for the displacement as well as the material frame. The solution set is shown to be robust to potential singularities from vanishing bending and twisting angle derivatives and from vanishing measured strain. Validation of the approach is performed through comparison with both finite element simulations and an experiment on a tube-like structure using limited fiber Bragg gratings. The average root mean square reconstruction error of 0.01%-1% of the total length, for reasonable sensor counts. Analysis of error due to extraneous noise sources and boundary condition uncertainty shows how error scales with those effects. The algorithm involves relatively simple operations, the most complex of which is square matrix inversion, lending itself to potential low-power embeddable solutions for applications requiring shape reconstruction.

8693-2, Session 1

Dynamic shape sensing using a fiber Bragg grating mesh

Douglas C. Bailey, Daniel T. Perry, Nikola Stan, Spencer Chadderdon, Stephen Schultz, Richard Selfridge, Brigham Young Univ. (United States)

Fiber Bragg gratings are capable of accurately determining the strain placed on an object. Imbedding a mesh of gratings into a substrate allows strain to be determined over a larger area. Using a high speed interrogator the incremental steps of the deformation are detectable. The high speed interrogator that is used can detect a 27.2 nm region at 100 kHz. The wavelength range can be increased by lowering the speed of interrogation.

Increasing the number of gratings in the mesh increases the resolution of the reconstruction but also causes the reflection peaks to overlap resulting in lost data. This possibility is minimized the closer together two peaks can be detected. Using an amplitude detection algorithm the peaks were identifiable when separated by 170 pm or more. When the amplitudes of the peaks are similar the peak detection algorithm is able to detect peaks as close as 20 pm apart. The ability to still determine where the individual peaks are after overlap allows more gratings to be used increasing the resolution of the mesh.

The strain data taken from the fiber Bragg grating mesh is then used to reconstruct the deformation of the substrate in the incremental steps at which it occurred. Using the cantilever equation the deflection between each set of gratings is determined and the deformation is tracked.

8693-3, Session 1

Filter-based interrogation unit for optical wavelength shift sensors

Thomas Härtling, Roland Wuchrer, Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren (Germany)

Optical sensors which detect parameters on the basis of wavelength shifts with high precision are promising candidates for applications in many fields of non-destructive evaluation. Examples for the latter range from structural health monitoring to biomedicine involving for instance fiber Bragg gratings (FBGs), surface plasmon resonance sensors, photonic crystals, or ring resonators. These types of sensors are small, robust, electrically passive, and integration into sensor systems can be achieved with reasonable effort. However, the applicability of these optical sensors is limited by the size and costs of the interrogation unit. Conventional interrogators such as grating spectrometers or interferometers can hardly be miniaturized without loss of spectral resolution. Hence, to provide the necessary spectral resolution in the pm regime they are bulky, demand special operation conditions such as air-conditioning or vibration-damped supports, and last but not least are expensive. Furthermore, they often need ambitious data processing techniques to resolve small wavelength shifts, which causes long integration time. The way around these problems is to use an optical filter with a spectral transmission gradient as the dispersive element. In this case and in contrast to a grating-based spectrometer, device dimensions and spectral resolution of the interrogator are decoupled. In the contribution we provide a brief overview over advantages and drawbacks of this sensor interrogation approach and present the development of an interrogator designed for the read-out of fiber Bragg gratings.

8693-4, Session 1

Plasmonic gradient structures of nanoparticle arrays for optical sensing applications

Susan Derenko, Roland Wuchrer, Christiane Schuster, Thomas Härtling, Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren (Germany)

Driven by a demand for integrated optical sensors in nondestructive evaluation and structural health monitoring, we present a method to enable the sensing of optical wavelength shifts. Therefore, nanoparticle arrays of gold are fabricated by interference lithography, which exhibit localized surface plasmons (LSPs). The plasmonic properties of such nanoparticles can be tuned by altering their size. In our approach, an additional photochemical growth by exposure to gold salt solution and light is used to manufacture gradients of nanoparticle sizes within the array. These gradients in turn induce different spectral responses depending on the illuminated region of the array gradient.

To enable sensing applications, such plasmonic gradient structures are placed as a filter in front of a photodetector to allow detection of transmitted optical signals from different locations of the array. The spatial shift of the maximum photocurrent generated in the detector determines the wavelength shift of the illuminating light, e.g. stemming from an optical sensor. The potential of this sensing scheme lies in the miniaturization of such spectral analyzers. Applications in SHM, e.g. in connection with fiber bragg gratings can therefore be envisioned, where the integration of such analyzers into sensor networks is desired.

8693-5, Session 2

A combination of novel thermographic and electrical techniques for low-velocity impact damage identification in multifunctional composites *(Invited Paper)*

Alkiviades S. Paipetis, Sotirios A. Grammatikos, Evangelos Z. Kordatos, Theodoros E. Matikas, Univ. of Ioannina (Greece)

Low-velocity impact damage is frequently encountered in aerostructures.

It is usually imposed during operation as well as its scheduled repair. An inexpensive and efficient damage inspection during the service life of these structures is essential for its safe function. A combined thermographic and electrical study is presented in this paper. Low velocity impact damage at different energy levels is applied on Carbon Fibre Reinforced Polymers (CFRPs). Pulsed phase thermography along with an electrical potential mapping technique was developed to pin-point the induced damage upon the employed materials. The results of both thermographic and electrical techniques were validated using C-scan.

8693-6, Session 2

Hybrid imaging of damage progress in composites through thermal imaging and embedded sensing

Sachin S. Pawar, Kara J. Peters, North Carolina State Univ. (United States)

In this paper, we investigate the fusion of imaging data obtained via pulsed phase thermography (PPT) with local temperature data obtained from embedded fiber Bragg grating (FBG) sensors for non-destructive evaluation of composite structures. In order to calibrate the FBG data to a known loading condition, we use the square pulse heating applied for the PPT imaging as the input thermal wave. Interpretation of the FBG response to the thermal load during both the heating and cooling transients are analyzed. In addition, the role of the local microstructure surrounding the FBG on the measured wavelength shift as a function of temperature is derived analytically. As this role changes with the progression of the composite damage condition at the location of the embedded FBG sensor, the local temperature cannot be obtained from only the peak wavelength shift. Fusing the FBG wavelength response with the PPT data at the corresponding pixel and depth is shown to provide a unique characterization of the local material condition. In addition, the FBG is shown to be more sensitive to damage in the early stages, whereas the PPT imaging can provide more information in the later phases of damage progression. Fusing the data from the two sources therefore provides a powerful technique for the detection and characterization of both damage initiation and damage progression in laminated composite structures.

8693-7, Session 2

Highly-localized thermal response measurements in composites using embedded fiber Bragg grating temperature sensors

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In this research, fiber Bragg grating (FBG) temperature sensors are embedded in composites in order to detect highly localized temperature gradients in the composite structures. The ultimate goal is to rapidly detect high energy electromagnetic radiation incident on the surface of a composite structure. A secondary goal is to use the sensors as a diagnostic tool to determine the optimal composite materials, architectures, or structures that are the least susceptible to high energy radiation damage.

Initial results will be discussed for a test matrix of various composite materials using a single sensor to measure temperature variations. The tests include measurements of the temporal and spatial response of the composite resulting either from an applied heat source or to high energy radiation incident on the surface. Additional tests demonstrate the response using a 3x2 array of sensors to simultaneously detect the response at varying depths in the composite, using three FBGs in line with the heat source, and three FBGs located a short distance (3cm) away from the heat source.

In addition, since FBGs respond to strain as well as to temperature, any strain in the composite is coupled into the embedded fiber and is also detected by the FBG sensors. Initial measurements demonstrate the simultaneous response of FBG sensors to both temperature and strain. The various components of strain that are observed in the composite will be discussed, and possible methods to isolate these components and mitigate their response will be considered.

8693-8, Session 2

Fabrication and thermal characteristics of metal-coated regenerated grating sensors for high-temperature sensing

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We have successfully fabricated regenerated gratings (RGs) with titanium-silver-nickel multiplayer coating in standard telecommunication fibers by magnetron sputtering and electroplating process. Optical testing shows that the optical properties of the metal coated RG are slightly affected by metallization process. We performed thermal tests to evaluate the characteristics with respect to the Ti-Ag-Ni coated RG sensor within the temperature of up to 600 oC. Results from experiments demonstrate that the titanium coating achieved good adhesion to fiber and that silver can be used as a conductive layer for electroplating process. The experimental results proved that the Ti-Ag-Ni coated RG sensor exhibited a satisfactory performance for its sensitivity, repeatability, and stability. In addition, compared with those of bare RGs, the temperature sensitivity of Ti-Ag-Ni coated RG sensors can be well enhanced by near two times with a value of 20.8 pm oC-1 below 250 oC and by more than two times with a value of 32.86 pm oC-1 up to 250-600 oC, compared to the bare RG. The theoretical results quite coincide with the experimental results below 250 oC. Whereas the disagreement above 250 oC between the theoretical and experimental results could be primarily attributed to the increment of the CTE and the reduction of the Young's modulus of the nickel above 250 oC, and the assumptions of fixed fiber core size and thermo-optic coefficient in the theoretical calculations. The metal coated RG sensors provide a potential possibility for temperature sensing or temperature compensation at high temperatures.

8693-9, Session 3

Improved distributed fiber optic sensing system based on single-ended double-pulse input Brillouin scattering

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Distributed fiber optics sensing system based on Brillouin backscattered light can measure temperature and strain simultaneously, which generally has two types in structure. One is Brillouin optical time domain reflectometry (BOTDR), and the other is Brillouin optical time domain analysis (BOTDA). The former is single-ended input which is convenient for applications, but its spatial resolution is limited and the signal is week. The latter is double-ended input, which has opposite characteristics.

For BOTDR, input light's pulsewidth is one of the restraining factors for spatial resolution. Brillouin backscattered light is usually too weak to be detected if input light's pulsewidth is very narrow (less than 10ns). Therefore, spatial resolution of BOTDR is low (more than 1 m), because its input light's pulsewidth cannot be less than 10 ns. Based on the principle of Brillouin scattered light generation, single-ended double-pulse input is used to strengthen Brillouin backscattered light by increasing the population of acoustic phonons, which can be called improved BODTR. The first pulse which can be called the pump pulse,

has a wide pulsewidth (tens or hundreds of us) and is used to generate a nonlinear population of acoustic phonons in the sensing fiber. Whereas the second pulse which can be called the probe pulse, has a different central wavelength and a much narrower pulsewidth (several ns), and is emitted into the sensing fiber with a controlled time delay to absorb the generated abundant acoustic phonons, so that strong Anti-Stokes light can be generated. By detecting the intense Anti-Stoke light, whose frequency is related to the frequency of the probe pulse, Brillouin backscattered light in BOTDR can be detected easily, leading to high signal to noise ratio and better spatial resolution (less than 1 m), as well as good temperature and strain resolution, and longer sensing distance.

8693-11, Session 3

Intelligent fiber-optic statistical mode sensors using novel features and artificial neural networks

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Fiber optic statistical mode sensors are based on different intensity distributions of the output that result from inter-modal interference between all guided modes in the fiber. Analysing the changes of the output pattern images, statistical mode sensors can be designed. In this work, novel statistical features were proposed for the design of statistical mode sensors. Experiments were conducted to measure force using statistical mode sensors but different features were extracted from the captured images and analyses were implemented using proposed statistical features. These new features were compared with the known statistical features in literature. Using the results, statistical features were compared in terms of different performance parameters such as linearity, precision, hysteresis and repeability. While certain features are better compared to the others in terms of certain performance parameters, they turn out to be worse compared to other aspects. Depending on the nature of the application, a statistical feature should be selected based on which performance parameter(s) are most important for the application. After that, Artificial Neural Networks (ANNs) with sensor fusion, intelligent sensor architecture was proposed to predict the force values measured by statistical mode sensors. It was seen that using the statistical features with sensor fusion provides better prediction of force values. Different ANN models were used in sensor fusion. Using sensor fusion with ANNs, statistical mode sensors can be calibrated and fault tolerance of the sensor can be decreased, hence more reliable and intelligent sensors can be designed.

8693-12, Session 4

The role of experimental validation in achieving reliable measurement data with applied FBG strain sensors *(Invited Paper)*

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Fibre optic strain sensors are increasingly used in very different technical fields. Sensors are provided with more or less comprehensive specifications and must sometimes be modified to meet measurement requirement. Even if the performance of sensor products is well specified, the strain characteristics of the sensor, the strain transfer factor, mechanical stability under thermal influences, the performance of applied strain sensors can seriously differ from the virgin sensor's performance. Sensor application can change the specific parameters of the sensing element, or at least influence the signal characteristics. The contribution will therefore focus on issues that can deteriorate the sensor function or reduce the reliability of measurement results (e. g. attachment and/or embedment procedures, materials combinations, aging processes due to environmental attacks).

In order to estimate the changes in the sensor characteristics or to proof the stability of the sensor function, experimental investigations and validation is needed. Important aspects how to come to reliable strain measurements and how to validate strain measurements of applied sensors are considered. Experimental procedures will be presented which reveal weaknesses in the sensor use. New methods for validation of integrated sensors will be discussed. Special focus is set on the optimization of the strain transfer zone of embedded fiber Bragg grating sensors. Test method and results will be presented.

8693-13, Session 4

A comparative analysis of FBG and low-coherence fiber-optic sensors for SHM of composite structures

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Composite materials, such as carbon fiber-reinforced plastic (CFRP), finding nowadays a broad application in different industrial fields. The most challenge area is aerospace industry due to specific environmental conditions, characterized by rather extensive span of thermal and mechanical load, under which an aircraft operates. Despite of high specific strength and toughness of composite materials, various on board occasions (bird-strike, hail-storm, cyclic loading) could induce some kind of material failure, e.g. cracks or delamination. Usage of fiber-optic Bragg gratings (FBG) for strain measurement is well-known technique in structural health monitoring (SHM). However, this technique based on shift of spectral peak, suffers from different spurious signals, particularly caused by thermal effect. Within this paper the authors will perform a comparative analysis of FBG and fiber-optic low-coherence interferometry based on experimental results of strain and deformation measurements of CFRP composite probe made of PEEK. Both sensors and thermocouple are firmly bonded onto PEEK probe simultaneously exposed to external stress by applying the three-point loading test according to ASTM D790. We used a sensing configuration where an Optical Spectrum Analyzer was interrogated with one FBG sensor with central wavelength at 1530,02nm and SLD light source at 1540nm. The interferometric configuration is basically of Michelson type, made of 3x3 singlemode fiber optic coupler. The interferometric 2π ambiguity is overcome using a low coherence light source at 1310nm. We tested the sensing technique exposing the sensing fiber tightly glued to the PEEK probe nearby the FBG, to an external force generated by a tensile test machine.

8693-14, Session 5

A chirped long-period grating sensor for monitoring flow direction and cure of a resin

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A chirped long period grating (CLPG) was used to perform both directional flow sensing and monitoring the extent of a chemical cure reaction of a UV-cured epoxy resin via the measurement of the change in refractive index of the resin during cure. The response of the CLPG in sensing liquid refractive indices lower and greater than that of the fibre cladding, 1.424 and 1.544 respectively, was demonstrated using known refractive index oils (Cargille oils). The former has an index close to the UV-cured epoxy resin used in the experiment and is normally applied to micro-moulding lenses for LCD projection and the latter is similar to the typical refractive indices of resin often used in composite material fabrication employed by the aerospace industry. The asymmetric nature of the CLPG led to the change in the shape of the attenuation bands of the transmission spectrum to be dependent on the direction of flow of the resin. The wavelength shift for the attenuation bands of the CLPG

and for a uniform period LPG were measured simultaneously during the resin cure. The largest measured wavelength shifts were comparable at 2.4 ± 0.1 nm and 2.8 ± 0.1 nm respectively. This implies sensitivity remains unaffected when a CLPG is used for cure monitoring. The change in the refractive index of the resin during cure was determined in the same experiment using a fibre optic Fresnel based refractometer, and correlated well (correlation coefficient greater than 85 %) with the wavelength shift profiles from the LPGs.

8693-15, Session 5

Multiplexed fibre-optic sensors for monitoring resin infusion, flow, and cure in composite material processing

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The infusion, flow and cure of RTM6 resin in carbon fibre reinforced preform have been monitored using a variety of multiplexed fibre optic sensors. The sensors were embedded in the middle and top of an 8-layer preform. The hot plate and vacuum bag process was employed for the infusion and cure. The resin and preform are typical materials used in the manufacture of aerospace components. The infusion of resin was performed with the hot plate at a temperature of 120oC, with the cure subsequently performed at an isotherm of 160oC for 2 hours. Fibre optic Fresnel sensors and tilted fibre Bragg grating (TFBG) sensors of relatively high tilt angle (3o) were configured to monitor resin infusion, flow and degree of cure via measurement of the refractive index of the resin. Temperature was measured using TFBG sensors of relatively small tilt angle (1.5o) and also using an embedded thermocouple. Fibre Bragg grating (FBG) sensors fabricated in highly linearly birefringent (HiBi) fibre were used to monitor the development of transverse strain during the cure process. The results obtained from the various sensors in monitoring the resin infusion and flow were comparable, and were in good agreement with visual observations. The cure data from the Fresnel sensors was converted to degree of cure using calibrations obtained from Differential Scanning Calorimetry (DSC) experiments. An alternative approach to infusion monitoring, based on an array of multiplexed tapered optical fibre sensors interrogated using optical frequency domain reflectometry, was also investigated in a separate carbon fibre preform.

8693-16, Session 5

Environmental barrier coating (EBC) durability modeling using a progressive failure analysis approach, part II

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The need for a protecting guard for the popular Ceramic Matrix Composites (CMCs) is getting

A lot of attention from most engine manufacturers and aerospace companies. This because the CMC has a weight advantages over standard metallic materials and more performance benefits. They are also commonly porous material and this feature is somewhat beneficial since it allows some desirable infiltration. They further undergo degradation that typically includes coating interface oxidation as opposed to moisture induced matrix which is generally seen at a higher temperature. Variety of factors such as residual stresses, coating process related flaws, casting conditions, may influence the strength of degradation. The cause of such defects which cause cracking and other damage is that not much energy is absorbed during fracture of these materials.

Therefore, an understanding of the issues that control crack deflection and propagation along interfaces is needed to maximize the energy dissipation capabilities of layered ceramics. These durability considerations are being addressed by introducing highly specialized form of environmental barrier coating (EBC) that is being developed and explored in particular for high temperature applications that is greater than 1100 °C [1, 3]. The EBCs are typically a multilayer of coatings and are in the order of hundreds of microns thick. Thus, evaluating components and subcomponents made out of CMCs under gas turbine engine conditions is suggested to demonstrate that these material will perform as expected and required under these aggressive environmental circumstances. Progressive failure analysis (PFA) is being performed to assess the crack growth of the coating under combined thermal and mechanical loading conditions. The PFA evaluation is carried out with the Genoa [4] software using a full-scale finite element model to account for the average material failure at the microscopic level. The roadmap for the analysis involves the following steps: (1) Reverse engineering of fiber and matrix properties from lamina properties, (2) Determination of residual stresses as a result of thermal cycling, (3) Assessment of degradation of material strength during cycling, and (4) Damage tracking and fracture using physics based failure criteria to determine life of the specimen under service load. Results related to crack growth; behavior and life assessment of the coating at the interface of the EBC/CMC will be presented and discussed.

8693-17, Session 5

Enzyme-linked monoclonal antibody microstructured optical fiber monitor

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A solid-core photonic crystal fiber (SC-PCF) with a microstructured all-silica steering wheel lattice containing a 3 μm diameter core is used to identify dye-free monoclonal antibodies (mAbs) of very small volumes <0.1uL for concentrations ranging from 0.1mg/mL to 【1x10】^(-12) mg/mL. The samples used in this study are mAbs, which are useful in detecting the presence of the botulism toxin. Human IgG antibodies (Southern Biotech Inc.) served as the “coating” antibody to detect an enzyme-linked mAb (Southern Biotech Inc.) - the “antigen”. The spectra for mAb samples linked with enzymes were compared to control samples without enzymes and conventional ELISA measurements.

The SC-PCF at lengths 1m and 0.5m were filled with ~ 0.008 μL of each sample was coupled with a broadband LED light source with emission peaks in the 1280-1700 nm range. Absorption characteristics associated with these mAbs were measured using a standard optical spectrum analyzer. Spectra were collected for control antibody samples, enzyme linked antibody and a third sample of a mixture of both antibodies. The measured spectra for the samples with varied concentrations were consistent with conventional ELISA measurements. Attenuation due to bend loss was also investigated. A compact, real-time sensor based on this dye-free technology has the potential to benefit water quality monitoring, drug manufacturing and food quality control.

8693-18, Session 6

Multi-element, high-temperature integrated ultrasonic transducers for structural health monitoring

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This paper reports recent developments on high-temperature, multi-element integrated ultrasonic transducers (IUTs). The multi-element IUTs are fabricated from a sol-gel route, where piezoelectric films are deposited, poled and machined into an array of 16 elements. Electrical wiring and insulation are also integrated into a practical, simple high-temperature assembly. These multi-element IUTs show a high potential for structural health monitoring at high temperatures (in the 200-500°C

range): they can withstand thermal cycling and shocks, they can be integrated to complex geometries, and they have broadband and suitable operating frequency characteristics with a minimal footprint (no backing needed). The specifics of multi-element transducers, including the phased array approach, for structural health monitoring are discussed.

8693-20, Session 6

Acoustic emission for fatigue damage monitoring in cross-welded aluminum plates

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Acoustic emission (AE) technique is commonly applied in different materials in order to evaluate their internal fracturing condition in real time. Apart from the number of acquired signals, which are correlated to the number of active cracking sources, qualitative features of the acoustic waveforms shed light in the dominant fracturing mode. This is due to the fact that the emitted waves depend on the relative motion of the crack sides at each incident. The fracture process of most engineering materials includes shift between modes and therefore, non invasive and real time characterization of the dominant mode supplies information on the current condition as well as poses an early warning before final failure. Although a lot of work has been done on acoustic emission characterization of fatigue damage, the work on welded components is scarse. In the present study aluminum plates are cross-welded and loaded until fracture in tension-tension fatigue experiments at different load levels. Their full acoustic activity is recorded by four sensors along with all mechanical parameters. It is shown that study of the acoustic emission rate relatively to the applied load, and qualitative waveform parameters like the frequency content and duration can be used to study the evolution of the crack under the different modes.

8693-21, Session 6

Monitoring of glass-ceramic composites under static and dynamic loading by combined NDE methods

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This work deals with the nondestructive evaluation (NDE) of the fracture behavior of ceramic matrix composite (CMCs) materials combining infrared (IR) thermographic and acoustic emission (AE) characterization. IR thermography as a non-destructive, real-time and non-contact technique, allows the detection of heat waves which are generated by the thermo-mechanical coupling and the intrinsic energy dissipated during mechanical cyclic loading of the sample. Three different thermographic methodologies, based on measuring the surface temperature, the sum of the principal stresses and the intrinsic dissipated energy respectively, were applied in order to monitor the crack initiation and propagation, the crack growth rate (Da/DN) and to assess rapidly the fatigue limit of cross-ply SiC/BMAS composites. The thermographic results on crack growth rate were found to be in agreement with measurements obtained by the conventional compliance method. Simultaneously, AE monitoring was taking place recording any type of cracking event from matrix cracking to fiber fracture and pull-out. AE event rate, as well as qualitative indices like the rise time and peak frequency reveal crucial information allowing the characterization of the severity of fracture in relation to the applied load. Additionally, rapid assessment of the fatigue limit of CMCs composites was also attempted by the AE. Testing a specimen at different load levels for predetermined blocks of cycles shows that the AE acquisition rate keeps low for loads below the fatigue limit, while it increases abruptly for higher levels. The thermographic assesment of fatigue limit is in total agreement with the AE results enabling the reliable evaluation of the fatigue limit of the material by testing just one specimen. The application of combined NDE techniques is proved very valuable for benchmarking purposes while the sensitivities of the methods act complementarily to each other providing a very detailed assessment of the damage status of the material in real time.

8693-22, Session 6

Large-area piezoceramic coating with IDT electrodes for ultrasonic sensing applications

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In the present work, the ultrasonic strain sensing performance of a large area piezoceramic coating with inter digitated (IDT) electrodes is studied. The piezoceramic coating is prepared using slurry coating technique and the piezoelectric phase has been achieved by poling under DC field. To study the guided wave induced strain sensing performance of the piezoceramic coating with IDT electrodes, the coating is deposited on the surface of a thin beam specimen as the substrate at one end and ultrasonic guided wave is launched with another piezoelectric wafer bonded on another end. Often a wide frequency band of operation is needed for the effective implementation of the sensors in context of Structural Health Monitoring (SHM) for various different types and sizes of damages and in several other applications. Such a wide frequency band of operation is achieved by varying the number of IDT electrodes. This alters the contribution of induced dynamic strain wave packet shape. Piezoelectric coefficient is estimated using an analytical model and experimental data. Strain magnitude of the launched guided wave is varied by the input voltage applied to the actuator of known characteristics. Its sensitivity is studied for various combinations with different numbers of IDT electrodes. Present investigation provides a methodology to use the piezoceramic coating in structural health monitoring application as an example that requires a wide frequency range of operation.

8693-23, Session 7

Optical strain measurements on a rotating disk

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The development of techniques for the health monitoring of the rotating components in gas turbine engines is of major interest to the NASA's Aviation Safety Program. As part of this on-going effort an experiment utilizing a novel optical Moiré based concept is being planned on a subscale turbine engine disk as a means of demonstrating a potential strain measurement and crack detection technique. Moiré patterns result from the overlap of two repetitive patterns with slightly different spacing. When this technique is applied to a rotating disk, it has the potential to allow the detection of very small changes in spacing and hence radial growth in a rotating disk due to a flaw such as a crack. This investigation is a continuation of previous efforts undertaken in 2011-2012 for the demonstration of this concept. The initial demonstration was attempted on a subscale turbine engine disk and was inconclusive due to the lack of radial growth experienced by the disk during operation. For this next phase of testing a new subscale turbine engine disk made out of Aluminum has been fabricated and improvements are being made to better demonstrate the concept. The experiment will involve laser etching a circular reference pattern onto the subscale engine disk and operating it at speeds up to 12 000 rpm as a means of optically monitoring the Moiré created by the shift in patterns created by the radial growth of the disk due to defects such as a crack. Testing will first be done on a clean defect free disk as a means of acquiring baseline reference data. A notch will then be machined on to the disk to simulate a crack and the testing will be repeated for the purposes of investigating the Moiré optical detection concept. Displacement data will be acquired using external blade tip clearance and shaft displacement sensors as a means of confirming the optical data and validating other sensor based crack detection techniques. In addition, a novel technique to measure strain using a cross-correlation imaging technique will also be attempted during this experiment. The results from this technique will be analyzed and compared to the data yielded from the Moiré experiment.

8693-24, Session 7

Turbine-engine rotor health monitoring and durability evaluation using spin tests data

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Safety and maintenance cost are among the major features that engine manufacturers strive for in their design approach to produce efficient and successful products. However, this design success is subject to manufacturing highly reliable rotating components that typically undergo high rotational loading conditions that subject them to various types of failure initiation mechanisms. To counter such design concerns; health monitoring of these components is becoming a necessity, yet, this 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 applications. Therefore, exploitation of suitable techniques to monitor the health of these rotating components is ongoing and its being invoked via other means such as nondestructive techniques to pre-detect hidden flaws and mini cracks before any catastrophic event occurs. These approaches or techniques extend more to assess materials' discontinuities and other defects that have matured to the level where a failure is likely.

This paper is pertained to presenting data collected from a spin experiment of a turbine like rotor disk tested at a range of rotational speeds up to 12000 rpm. It further includes an analytical modeling of the rotor vibration response that is characterized a combination of numerical and experimental data. The data include blade tip clearance, tip timing measurements and shaft displacements. The tests are conducted at the NASA Glenn Research Center's Rotordynamics Laboratory, a high precision spin rig. The results are evaluated and scrutinized 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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8693-25, Session 7

Optical method of measuring strain on a rotating disk using a cross-correlation imaging technique

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The NASA Aviation Safety Program has a high interest in the development of fault detection techniques for gas turbine engines in an effort to detect flaws in key engine components before failure. A cross-correlation imaging technique, which builds off of the principles of Background Oriented Schlieren (BOS)1-3, is investigated as a possible technique to optically measure a localized strain field resulting from an induced crack on a subscale turbine engine disk. As performed in previous crack detection studies4-7, a notch will be machined on to the disk to simulate a crack; the disk will be studied under static conditions at 0 rpm (unloaded condition) and at 12 000 rpm (loaded condition). Spinning the cracked disk at high speeds induces a load, resulting in a radial growth of the disk in the flawed region and hence, a localized strain field. Similar to BOS, two data images will be acquired: a reference image of the cracked disk will be acquired at the unloaded condition, while a secondary image will be acquired of the flawed disk at the loaded condition. When imaging the cracked disk under static conditions, it is thought that the disk will appear undistorted. However, during rotation the cracked region will grow radially, thus causing the high-contrast random background adhered to the disk to appear deflected. Due to the small amount of deflection during rotation, it will be necessary to work towards the development of an optimal background that will be sensitive enough to detect the fault of the subscale turbine engine. Therefore, different background, sizes, shapes, and densities will be investigated in an effort to reach the desired crack detection sensitivity. The corresponding image displacements between the two acquired disk images will be calculated using existing PIV cross-correlation algorithms, as is the case with BOS. It will also be attempted to map the observed deflection into a strain field, which will be compared to finite element analysis and external sensor data.

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8693-32, Session PTues

Axle weights identification with moving force identification theory

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When evaluating existing bridges, information based on the actual resistance and traffic load expected over the structure will result in more accurate and reliable evaluation of the safety of existing bridges. An innovative bridge weigh-in-motion (BWIM) technique can provide accurate traffic load effect. BWIM system uses instrumented bridge as a large sensor, and the transducers are mounted on the bottom flange of each girder to identify axle weight of heavy trucks, and the transducers mounted right under the slab are to acquire the silhouette of the passing vehicles, such as speed and axle space. This paper proposes an algorithm to identify axle weights of moving vehicles varying with time with the application of two-dimensional moving force identification (MFI) theory associated with dynamic programming method together with first-order Tikhonov regularization technique. An eigenvalue reduction technique is applied to reduce the dimension of the system. Minimization of least-squares of the difference between measured strains and theoretical ones are applied for the inverse problem. Hansen's L-Curve method is employed to optimally estimate the smoothing parameter and the first-order Tikhonov regularization technique is also applied to obtain smoother result. The dynamic programming method is then used to provide an efficient solution to the recursive least squares formulation. Field testing of the bridge on highway 78 in Alabama in the U.S. is applied to verify the proposed MFI algorithm by comparing the equivalently static measured axle loads with the predicted ones. The proposed MFI algorithm illustrates considerable potential to be the basis for a highly accurate BWIM system.

8693-33, Session PTues

Diagnostic on acceleration and information recovering using data fusion

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The acceleration information is significant for the structural health monitoring, which is the basic measurement to identify structural dynamic characteristics and structural vibration. The efficiency of the accelerometers is subsequently important for the structural health monitoring. In this paper, the distance measure matrix and the support level matrix are constructed first and the synthesized support level and the fusion method are given subsequently. Furthermore, the synthesized support level can be served as the determination for diagnostic on accelerometers, while the consistent data fusion method can be used to recover the acceleration information in frequency domain. The acceleration acquisition measurements from the accelerometers located on the real structure National Aquatics Center are used to be the basic simulation data here. By calculating two groups of accelerometers, the validation and stability of diagnostics and recovering on acceleration based on the data fusion are proofed in the paper.

8693-26, Session 8

Large field optical tomography system

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Optical measurement technologies become more and more import in many fields of nondestructive testing. One of these technologies is the optical coherence tomography (OCT). By now mostly used in medical applications, such as ophthalmology and dermatology, the relevance of OCT for testing non biological probes in manufacturing and research is increasing. In this paper we present an automated high speed swept source based OCT system with a scan rate of 100.000 A-scans per second. The advantage of high scan rates of such systems until know lead into high costs for appropriate light sources. Furthermore the big size of available sources makes system integration and miniaturization difficult. With a new kind of MEMS-based light sources, there are sources which combine small dimensions with a cost reduction of more than 50%. We combine the MEMS-based swept source OCT system with a table top robot. Thereby measurements of big samples become possible. The field of view of commercial systems is limited to few centimeters. Our system is capable of measuring up to 400mm in square. With inherent software the acquisition of A-Scans at any position in the working area and of any quantity is possible. Once calibrated for a probe, the system can perform an automated measurement. We compare the presented system with an equivalent Swept Source OCT system with a not MEMS-based source and show comparable sensitivity and signal quality. Therefore our OCT system can be used as a tool for testing scenarios in research, for failure analyses and for semi-automated production processes.

8693-27, Session 8

Polarization control in optical fibers and applications in optical microscopy and spectroscopy

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The nondestructive evaluation of an increasing number of novel nanoscale devices and nanostructured materials requires feasible and reliable methods for material characterization with high spatial resolution and a maximum of physical information. To achieve both at once, we combine Raman spectroscopy and transmission near-field optical microscopy. The light polarization in the fiber optical probe plays a major role for this task and needs to be carefully controlled. Specific polarization modes, e.g. radial polarization, can be excited by means of long period gratings (LPGs) and if index-tailored fibers are used, these modes can be transmitted without distortion to a fiber optic near-field probe [1]. The LPG can thus be used as a fiber polarization controller for complex polarization states.

This fiber polarization controller is implemented into our scanning near-field optical microscope (SNOM). The main advantage of using radially polarized light (as input for the SNOM probe) is that transmission through an apertureless probe becomes more efficient, since the electric field is perpendicular to the metal coating of the fiber tip and excites corresponding surface plasmon polaritons. With the resulting plasmon mode, the typical trade-off between resolution and signal strength, due to mode cutoff for small probe diameters, can be overcome [2]. The main advantages of this technique are 1) that these transmission probes provide a pure near-field illumination of the specimen without background signals and 2) the fabrication is significantly simplified compared to aperture probes.

[1] C. Zeh, et. al., Appl. Phys. Lett. 97, 103108 (2010).

[2] A. Bouhelier, et. al., Journal Microsc. 210, 220-4 (2003).

8693-28, Session 8

Time-resolved luminescence measurements on up-conversion phosphors for electron-beam sterilization monitoring

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We present our recent investigations on time-resolved measurements of alterations in the temporal luminescence decay of up-conversion phosphors induced by electron beam treatment. The latter is a promising alternative to low-temperature and dry sterilization of surfaces for sensitive packaging materials. Especially in the food and medical sector regulations concerning sterility are increasingly tightened. For this, a secure proof for electron-beam-assisted sterilization is required. However, no non-destructive and in situ method exists up to now.

Our approach to provide a secure proof of sterilization is to place a suitable marker material based on rare-earth-doped phosphors inside or on top of the packaging material of the respective product. Upon electron irradiation the marker material changes its luminescent properties as a function of applied energy dose. We verified the energy dependence by means of time-resolved measurements of the luminescent decay of different up-conversion materials.

In our experimental realization short laser pulses in the near-infrared range excite the marker material. The emitted light is spectrally resolved in a monochromator, collected via a silicon photodiode, and analyzed with an oscilloscope. As the main results we observe a reduction of luminescence lifetime due to electron beam treatment dependent on the emission wavelength. Hence, the electron beam induces changes in the particles' up- and down- conversion properties from which the applied energy dose can be derived.

8693-29, Session 9

Microstructured optical fiber monitor for cryogenic applications

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Monitoring intracellular ice formation (IIF) as well as understanding the cellular freezing process at temperatures nearly at -40°C is beneficial to the study of cryopreservation. This paper discusses the use of optical absorption spectroscopy to examine the thermal changes occurring in cells as they reach cryogenic temperatures.

The presented arrangement employs a 0.6 m all-silica steering-wheel photonic crystal fiber (SW-PCF) filled with 20uL of di-ionized water that is fusion spliced with a 1.07 m single mode fiber (SMF). The fluid filled SW-PCF is placed on a two-stage thermoelectric cooler (TEC). One end of the SW-PCF is coupled to an optical spectrum analyzer, while the SMF couples broadband LED light with emission peaks at 1350nm, 1450nm, 1550nm and 1650nm.

Unlike our previous cryogenic freezing arrangement, a water circulated cooling system consisting of a cold plate with an attached radiator promotes operation temperatures of nearly – 40 °C. Styrofoam insulates the fiber/TEC configuration to provide thermal stability and prevent undesired ice condensation on the thermal system. A resistance temperature detector (RTD) monitored the thermal changes occurring over a range of temperatures between 5°C to -38 °C in 5 degree increments. The measured the absorption spectra of the 20µL di-ionized water sample filled PCF show absorption characteristics consistent with standard spectra for water vapor at cryogenic temperatures.

8693-30, Session 9

Improvements in electric-field sensor sensitivity by exploiting a tangential field configuration

Spencer Chadderdon, Leeland Woodard, Daniel T. Perry, Stephen Schultz, Richard Selfridge, Brigham Young Univ. (United States)

Slab-coupled optical fiber sensors (SCOS) provide an effective alternative for electric field sensing applications requiring small, minimally intrusive electric-field sensors. One such application involves testing the effectiveness of electronic shielding as a means of safeguarding electronic systems from high powered microwave weapons. The sensors use resonant coupling of light between an optical fiber and nonlinear electro-optic (EO) slab waveguide. Traditional SCOS are comprised of a potassium titanyl phosphate (KTP) crystal mounted on a D-shaped optical fiber. The crystal slab is cut and oriented such that its optic axis is normal to the flat of the crystal (z-cut). The small size of the sensor allows it to be placed anywhere suitable for an optical fiber; however, it also lowers its sensitivity. This paper presents improvements to slab-coupled optical fiber sensors (SCOS) for electric-field sensing by exploiting a tangential boundary configuration. The sensitivity improvements are based on changing the crystal cut and orientation of KTP from z-cut to either x-cut or y-cut, with the crystal's optic axis oriented transverse to the flat of the D-fiber. The alternate slab cut and orientation result in improved electric field sensitivity due to (1) maximizing the effective EO coefficient of the KTP, which improves the EO response of the sensor, and (2) increasing electric field penetration into the slab by exploiting tangential boundary conditions. This paper provides a detailed comparison of the improved x-cut sensor showing an 8x improvement in sensitivity when compared to the z-cut sensor.

8693-31, Session 9

Multimode polymer optical fiber-based SMS structure for large-strain measurement

Jie Huang, Xinwei Lan, Hanzheng Wang, Lei Yuan, Hai Xiao, Missouri Univ. of Science and Technology (United States)

Fiber optic strain sensors have unique advantages such as high signal-to-noise ratio, light weight, small size, and are insensitive to ambient electromagnetic fields. A series of strain sensors based on optical fibers have been reported and some of them are commercially available. However, most of the optical fiber based strain sensors are made of fused silica, which may lead to a limited dynamic range of 4000 με (0.4%). This will limit their applications, especially in some highly loaded engineering structures, such as bridges, buildings, pipelines, dams, offshore platforms, etc. A fiber optic strain sensor with large dynamic range is highly demanded. Polymer optical fibers (POFs) as strain-sensing substrates have been attracting much more attentions.

Since the commercially available single mode POF currently holds a very high cost, multimode POF has been increasingly gaining attention. So far, most of the existing strain sensors based on multimode POFs are based on time-domain signal analysis or measuring the transmission loss. This paper discusses a novel type of strain sensor which uses multimode POF with the frequency-domain signal interrogation method that has relatively high resolution. The multimode POF was sandwiched between two silica based single mode fibers to form a single-mode-multimode-single-mode (SMS) structure. The SMS structure has been successfully applied in sensing application based on the multimode interference (MMI) theory. The strain sensing mechanism of the device was investigated and experimentally verified. A large dynamic range of 2x104 με (2%) and a detection limit of 33 με have been demonstrated.

Conference 8694: Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security VII

Sunday - Thursday 10–14 March 2013

Part of Proceedings of SPIE Vol. 8694 Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security 2013

8694-1, Session 1

The influence of multimode failures in composites on the characteristics of elastic waves

Lu Zhang, Harbin Institute of Technology (China); Didem Ozevin, Univ. of Illinois at Chicago (United States)

Based on the micromechanical approaches, high frequency elastic waves are generated in carbon fiber/polymer composites due to fiber breakage, matrix crack or delamination. The occurrence of damage mode depends on the ratios of energy release rates. Simultaneous generation of damage modes such as multiple fiber breakage called as fiber fragmentation influences the characteristics of propagating elastic waves which are used for detecting, locating and understanding damage modes for acoustic emission method. Understanding the wave characteristics via experimental methods is difficult as the control of damage mode sequence is a challenge. In this paper, wave propagations due to single or multiple fiber breakages positioned at various locations along the laminate and through thickness as well as matrix cracking on [0]4 composite lay-up are studied using dynamic finite element models. Fiber breakage is defined as a point load with the rise time of 1 usec. The load amplitude is identified using stress-strain curve of carbon fiber. The amplitude of matrix cracking is defined as crack opening displacement as a boundary load to the finite element model. The positions and amplitudes of damage modes are varied to understand the characteristics of waveform signatures. Each lamina is defined as a different plate and orthotropic material properties are entered as input to the model. The paper shows that multi-mode simultaneous damage in composites causes complex waveform generation, which makes pattern recognition based on amplitude and frequency real time a challenging task.

8694-2, Session 1

Stiffness matrix determination of composite materials using Lamb-wave group velocity measurements

Osvaldas Putkis, Anthony J. Croxford, Univ. of Bristol (United Kingdom)

The use of Lamb waves in Non-Destructive Evaluation (NDE) and Structural Health Monitoring (SHM) is gaining popularity due to their ability to travel long distances without significant attenuation, therefore offering large area inspections with a small number of sensors.
The design of Lamb wave based NDE/SHM system for composite materials is more complicated than metallic materials due to the directional dependence of Lamb wave propagation characteristics such as dispersion and group velocity. Propagation parameters can be theoretically predicted from known material properties, specifically the stiffness matrix and density. However, in practice it is hard to know the stiffness matrix of a particular material or structure with high accuracy, hence introducing errors in theoretical predictions and inaccuracies in the resulting propagation parameters. Measured Lamb wave phase velocities can be used to infer the stiffness matrix but the measurements are limited to the principal directions due to the steering effect (different propagation directions of phase and corresponding group velocities). This paper proposes the determination of the stiffness matrix from the measured group velocities as they can be unambiguously measured in any direction. A highly anisotropic CFRP composite plate is chosen for the study. The influence of different stiffness matrix elements on the directional group velocity profile is investigated. Thermodynamic Simulated Annealing (TSA) is used as a tool for an inverse and multi-variable inference of stiffness matrix. A relatively good estimation is achieved for various matrix elements. Multiple frequency measurements are proposed for elimination of non-unique matrix solutions at a single frequency.

8694-3, Session 1

Monitoring damage development around stress raisers in carbon/epoxy laminates

Letchuman Sripragash, Chantly D. Smith, Mannur J. Sundaresan, North Carolina A&T State Univ. (United States)

An experimental and numerical investigation was carried out for the feasibility of determining damage development in carbon/epoxy composite laminates with circular hole. The study involved flash thermography and Laser Vibrometry to map the region of damage in these specimens. First, thermographic response of implanted delaminations in composite laminates was examined using both numerical and experimental approaches. Next, damage development around a circular hole in a composite specimen was examined using thermography. The specimen was cyclically loaded until fracture to generate different levels of damage near the center of the specimen. Thermographic images of damage development at different fractions of fatigue life were recorded. Numerical models of thermal response of the region with evolving damage were also examined to assess the effectiveness of flash thermography under different conditions.

The interaction of stress waves with the damage region was examined using Laser Vibrometry. Narrow band gated sine waves were launched using piezoelectric patches bonded in the neighborhood of the damage sites and the stress waves propagating through this region were recorded using the Vibrometer. A range of frequencies from 100 kHz to 400 kHz was used in these experiments. The results from the two different approaches were compared.

8694-4, Session 1

Nondestructive and independent-of-fabrication-processes method to characterize residual stress within composite micromachined beams

Adrian A. Rendon-Hernandez, Sergio O. Martinez-Chapa, Sergio Camacho-León, Tecnológico de Monterrey (Mexico)

Residual stress can affect the performance of thin-film micromachined structures and lead to distortion in the frequency of resonant devices as well as an initial state of curling in cantilevers. As the origin of residual stress is dependent on the fabrication processes, a method for characterization of residual stress, being independent of processes conditions and nondestructive, is crucial to provide a rapid way to effectively design microcantilever-based microsystems.

In this paper we present an analytical model that characterizes the residual stress within composite microcantilever beams towards predicting its initial deflection profile. The model relies on the contribution of a linear gradient stress and the approach of a quadratic deflection profile due to residual stress within a composite microcantilever.

In addition to proposing an analytical model, this work presents a series of finite element simulations validated experimentally that provide valuable design insights on the state of residual stress within the microcantilevers.

A set of fifteen test structures is fabricated for residual stress characterization. The structures are basically microcantilever beams with different composition layers formed using a CMOS-MEMS fabrication process. These structures are formed with a unique composition layer for each one.

The model methodology comprises first, measuring the surface curvature profile of the structures by white-light interferometry, then, extracting its curvature component, later computing linear gradient stress by using a parametric analysis, and finally, analytical and experimental results are compared, exhibiting an accuracy between maximum displacement up to 3% error and a root-mean-square error between its curvature profiles up to 7%.

8694-5, Session 2

Theoretical and experimental study on estimation of chloride content in concrete using electromagnetic wave

Junichiro Nojima, Hiroki Ikeda, Toshiaki Mizobuchi, Hosei Univ. (Japan)

Reinforcement corrosion caused by the presence of chloride ions in the neighborhood of the re-bars has been identified as one of the major causes of deterioration of concrete structures. Especially, when cracks caused by reinforcement corrosion were generated in concrete surface, the reinforcement corrosion is accelerated. However, a definite understanding about any corrosion of reinforcement is very difficult unless corrosion induced cracks appear on the surface.

In order to detect chloride-induced corrosion at an early stage, chloride content within concrete needs to be investigated using cores drawn from the RC structure and carrying out chemical analysis. Drawing cores could be damage the reinforcement and evaluation at one point of drawing cores. In addition, evaluation of the chloride content in concrete by drawing cores could not make it possible to change the chloride content over time at exactly the same place.

Thus, development of truly non-destructive tests to estimate the chloride content in concrete could make it possible to detect the changes in chloride concentration over time at exactly the same place, without having to drawing cores from the RC structure, or causing any damage. Such method would greatly improve the ability to predict the possibility of reinforcement corrosion at early stages, and enable us to contract of repair work at an appropriate time.

In this report, in order to evaluate the applicability of non-destructive method which is possible to estimate the chloride content included in cover concrete, the results of theoretical and experimental attempts to estimate the chloride content in cover concrete of the RC structure using the electromagnetic waves are reported.

8694-6, Session 2

Early corrosion monitoring of prestressed concrete piles using acoustic emission

William Velez, Fabio Matta, Paul H. Ziehl, Univ. of South Carolina (United States)

The depassivation and corrosion of bonded prestressing steel strands in concrete bridge members may lead to major damage or collapse before visual inspections uncover evident signs of damage, and well before the end of the design life. Recognizing corrosion in its early stage is desirable to plan and prioritize remediation strategies.

The Acoustic Emission (AE) technique is a rational means to develop structural health monitoring and prognosis systems for the early detection and location of corrosion in concrete. Compelling features are the sensitivity to micro- and macro-damage related events, non intrusiveness, and suitability for remote and wireless applications. However, there is little understanding of the correlation between AE and the morphology and extent of early damage on the steel surface.

In this paper, the evidence collected from prestressed concrete (PC) specimens that are exposed to salt water is discussed vis-à-vis AE data from continuous monitoring. The specimens consist of PC strips that are subjected to wet/dry salt water cycles, which represent portions of bridge piles that are exposed to tidal action. Evidence collected from the specimens includes: (a) values of half-cell potential and linear polarization resistance to reliably recognize active corrosion in its early stage; and (b) scanning electron microscopy micrographs of steel areas from two specimens that were decommissioned once the electrochemical measurements indicated a high probability of active corrosion. These results are used study acoustic emission activity resulting from early corrosion.

8694-7, Session 2

Real-world application and validation of vehicle-mounted pavement inspection system

David M. Vines-Cavanaugh, Ming L. Wang, Northeastern Univ. (United States); J. Gregory McDaniel, Boston Univ. (United States); Chris Mickle, CDM (United States)

Cities use pavement management strategies to prioritize maintenance and repair needs. These strategies require a city-wide survey to determine a pavement condition value for every street. Surveys are typically done manually by inspection teams. They can be expensive and can take several months to complete. Additionally, since limited resources prevent inspection teams from being able to cover the entire area of every street, street condition values are often based on survey results from just a few representative sections. This non-continuous approach makes it difficult for researchers to use survey data as a tool for understanding pavement deterioration and improving design procedures. This paper considers a vehicle-mounted pavement inspection system that aims to be more affordable and faster than manual surveys, and has the ability to provide continuous results that can cover the full street area. The system is comprised of a vehicle outfitted with a multi-modal sensor array that includes accelerometers, microphones, radar, tire pressure, and video. In a first step, each channel is processed individually to extract parameters related to friction, roughness, and distress. The second step applies data fusion concepts to combine all sensor data into a single pavement condition value. This paper elaborates on this system and describes an application to real-world city streets. The primary contribution is a validation of the system by comparing results to those from a conventional manual survey.

8694-8, Session 2

Evaluating road surface conditions using tire generated noise

Yubo Zhao, Northeastern Univ. (United States); H. Felix. Wu, Univ. of North Texas (United States); J. Gregory McDaniel, Boston Univ. (United States); Ming L. Wang, Northeastern Univ. (United States)

Classifications of road conditions are crucial because officials prioritize road maintenance decisions based on them. Manual pavement condition index (PCI) surveys are used by many cities in the US to evaluate road surface conditions. In this paper, a more efficient method is used to detect road surface conditions. This method applies a probabilistic analysis to acoustic pressure data collected from a vehicle-mounted microphone. The data is collected during the driving and processed in real time. Acoustic pressure data contains the information of road surface conditions because acoustic pressures are different when the tire impacts different road surfaces. This change is audible in human ears, for example, when a driver transitions from a normal road to a bridge. The acoustic pressure data used in this paper was collected from roads with known PCI values that are used as a reference. To reveal the dominant common features and neglect trivial differences within a certain length of road, a probabilistic method is used to evaluate road surface conditions.

This approach uses the Weibull probability density function (pdf) to evaluate road surface conditions. This distribution is chosen because it is closest to actual pdf among other distributions like normal distribution and lognormal distribution. A key finding of this paper is that the Weibull pdf shows a dramatic change between roads with different PCI values. Another finding is that the Weibull pdf changes when the van hits road defects such as cracks and patches.

8694-9, Session 2

Enhanced polymer nanocomposites for condition assessment of wind turbine blades

Hussam S. Saleem, Mahendra Thunga, Iowa State Univ. (United States); Matthias Kollosche, Univ. Potsdam (Germany); Michael R. Kessler, Simon Laflamme, Iowa State Univ. (United States)

Damages in composite components of wind turbine blades and large-scale structures can lead to increase in maintenance and repair costs, inoperability, and structural failure. The vast majority of accepted condition assessment techniques are NDE-based, which cannot be used continuously and may be further impeded by the anisotropy of the composite materials, conductivity of the fibers, and the insulating properties of the matrix. In previous work, the authors have proposed a novel flexible and robust capacitive-based sensor for monitoring of large surfaces. This soft capacitor is fabricated using a highly sensitive elastomer sandwiched between electrodes and is sensitive to strain. Here we present an optimized nanocomposite mix for applications to structural health monitoring of wind turbine blades. Nanoparticles are used to enhance the mechanical and the electrical properties of the polymer using different fabrication processes. The resulting capacitor has enhanced robustness, sensitivity, and manufacturability. Preliminary results demonstrate that the sensor can be used for continuous real time condition assessment of large composite members.

8694-10, Session 2

Structural condition assessment of offshore wind turbine monopile foundations using vibration monitoring data

Hugo Gomez, Turel Gar, Dan Dolan, MMI Engineering (United States)

A monitoring system, consisting of two bidirectional accelerometers and an inclinometer, was installed on the towers of four existing offshore wind turbines. The objective of the monitoring campaign was to correlate identified structural natural frequencies with the structural performance of the turbine monopile foundations. An approach was developed that used operational modal analysis and system identification techniques using acceleration response data and the calibration of finite element models. Frequency levels were established as an indication of structural performance limit states including vibrating resonance of the tower with the turbine rotor, lack of foundation stability, and yielding of the monopile material.

8694-11, Session 2

Mechanical characterization of DCPD resins partially reinforced asphalt mix for pothole patching materials

Wei Yuan, Jenn-Ming Yang, Univ. of California, Los Angeles (United States)

We have applied dicyclopentadiene (DCPD) resin for reinforcing pothole patch materials due to its unique properties – low cost, low viscosity at beginning and ultra-toughness after curing, chemical compatibility with tar, tunable curing profile through catalyst design. In this paper, we have partially infiltrated DCPD resin into a hot and porous asphalt mix, and investigated the mechanical properties after this DCPD partial infiltration. The surface rutting resistance was tested with a wheel rutting tester. The strength reduction after 5 cycle of freeze-thaw and the DCPD cage effect to prevent the crack forming were characterized with a wheel penetration test. The results show that this partially infiltrated DCPD resin has greatly increased asphalt mix resistance to failures caused by wheel rutting, freeze-thaw, and increased wheel stress.

8694-12, Session 2

Road profile estimation of city roads using DTPS

Qi Wang, Northeastern Univ. (United States); J. Gregory McDaniel, Boston Univ. (United States); Ming L. Wang, Northeastern Univ. (United States)

This work presents a non-destructive and non-contact acoustic sensing approach for measuring road profile/vertical road height with vehicles running at normal speed without stopping traffic. This approach uses an instantaneous dynamic tire pressure sensor (DTPS) that can measure dynamic response of the tire-road interaction and increases the efficiency of currently used road profile measuring systems with vehicle body-mounted profilers and axle-mounted accelerometers. A data analysis algorithm developed in our previous work was used to remove axle motion and to find the transfer function between dynamic tire pressure change and the road profile. Field tests in the city of Brockton, Massachusetts have been performed to compute road profile and test the real time road height algorithm. Numerical and experimental studies of the Brockton test show that road profiles can be computed with a vertical resolution of 0.01inch for most road features, and with a horizontal spatial resolution of 5 inches along the line of travel direction, which is only restricted by the contact length of the tire. Comparisons between road profiles and the Pavement Condition Index (PCI) for the city of Brockton have been investigated. The average road height found using this approach aligns closely with known PCI values and agree qualitatively with images taken by an onboard high speed camera for different road conditions.

8694-13, Session 2

Measurement of elastic constants of rail steel at elevated temperatures using ultrasound, sonic resonance, and laser detection methods

Haifeng Zhang, Mehdi Ahmadi , H. Felix Wu, Univ. of North Texas (United States)

An understanding of the mechanical properties of rail steel at elevated temperatures is critical for the modeling of thermally induced stress, considered to be the main factor that causes buckling of rails in railroad track. In this article, we report the measurement of elastic and shear moduli for rail steel at elevated temperatures up to 350 °C using three different methods: ultrasound pulse-echo, sonic resonance, and laser detection. A comparison is made for the results obtained through these three methods, and a good agreement is achieved. It was found that both elastic modulus and shear modulus decreased as the temperature increased. The measured data will provide an important reference for designing railroad track resistant to buckling.

8694-14, Session 2

Advanced inspection methods for the testing of solid and hollow railway axles

Dimosthenis Liaptsis, Dawei Yan, Stavros Avramidis, TWI Ltd. (United Kingdom)

Monitoring the structural integrity of train axles is one of the most important factors for safety precautions in rail industry. For the minimization of risk of the danger of failures of the wheelsets, a number of inspections have to be carried out during the service life of train axles. Most common techniques used nowadays in the railway industry for manual inspection are visual and magnetic particle techniques as well as ultrasonic testing. However they mostly require removal of the wheelset from the wagon bogie and the full disassembly of the wheelset in order to facilitate access. This paper will present two inspection scenarios that are under development: (1) inspection of solid railway axles from the end face using phased array ultrasonic testing techniques and (2) Inspection of hollow railway axles from inside the bore using electromagnetic techniques.

For the phased array technique development, the modeling activities that have been carried out to design an innovative phased array transducer that allow the inspection of solid axles with different end face diameters and end face configurations will be presented. Furthermore, the experimental results obtained using the new transducer design from solid axle samples with representative defects will be shown.

Furthermore, an electromagnetic method and system for the inspection of the hollow axles is presented and discussed. Several configurations of the system are applied and selected results of the preliminary experiments and modeling activities will be presented. The performance of the system is verified using samples made of real hollow axle having artificial notches of different depth.

8694-15, Session 3

Finite element simulation of GPR surveys of concrete bridge decks

Nenad Gucunski, Rutgers, The State Univ. of New Jersey (United States)

Ground Penetrating Radar (GPR) is commonly used in the condition assessment of bridge decks. Parameters that significantly influence GPR results include: the concrete's dielectric constant and electrical conductivity, reinforcement depth, and antenna height. Developing a better understanding of how variations of these parameters influence the GPR results is imperative to effectively interpret GPR data to assess the deck condition beyond the top rebar level. To gain a better understanding of these important electromagnetic and geometric parameters, a three dimensional finite element (FE) model of a reinforced concrete slab was developed. Three scenarios were considered in modeling the concrete slab: homogenous concrete with typical dielectric and conductivity values, homogenous concrete with higher dielectric and conductivity representing the presence of moisture and chloride ions, heterogeneous concrete consisted of the aforementioned types of concrete. In each of these three scenarios, the antenna height and the rebar depth were varied to understand their effect on the results. The resulting A- and B-scans along with the electric field contour maps are presented. The GPR antenna simulated in the FE model was primarily a single bow-tie antenna of a 2.6 GHz center frequency. However, the performance of antennas of other frequencies was examined. ANSYS HFSS (Ansoft) was used for numerical modeling.

8694-16, Session 3

Microwave tomographic imaging of concrete columns

Tomasz M. Grzegorczyk, Delpsi, LLC (United States); Paul M. Meaney, Dartmouth College (United States)

Microwave technology applied to imaging problems presents two non-trivial challenges. First, the data need to be sufficiently diverse -- typically from all around the target -- to allow for a large information content, putting constraints on hardware data acquisition systems. Second, the interpretation software, which turns microwave data into electric permittivity and conductivity maps, needs to solve an inverse problem while avoiding local minima and long computational times. As a result of these challenges, microwave imaging of concrete structures has been mostly limited so far to the detection of reinforced metallic bars whose properties contrast with the surrounding cement-base background are sufficiently large to simplify the mathematical problem. In this work, however, we are interested in imaging lower contrast material properties, such as that between a crack and the surrounding cement, or that between different constituent materials such as cement and mortar cement. The solution we propose is based on our past work on biomedical microwave imaging for breast cancer detection, and is shown to properly detect and locate rebars within a column as well as a dielectric inclusion otherwise invisible from surface inspection, and to properly differentiate two concrete columns of different material properties. The method does not present unrealistic assumptions, works in both 2D and 3D, and can deal with inhomogeneous structures where inhomogeneity dimensions are on the centimeter scale.

8694-17, Session 3

Wideband subsurface radar for bridge structural health monitoring and nondestructive evaluation

Che-Fu Su, Tzu-Yang Yu, Univ. of Massachusetts Lowell (United States); Yu-Jiun Ren, Chieh-ping Lai, LR Tech (United States); H. Felix Wu, Univ. of North Texas (United States)

In the past two decades, the nondestructive evaluation (NDE) inspection for building and bridge structures has attracted a lot of attentions for the fundamental research and the sensor system development. The most popular NDE techniques are including ground penetrating radar (GPR), acoustic sensors, radiography, and some experimental types of sensors. The radar technology like GPR has been widely used for bridge structure inspection using microwave sensing. However, the technique has to consider the tradeoff between a high range resolution and a deep penetrating depth. If you want to have a better down-range resolution, you will need a wider microwave bandwidth which is easier to achieve to have an antenna designed for a higher frequency range. Unfortunately the path loss is increasing with the radar frequency and it limits the penetrating depth. If we increase the transmit power, the coupling from the transmitter and reflections from the clutter may degrade the receiver sensitivity.

In this paper, we will be focus on the structure subsurface detection and the radar operating frequency has been determined by the link budget calculation and also the 3-D Electromagnetic simulation. The operating frequency of the radar system is from 1 GHz to 18 GHz and it is designed for the standoff detection which is different from the GPR has to be close to the ground. It is a 2-D scanning system that can work along x axis and z axis. The radar antenna has a high gain across a very wide bandwidth from 1 GHz to 18 GHz. The radar antenna is connected to Agilent 8722ET network analyzer for the conventional S21 measurement then compared to the results of using a FMCW radar transceiver. From the theoretical analysis and the initial experimental results, it is proved that the proposed subsurface radar system can effectively detect the crack location and identify the decaying area near the subsurface of the target structure. The results and findings are discussed in this paper.

8694-18, Session 3

A two dimensional entropy and short time Fourier Transform application on ground penetrating radar data analysis

Panglijen Candra, Dryver R. Huston, Tian Xia, The Univ. of Vermont (United States)

In order to maintain safety of transportation structures such as bridge rebar supports, railroad track, building foundation, a non-destructive inspection method is needed. As an effective non-destructive evaluation technology, Ground penetrating radar (GPR) system has been actively studied and commercially employed for this purpose in the last decade. GPR system utilizes electromagnetic radiation by transmitting microwave signals into the subsurface structure and detects and characterizes the reflected signal. The reflected signal varies in amplitude and time delay depending on the subsurface material's dielectric constant and the burying depth.

Detecting the sporadically located features such as the rebar under concrete surface is one of the basic functions needed for GPR in bridge deck or roadway inspections. Since the dielectric constants of concrete (ε = 4~7) and rebar are distinctively different, one can plot image of the rebar reflection signal accordingly. Most GPR data analysis methods focus on applying the signal processing method to the entire scanning data even though rebar data populates only a small portion of the whole scanning data set. While these methods are meticulous, they can consume significant time and computational resources. Moreover, they require intensive human interventions to estimate and identify features of interests. These methods are slow and their data interpretation process is very subjective, and is heavily depent on the operator's experience. To leverage GPR data processing efficiency, and to automate feature extractions and characterizations, this paper proposes the use of 2D entropy algorithm on GPR data to automatically detect data sections that contain unique features such as rebar image. Entropy algorithm has the capability to rapidly identify similarities and unique portions from a big data set. In contrast to paper [1] where the authors automate only cylindrical images detection through arc detector and estimation, entropy can be used to detect any shape of distinctive features within a common background. For example the entropy method has been demonstrated in to remove artifact from multiple antennae arrays. In this paper, entropy processing on 2D GPR data will be applied to remove stationary background signal and noise in rebar scanning data, and to make the rebar areas pronounced. Thus the area of interest can be quickly identified, and the data size for post-processing will be significantly reduced. Subsequently we will utilize Short Time Fourier Transform (STFT) algorithm to characterize the interested rebar features on the data highlighted by the entropy processing. STFT has been demonstrated to gain frequency and time information to extract the unique characteristics of underlying materials. By automating GPR data analysis through both entropy and STFT algorithm, one can reduce computation cost and human intervention significantly. Even though this paper uses rebar as the study case, the combination of entropy and STFT analysis method can be applied to improve analysis efficiency of searching and characterizing other unique signal features within a large common background.

8694-19, Session 3

Digital Control and Data Acquisition for High Performance Ground Penetrating Radars

Dryver R. Huston, Tian Xia, Anbu Venkatachalam, The Univ. of Vermont (United States); Xianlei Xu, The Univ. of Vermont (United States) and China Univ. of Mining and Technology (China)

This paper will discuss the incorporation of digital techniques to improve and better control the performance of ground penetrating radars (GPRs). The primary motivation is to develop GPRs for the subsurface inspection of reinforced concrete structures, such as bridge decks. To date the migration of digital technology into radar systems has been relatively modest. This lack of activity is primarily due to the high frequencies and data rates involved, along with the reasonable viability of analog techniques. Nonetheless, digital techniques on the control side offer advantages in terms of flexibility, quick changing, and even cognitive control. On the data acquisition side, full wave form digital techniques allow for the elimination of slower and radiated-power inefficient sub-sampling methods. This paper will describe and present results from a series of developments that include FPGA control of source signals, pulse rates and frequency bands; and full waveform digitization of the received signals. Designs and performance test results will be presented for a real time switchable dual-band ultrawideband GPR that operates at pulse repetition frequencies up to 40 kHz with full waveform digitization of the return signals at 8GBs with 10-bit dynamic range. Technical issues including the design of dual-band pulsers and antennas that operate in the 0-1 GHz and 3-4 GHz bands will be presented. The high-speed data pipeline following digitization along with along with the use of limited duty cycle buffering will also be presented. The system presently works in the laboratory on reinforced concrete slabs, but is designed with performance specifications' for highway speed multichannel full lane width measurement while remaining compliant with FCC 02-48 radiated emission regulations. The future directions including the possibility of cognitive adaptive control will be presented.

8694-20, Session 3

A novel clutter reduction approach for GPR data from concrete structures

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Ground penetrating radar (GPR) is recognized as one of the promising nondestructive evaluation methods for detecting internal anomalies of concrete bridge decks. In practice, GPR antenna must be elevated above the ground. This requirement results in heavy surface clutter, which is one of the most important problems in the GPR application. The performance of the GPR in detection can be heavily limited by clutters. A commonly used procedure of time gating and background average subtraction is not suitable for applications with shallow rebar reflections beneath a rough concrete surface.

In this paper, a signal processing technique based on matching pursuit is developed to reduce clutter due to undulated ground bounce, surface roughness scattering, external anomaly reflections and imperfect antenna caused crosstalk in GPR measurements. The algorithm is implemented as a nonlinear signal processor, which builds a concise atom library for the presence of a reference clutter waveform in a 1-D GPR return. The atom library is then applied to all signals in a 2-D or 3-D GPR radargram for clutter suppression in an automated fashion. The concise atom library also enables time-efficient search of the matching pursuit method. The effectiveness of the proposed approach has been demonstrated with a synthetic model developed under GPR simulation software GprMax 2.0 and a concrete bridge deck fabricated at the University of Texas at El Paso.

8694-21, Session 4

Monitoring of out-of-autoclave BMI composites using fiber-optic sensors

Sudharshan Anandan, Sriram Nagarajan, Amardeep Kaur, K. Chandrashekhara, Hai Xiao, Missouri Univ. of Science and Technology (United States); Nam Phan, Naval Air Systems Command (United States)

Bismaleimide (BMI) composites are used in applications that require good mechanical properties at high temperatures. In this paper, we present a Non-destructive inspection technique for BMI composites which can be used at high temperatures. Hybrid fiber optic sensors comprising of cavity based External Fabry-Perot Interferometer (EFPI) and long-period fiber grating (LPFG) have been developed and embedded in the laminates. These sensors are capable of operating in temperatures up

to 400°C. The embedded sensors are used to perform real time cure monitoring of a BMI composite. The composite is cured using an out-of-autoclave (OOA) process. The OOA process does not require the positive pressure of an autoclave but still produces high quality composite parts at atmospheric pressure. Once the composite is cured, the same sensors are used to measure mechanical performance of the laminate. The performance of the embedded sensor is investigated under tensile and flexural loadings at room temperature as well as elevated temperatures.

8694-22, Session 4

High-dynamic range, high-sensitivity FBG interrogation

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We present a Fiber Bragg grating interrogation method with high strain sensitivity over a wide range of strain values . This interrogation method is optimized for detecting weak high frequency (30kHz) waves where strong low frequency (100Hz) vibrations are also present in the system, in particular for “in situ” structural health monitoring of windmill blades exposed to strong winds using Fiber Bragg Grating sensors for detection of ultrasonic acoustic waves. Operation of the interrogator is based on the edge detection method and it uses a tunable light source with a control feedback loop to tune the interrogation wavelength in real time to the point on the FBG spectrum with the highest strain sensitivity. The control feedback loop captures all information about the low frequency vibrations and eliminates its detrimental effect on the strain sensitivity while it stays insensitive to high frequency vibrations which are picked up by the Fiber Bragg Grating sensor as the useful signal. Two implementation approaches are described, a mostly digital approach using a microcontroller chip and a DA converter, and an all analog approach using operational amplifier circuits in stages. Advantages and disadvantages of both implementation approaches are discussed. The effect of increasing dynamic range while still keeping high strain sensitivity by using the feedback control loop is demonstrated in both analog and digital implementation.

8694-23, Session 4

Fiber optics monitoring of a scarc specimen with crack location prediction

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Ash carbon concrete (ACC) is a new conception developed to simultaneously reduce waste from coal-fired energy production, namely fly ash and carbon dioxide (CO_2). ACC is composed of varying combinations of cement, fly-ash, aluminum powder, and water, which exert pressure due to material expansion. The resulting ACC is a hardened porous material that traps CO_2 in its formation and can be applied in mine void backfilling, ash pond stabilization, and material reuse. To understand the behaviors of the material during the backfill process, the Simulated Carbon Ash Retention Cylinder (SCARC) model was designed, to mimic the material expansion and stressing of rock materials. To monitor the stressing of SCARC, due to in-tube ACC material expansion, fiber brag grating (FBG) sensing equipment was suggested. Fiber optic sensors were utilized because of their accuracy and resistance to imprecision from corrosive/hydraulic material interaction. The fiber optic sensors were implemented in a distributed array to gather hoop strain data about the outer circumference of the. In this fashion, the FBG strain values generated the potential for global crack prediction, and monitoring, on enhanced-scale fiber optic applications on SCARC projects, and specimens with similar geophysical boundary constraints. Experimental results indicated that the FBG sensors accurately predicted the fracture locations, when the recorded values exceeded the rupture properties of the cement cylinder. This is illustrated in the paper by an analysis of strain data-interrogation plots from affected FBG sensors.

8694-24, Session 4

Nondestructive characterization for PDMS thin films using a miniature fiber optic photoacoustic probe

Xiaotian Zou, Nan Wu, Ye Tian, Xingwei Wang, Univ. of Massachusetts Lowell (United States)

This paper presents a nondestructive ultrasound test method for characterizing mechanical properties of polydimethylsiloxane (PDMS) thin films by using a miniature fiber optic photoacoustic (PA) probe. The PA probe was fabricated with an optical fiber and the synthesized gold nanocomposite. Both static and dynamic membrane vibration model was developed. During the experiment, a PDMS film with thickness of 25 μm was cured and immersed into water media within a designed holder to clamp the film. An acoustic pulse was generated from the PA probe, propagated in the water media and excited the clamped film. A fiber optic pressure sensor based on Fabry-Perot (FP) principle was applied to collect excited acoustic signals on the other side of the PDMS film. The sensed response of the acoustic pulse was used to compute the mechanical properties of the PDMS thin film based on both static and dynamic membrane modeling.

8694-25, Session 4

Fiber optic photoacoustic ultrasound generator based on gold nanocomposite

Nan Wu, Ye Tian, Xiaotian Zou, Xingwei Wang, Univ. of Massachusetts Lowell (United States)

Recently, many advanced ultrasound applications require wide bandwidth and compact ultrasound generators to achieve better resolution as well as the capability of being operated in a compact space. Generating ultrasound signals through photoacoustic principle is a promising way to generate wide bandwidth ultrasound signals by the optical approach. Meanwhile, optical fibers are ideal candidates for applications where compact size is required. Therefore, fiber optic photoacoustic generators, which put advantages of the photoacoustic principle and optical fibers together, lead to novel ultrasound generation devices which can meet the most advanced ultrasound applications requirements. This paper firstly reports using the gold nanocomposite to achieve the fiber optic photoacoustic ultrasound generator. The gold nanocomposite was synthesized by directly mixing the gold salt in polydimethylsiloxane. The gold nanocomposite showed high optical energy absorption capability and the high coefficient of thermal expansion. The photoacoustic generation efficiency was increased by applying such material. The synthesis protocol of the gold nanocomposite was presented in this paper. The optical fiber was coated with the gold nanocomposite to generate ultrasound signals. Experimental results have demonstrated that ultrasound signals can be generated by this approach and the fiber optic ultrasound generator can be used in ultrasound applications.

8694-26, Session 5

Performance evaluation of a combined neutron and X-ray digital imaging system

Vaibhav Sinha, Anjali Srivastava, Hyoung Koo Lee, Xin Liu, Missouri Univ. of Science and Technology (United States)

A superior method for non-destructive evaluation has been developed using a neutron/X-ray combined computed tomography system (NXCT)

at the Missouri University of Science & Technology. The NXCT system is housed within the Missouri S&T Reactor building at Missouri S&T, and is the first such imaging platform and synthesis method to be developed. The system receives neutrons directly from the reactor core, and X-rays from a nearby x-ray source. This novel imaging system holds great promise for non-destructive material detection and analysis. Characterization of the newly developed digital imaging system is imperative to the performance evaluation, as well as for describing the associated parameters. The NXCT system will be evaluated in terms of image uniformity, linearity and spatial resolution. Additionally, the correlation between the applied beam intensity, resulting image quality, and system sensitivity will be investigated. This will be the first time that a combined neutron/X-ray digital imaging system will be evaluated in terms of DQE, NPS and MTF and results will be detailed. Finally, the addition of gamma and fast neutron filters, along with a newly developed collimator for improved beam diagnostics will be detailed in terms of the resulting system performance.

Summary

This is the first time that a combined neutron and X-ray imaging system will be evaluated in terms of Modulation Transfer Function (MTF), Noise Power Spectrum (NPS) and Detective Quantum Efficiency (DQE). The above mentioned image quality parameters are not a common image quality evaluation parameters in the neutron imaging industry. This new approach will establish a new perspective and will also help to standardize the digital neutron imaging quality parameters. This will also be the first time to demonstrate a new type of image quality tool is developed for image performance measurement during the neutron imaging operation and compared with the similar fashion standardized tool of an X-ray imaging performance measurement. The optimization of fast neutrons and gamma filters is crucial for neutron image quality and has been shown in this paper by comparing set of images with and without filters. This paper will be useful in terms of comparison between image quality standards of X-ray and neutron imaging especially about digital imaging.

8694-27, Session 5

Analysis of air voids distribution in concrete specimen using x-ray computed tomography

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Portland Cement Concrete (PCC) and concrete containing Reclaimed Asphalt Pavement (RAP) as aggregate were evaluated by the Superpave Indirect Tensile (IDT) strength test in conjunction of X-ray Computed Tomography (CT). Each concrete specimen for Superpave IDT strength test was subject to several procedures of preparation: concrete slicing, air drying, surface cleaning, gage points mounting, and LVDTs aligning. The concrete specimen was administrated a specified load level for ten seconds and then unloaded. A pre-sitting load of ten to fifteen pounds was constantly applied in order to hold still the concrete specimen. The load level was repeated with approximately 10% increment of peak stress (eg., 10%, 20%, 30%...etc.), until when the fracture of concrete occurred. The X-ray CT scans were performed: before the load was initially applied and after the load was released. It was to identify subtle changes in concrete before and after the repeated load levels were administrated. An image-processing technique was developed to assess the air voids distribution for each load level. The maximum variation of air voids measured near the central area of the specimen was within . The volume of air voids in the concrete was observed to increase significantly when the concrete specimen was loaded to fracture. The significance of this study is a better understanding of microstructural property in terms of air voids distribution by using X-ray CT to assess the microdamage in concrete before fracture.

8694-80, Session PTues

Nondestructive testing in an automated process chain for mass manufacturing of fiber-reinforced thermoplastic components

Michael Kalms, Sandra Hellmers, Christoph von Kopylow, Ralf B. Bergmann, Bremer Institut für Angewandte Strahltechnik GmbH (Germany)

The application of fiber-reinforced thermoplastic materials in the transport industry and the energy sector gains an increasing importance. But up to now, the process chain for manufacturing these components is not automated completely, lacking a thorough inline quality control. To ensure an economic mass production with a cycle time of one minute and a low rejection rate by a simultaneously effective utilization of material, a nondestructive in-line testing in the production process is required. We report about the application of laser ultrasound for nondestructive testing of carbon reinforced thermoplastics. For this purpose the detection system has been redesigned for integration into the process chain. The system consists of an excitation laser, a sophisticated detection system, a robot for handling of the parts in question and an overall control system including the signal analysis. The detection system uses a commercial available continuous wave MOPA (master oscillator power amplifier) laser in combination with a redesigned confocal Fabry-Perot interferometer for fast and reliable detection of ultrasound signals. The stabilization is performed with modern micro-controller technology. The interferometer is able to work in transmission mode, in reflection mode or in both at the same time. Handling of the complex shaped parts is carried out by a robot. The moving and turning of the complex parts in front of the detector optics results in a very good signal to noise ratio since most of the retro-reflected light of the detection laser can be collected. Objective of this system is to measure a clip with a curved surface of about 100 cm? in less than a minute effectively enabling in-line quality control.

8694-81, Session PTues

Agent-based damaged detection in composite laminates

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In this paper, we present undamaged agent based, an effective damage identification technique along with Eigen-system Realization Algorithm (ERA) for damage assessment in laminated composite structures. Unlike the use of frequency measurements, this technique has the potential to readily pinpoint the location and the extent of damage, in addition to alerting to its occurrence. The proposed technique is implemented through numerical simulation and experimentation on laminated beams with and without delaminations. For numerical simulation, a Sate-space based finite element system model (SS-FESM) is employed to generate transient impulse response signals. In this study, we employ ERA for system identification of fibre reinforced composite laminates to identify the presence of delaminations and assess their location and severity. The impulse response and the input signals are feed into ERA to estimate the normalized dynamic properties, namely the stiffness and damping coefficients of all elements in the structure. Variations in the dynamic properties readily identify the presence of damage, however, the location and severity of the damage is assessed or determined through undamaged agent based iterating technique. The numerical simulation of 8 ply quasi-isotropic Carbon Fiber Reinforced Polymer (CFRP) laminated beams demonstrate the delaminations as small as one percent of the beam length in size can be identified and assessed using the present method. Experimental simulations indicate that noise in the measured impulse signals need to be eliminated for successful practical implementation of the technique.

8694-82, Session PTues

Damage assessment of hydrokinetic composite turbine blades

Steve E. Watkins, Kevin E. Robison, James R. Nicholas, Greg A. Taylor, K. Chandrashekhara, Joshua L. Rovey, Missouri Univ. of Science and Technology (United States)

Composite blade performance is investigated for hydrokinetic turbine applications. Composite blade designs are well suited for marine environments and are compatible with smart structures instrumentation. However, composites are susceptive to low-velocity impact damage from debris in flow. In the present work, strain characteristics are used for damage assessment of the composite blades. The blades are carbon/epoxy laminates that are made using an out-of-autoclave process. The out-of-autoclave (OOA) process is a new generation vacuum-bag-only cure process that uses special prepregs that can be cured in low pressure to allow embedment of sensors. The blade design is based on a hydrofoil with a constant cross-section. Both undamaged and damaged blades are manufactured and instrumented with strain sensors. Signal profiles for extrinsic Fabry-Perot interferometric (EFPI) fiber optic sensors are obtained and are validated with strain measurements from electrical resistance gages. Testing are conducted in a water tunnel with varying flow velocities. Strain response characteristics in water are measured for four different pitch angles. The results are compared with a theoretical simulation. The simulation is based on a combined blade element momentum (BEM) theory and finite-element method (FEM). The influence of damage on the response characteristics is assessed. The results are discussed in the context of using in-situ strain monitoring as an indicator of structural health.

8694-83, Session PTues

Dielectric measurement of aged concrete as a function of moisture content in the frequency range of 0.5GHz to 4.5GHz

Hao Liu, Tzu Yang YU, Univ. of Massachusetts Lowell (United States)

Inspection of aged reinforced concrete (RC) structures has become an important issue in the maintenance of critical civil infrastructures in the U.S. Various radar sensors are used for the inspection of steel corrosion, measurement of concrete cover, and detection of concrete cracking in RC structures. To improve the accuracy of radar inspection, reliable dielectric measurement of concrete is necessary. It is known that moisture content in concrete has significant influence on the dielectric properties of concrete due to the high dielectric contrast between water and concrete in the practical frequency range (0.5GHz to 2.6GHz) of radar sensors used in civil engineering. In this paper, dielectric measurements of aged concrete specimens with different moisture contents are reported. Aged concrete disk specimens with various moisture contents were artificially created (e.g., room conditioned and oven dried) and measured by an open-ended coaxial probe system. Both dielectric constant and loss factor were measured in the frequency range of 0.5GHz to 4.5GHz. From the results, moisture-dependent dielectric constant and loss factor values were measured and modeled. Such quantitative information can help civil engineers to better understand the complicated interaction between moisture content and age of concrete.

8694-84, Session PTues

Study on style and mechanism of aerostatic instability for long span cable-stayed bridge

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With modern bridges becoming longer and more flexible, the effects of geometric nonlinearity and the aerostatic load nonlinearity of long-span bridges under strong wind load shouldn't be neglected. Therefore, the modified increment and double iterations method was combined to analyze the aerostatic stability of the long span bridge. The paper discussed the aerostatic stability style, mechanism of aerostatic stability, and the mutual effect between buffeting responses and aerostatic stability.

The actual aerostatic instability of cable-stayed bridges is the No. II stability, which consists of the II1 and II2 types. Further more, the II2 type can be divided into the II2a and II2b subtypes. Taking Hangzhou bay bridge, Donghai bridge and Sutong bridge as the study cases, the difference of aerostatic stability style of various span was analyzed. The results show that the proposed styles of aerostatic stability are demonstrated, and there is an initial attack angle to distinguish the two kinds of aerostatic stability. For cable-stayed bridges, the instability style is characterized by coupling of bending and torsion deformation, which is mainly about vertical bending or torsion deformation of the girder. As extra long-span cable-stayed bridges, there is another character of especially large lateral bending deformation. The turbulent flow has a beneficial or negative effect on the aerostatic stability of the long span bridge. Low turbulence flow may increase the aerostatic stability of the long span bridge, but the normal turbulence intensity may destroy the aerostatic stability.

8694-85, Session PTues

Effect of creep on magnetic domain structure of heat resistant steels

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The magnetic domain and magnetic properties of heat resistant steels including 10CrMo910, P91 and 23CrMoNiWV88 are investigated in the present work. The magnetic properties characterized by magnetic hysteresis loop under 500-600°C of the three materials are measured by vibrating sample magnetometer(VSM). The magnetic domain structure of as-received and crept specimens is observed by magnetic force microscope (MFM). It is shown that the coercivity and remanence of each material has a remarkable decrease at 500-600°C especially for P91 almost 64% decrease. The magnetic domain of ferrite phase change from initial stripe pattern to maze pattern during creep. All the crept specimens have an increase in coercivity comparing to the as-received 10CrMo910 specimens. The black and white fringes and stripe-like pattern have also been found in the P91 and 23CrMoNiWV88 specimens, respectively. The experiment results reveal that the magnetic domain structure is strongly influenced by different microstructure with different distributions of the carbides.

8694-86, Session PTues

Fiber optic photoacoustic ultrasound generator using optimized gold nanopattern with high absorption efficiency

Ye Tian, Nan Wu, Xiaotian Zou, Xingwei Wang, Univ. of Massachusetts Lowell (United States)

Ultrasound generation on optical fiber based on photoacoustic principle is a promising approach for many advanced ultrasonic applications, which require wide bandwidth and compact size in order to achieve high resolution as well as the capability of being operated in limited space. This paper reports a fiber optic photoacoustic ultrasound generator using gold nanopattern. As a key factor affecting photoacoustic generation efficiency, the laser absorption efficiency needs to be optimized before the experiment. Compared to Mie theory and discrete dipole approximation (DDA), finite difference time domain (FDTD) is a more accurate and efficient method for this case. The absorption spectra of different 2D/3D periodic nanofeatures were simulated using FDTD method. The optimized nanopattern with high absorption efficiency was fabricated using focused ion beam (FIB) on the fiber endface, which

was excited by a nanosecond laser to generate ultrasound signals via the photoacoustic principle. Experimental results demonstrated that ultrasound signals can be generated by this approach and the fiber optic ultrasound generator can be used in the advanced ultrasonic applications.

8694-87, Session PTues

Using smart pressure map sensors to detect reflective cracks of pavements

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The objective of this paper is to develop a pressure sensor map to detect reflective cracks of pavements. Both rigid and flexible existing pavements have been rehabilitated with bituminous overlays in many countries. These new overlays usually crack after a few winters. Reflective cracking in Hot Mix Asphalt (HMA) overlays of flexible and rigid pavements become a common roadway distress for road users. Reflection cracking occurs in new overlays due to the movement of existing pavements under environmental or traffic loads, and/or a combination of both. However it is very difficult to accurately predict and detect such cracks in the roads with any technologies like ground penetration radar or other technologies. In this study, a pressure map was used to monitor loading profile of an asphalt pavement structure as an indirect method to detect such internal cracks. The pressure map was made of two layers of parallel conductive strips placing in perpendicular to each others, forming a grid of contact nodes. The resistance of the contact nodes was measured by measuring the electrical resistances via the corresponding conducting strips. A stress sensitive layer was placed between the two conductive layers. Stress loading on the pressure map caused the resistance of the stress sensitive layer to change, allowing stress/pressure monitoring at the contact nodes. This technology allows monitoring of internal crack development by detecting the low pressure regions of the pressure map for the pavements. It was found this technology can accurately predict the development of crack evolution during the loading time.

8694-28, Session 6

Acoustic emission signatures of damage modes in structural materials

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The prediction of the remaining life of a structure can be assisted by the characterization of the current cracking mode. Usually tensile phenomena precede shear fracture. Due to the different movement of the crack sides according to the dominant mode, the emitted elastic energy possesses waveforms with different characteristics. These are captured by acoustic emission sensors and analyzed for their frequency content and waveform parameters. In this study fracture experiments on structural materials are conducted. The goal is to check the typical acoustic signals emitted by different modes as well as to estimate the effect of microstructure on the emitted wave as it propagates from the source to the receivers. The dominant fracture mode is controlled by modification of the setup and acoustic emission is monitored by two sensors at fixed locations. Signals belonging to tensile events acquire higher frequency and shorter duration than shear ones. The influence of heterogeneity is also obvious since waveforms of the same source event acquired at different distances exhibit shifted characteristics due to damping and scattering. The materials tested were cement mortar, as a material with microstructure, and granite as representative of more homogeneous materials. Results show that in most cases, AE leads to characterization of the dominant fracture mode using a simple analysis of few AE descriptors. This offers the potential for in-situ application provided that care is taken for the distortion of the signal, which increases with the propagation distance and can seriously mask the results in an actual case.

8694-29, Session 6

Acoustic emission monitoring of FRP-strengthened reinforced concrete columns subjected to reversed cyclic loading

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During the last two decades, Fiber reinforced polymer (FRP) has been widely used in repairing and strengthening reinforced concrete (RC) columns. Under seismic excitations, the damage state of the FRP covered concrete is invisible and it is necessary to develop a nondestructive method to assess its damage state. Based on acoustic emission (AE) techniques, this paper studied the damage process of the FRP-strengthened RC columns subjected to reversed cyclic loading. Two large size RC columns, 300x300 mm in section dimension and 1125 mm in length, were fabricated in the tests. One column was used as control specimen and the other column was strengthened with FRP. AE signals were collected by surface bonded commercial AE sensors and embedded piezoelectric lead zirconate titanate (PZT) transducers developed in-house. The AE events can effectively reflect the damage trends of the unstrengthened and FRP-strengthened RC columns subjected to reversed cyclic loading. The fracture processes of the unstrengthened and FRP-strengthened RC columns were intensively studied through b-value and improved b-value (Ib-value) analyses. The b-value and Ib-value analyses revealed the fracture magnitude of the concrete cracks during the reversed cyclic loading. The AE monitoring results indicated that the in-house developed embedded PZT transducers was effective and could be used in the nondestructive testing (NDT) field of concrete structures.

8694-30, Session 6

Monitoring damage growth in carbon/epoxy composite panels

Kassahun M. Asamene, Travis Whitlow, Mannur J. Sundaresan, North Carolina A&T State Univ. (United States)

Composite structural materials are finding increasing usage in aerospace applications. These materials experience complex damage states that include matrix cracking, fiber breaking, and delaminations. The damage is often distributed over an area surrounding stress raisers or impact damage. The different damage mechanisms in composites are source of acoustic emission signals. These signals could contain information which helps to identify the types of damage mechanisms involved and the rate of damage progression due to loading. In addition, the development of damage is also accompanied by local strain redistribution. Hence, an online strain measurement technique can serve as a valuable tool for assessing this load redistribution.

The objective of this research is to monitor carbon/epoxy panels subjected to quasi-static as well as fatigue loading conditions. Two 12” wide Quasi-isotropic and cross-ply panels were tested in this program. First, the nature of acoustic emission related wave propagation in these laminates was first quantified. Using separate coupon tests, acoustic emission signals corresponding to individual failure modes were monitored. The panels were instrumented with acoustic emission and fiber-optic sensors. The fiber-optic sensors were capable of distributed strain measurement around stress raisers. Results from these experiments including damage related acoustic emission signals and strain redistribution around damage will be presented.

8694-31, Session 6

Monitoring friction related surface degradation using acoustic emission technique

Kassahun M. Asamene, Bonaventure Mills-Dadson, Abm

Iftekharul Islam, Mannur J. Sundaresan, North Carolina A&T State Univ. (United States)

Machine parts often contain components which experience relative motion during service. Relative motion between surfaces causes surface deterioration and sometimes fretting fatigue cracks. The degradation to the surfaces has been monitored using vibration characteristics as well as acoustic emission signals generated during the relative surface movements. In particular, acoustic emission signals were found to be sensitive to some of the microscopic processes occurring at the frictional interface. In this study, relative motion between two surfaces was monitored under controlled conditions. Participating materials, relative velocity, normal load, contact geometry, and surface roughness values could be selected in these experiments. The surfaces were subjected to cyclic motion with different changes to the surfaces were monitored using surface roughness measurements and microscopy. Friction and damage related acoustic emission signals generated during this process were recorded and analyzed to understand the relationship between the signals generated and the physical processes giving rise to these signals.

Acoustic emission signals with frequencies in excess of 1 MHz were generated by the frictional process. Information related to the stick-slip movements during the cyclic motion could be observed from the signals. Features within the waveforms were found to reveal the conditions existing at the interface. In particular the rate of changes in the surface roughness and wear could be readily observed from the acoustic emission signals. The experimentally observed acoustic emission signals were compared with those from numerical models of this frictional process.

8694-32, Session 6

One Dimensional Predictive Model of Adhesion Strength in FRP-bonded Concrete System using Acoustic Technique

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Fiber-reinforced polymer (FRP) have become increasingly popular in the application of strengthening and retrofitting existing concrete elements, such as beams, columns, slabs, and bridge decks. In view of the maintenance and safety issues against these retrofitted systems, development of a robust and reliable nondestructive testing (NDT) techniques that provides an accurate and remote assessment of interfacial properties in the FRP-bonded concrete system is required. In this study, a one dimensional predictive model of adhesion strength in the FRP-bonded concrete system based on an NDT using acoustic wave is proposed for a preliminary measurement of the adhesion strength in such bonded system. This model is constructed based on the traditional beam theory in which an infinitely long beam sits on top of a series of springs, which can be regarded as a soft foundation. Together with the acoustic NDT technique, the resonance frequency is found to be highly material dependent. The result from this predictive model is compared with the existing experimental data on the measurement of adhesion strength in FRP-bonded concrete system and a good agreement is observed.

8694-33, Session 6

Acoustic emission monitoring and fatigue prediction of steel bridge components

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Acoustic emission (AE) has been recognized for its unique capabilities as an NDT method. However, there is untapped potential for the practical application of AE to structural health monitoring and prognosis. As part of the development of a wireless sensor network for structural bridge health monitoring, this study aims to estimate fatigue damage and remaining life of steel bridge components through AE monitoring.

Twelve compact tension (CT) specimens and nine cruciform fillet welded joints are used in AE-monitored fatigue tests to investigate the correlation of AE features with crack growth in base material and weldments. The material (structural steel A572 Grade 50) and the welding procedures are representative of those used in actual bridge construction. Based on the balance between AE signal energy and the energy released due to crack growth, deterministic models are presented to predict crack extension and remaining fatigue life for stable and unstable crack stages. The effect of weld length and fatigue load ratio on the AE activity is evaluated.

The presence of noise is inevitable in the application of AE monitoring. The efficiency of data filtering and reduction algorithms is key to minimize the power and data storage demand of the wireless sensing system. An AE data filtering protocol based on load pattern, source location, and waveform feature analysis is proposed to minimize noise-induced AE and false indications due to wave reflections.

8694-34, Session 6

Detection and assessment of damages in hybrid composite structures by acoustic emission

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Structural health management is one of the major issues for monitoring and assessing of the integrity of large structures like a huge wind turbine blade. There are two key interested things that can contribute as non-destructive technology point of view. One is how to detect defects inside more exactly after manufacturing of each component. The other one is how to monitor its integrity during operation. So, it is very important to detect and locate the damages early in the structures, since it can tell a symptom of damage propagation before catastrophic failure. In this study, we have tried to solve the existed source location problem for hybrid composite blade consisted of GFRP/PVC/epoxy/wood materials. So, we focused to enhance a source location method based on database map which is developed before and to develop a new damage index for more clear damage identification. And also we have done a practical application study to monitor and assess the damages from a full scale wind turbine blade. First, it was needed to understand and analyze the characteristics of wave propagation crossing each different material. And then we measured the activities of debonding acoustic emission generated between the GFRP shell and web/edge components in the wind turbine blade. That is, this study aims to locate and identify the damages from blade bonding interfaces, since it is very difficult to find an exact location of damages in this kind of complex composite structures. From the experimental results, new enhanced source location method and damage index identification showed very good performance for detection and assessment of damages in the hybrid composites structures.

8694-56, Session 7

Detection of fretting damage in aerospace materials by thermoelectric means

Hector G. Carreon, Univ. Michoacana de San Nicolás de Hidalgo (Mexico)

Fretting is a wear phenomenon that occurs when cyclic loading causes two surfaces in intimate contact to undergo small oscillatory motions with respect to each other. During fretting, high points or asperities of the mating surfaces adhere to each other and small particles are pulled out, leaving minute, shallow pits and powdery debris. Sometimes these surface conditions are neglected, but they are important in some application such as the aerospace industry. In this research work, non-contacting and contacting thermoelectric power techniques are performed in fretted 7075-T6 and Ti-6Al-4V specimens. It has been found that the contacting and non-contacting thermoelectric power measurements are associated directly with the subtle material variations such as work hardening and compressive residual stresses due to plastic

deformation produced in the fretting zone but surface topography. Therefore, both techniques could be used for a global characterization of the most relevant fretting induced effects. Potential of these techniques to monitor subsurface changes in other severe surface plastic deformation processes are clearly envisaged.

8694-57, Session 7

Electromechanical impedance for SHM of aircraft bolted joints

Vitalijs Pavelko, Riga Technical Univ. (Latvia)

The problem of indication of bolt-joint loosing is general goal of this presentation. Experimental study was performed using the bolted joint of the Mil-8 helicopter tail beam. The piezoceramics transducers (6.35x6.35x1mm) were placed at the surface of the tip Al frame of the tail beam closely to the 8mm steel bolt heads. The EMI was measured for different level of bolt pre-load (60, 80, and 100% of maximal pre-load). It was assumed that the effect of loosing of the bolted joint to EMI is caused by friction into contact surfaces. Therefore the smoothed result of EMI measurement was analyzed by comparison of real part of EMI for different levels of pre-load in several narrow ranges of frequency. The stable effect of pre-load influence to this parameter was fixed with the high level of confidence.

Theoretical study contains the 2D model of constrained transducer using the modal decomposition of displacements as transducer, as the host structure, and was focused to simulation of friction effect in bolt-joint. Simulation and test results comparison is discussed.

8694-58, Session 7

Efficient characterization of variation propagation in cyclically periodic structures

Jiong Tang, Kai Zhou, Univ. of Connecticut (United States)

Cyclically periodic structures, such as aero-engine blade-disk assembly, are widely used in the engineering practice. While these structures are generally designed to be periodic with identical substructures, it is well known that small random variations of the substructure may sometimes cause drastic change in the dynamic responses which are referred to as vibration localization and general harmful to structural health. In this research, we explore a suite of computational analysis tools to analyze the two-way variation propagation between the structural uncertainty and the response variation. We first develop a perturbation analysis-based algorithm to efficiently quantify the variation of vibration response under structural uncertainty, in which the singularity issue of the periodic structures due to closely-spaced eigenvalues is addressed. We then develop an inverse approach to identify small changes of the mean properties of the substructures that can lead to the reduction of response variation. The new algorithms will be implemented to large-scale structure analysis by means of efficient order reduction through the component mode synthesis approach. The results of this research will have positive impact to the design, control, and online monitoring of periodic structures with uncertainty.

8694-59, Session 8

Output-only Structural System Identification Method with a New Two-stage Kalman Filter and Incomplete Measurement

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Numerous algorithms in time domain based on Kalman Filter (KF) have been proposed to identify unknown parameters or external excitation of structural system, such as extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF). To improve the computational effort, methods have been proposed to promote the identification speed and improve the accuracy, such as the reduced extended Kalman Filter (REKF). However, most of them cannot identify the unknown parameters with incomplete acceleration measurement.

A structural parameter identification method with incomplete acceleration measurement is implemented. Firstly, incomplete response is obtained from the structure. The unmeasured structural response could be re-constructed with average-acceleration discrete algorithm Kalman filter. Secondly, structural parameter is identified by EKF with both re-constructed structural response and measured structural response. This two-stage structural system identification method achieves the structural model updating and force identification with incomplete acceleration measurement.

The proposed method was validated numerically with the simulation of a fifteen-story shear frame structure. A model of a fourteen-storey concrete shear wall building is studied experimentally with shaking table tests to further validate the proposed method. The shear wall structure has a two-storey steel frame on top. Both the stiffness of the model and the interface force in the isolator at the bottom of the steel frame during the seismic excitation are estimated with the proposed method. Results from both numerical simulations and laboratory tests indicate the proposed method is capable to identify the dynamic load and structural parameters fairly accurately with measurement noise, model error and environmental disturbances.

8694-60, Session 8

Active sensing waveform design for estimating progressive fatigue damage in structures

Daniel Huff, The Boeing Co. (United States); Narayan Kovvali, Antonia Papandreou-Suppappola, Aditi Chattopadhyay, Arizona State Univ. (United States); Subhasish Mohanty, Argonne National Lab. (United States)

Structural integrity assessment is important for many civil, military, transportation, and other components and it is advantageous to be able to accurately monitor flaw level within critical structures. In this work, we explore a stochastic filtering approach for tracking progressive fatigue damage in structures, wherein physically based damage evolution information is combined with active sensing guided wave measurements. In the proposed method, the input waveform used to excite dispersive modes within the structure is adaptively configured so that the received sensor measurements, when processed, yield maximally accurate damage estimates. The damage (fatigue crack) growth model used is based on Paris' Law fracture mechanics. Features representing signal energy distribution within the time-frequency plane are extracted from the received signals using the matching pursuit decomposition algorithm and then modeled using hidden Markov models. Given the transmitted waveforms and received sensor measurements, and the crack growth and measurement models, the unknown crack length is estimated in a Bayesian stochastic filtering framework. Since the models are nonlinear and non-Gaussian, particle filtering is employed. At each time step, the optimization of the waveform to be transmitted at the next time step is performed by utilizing a minimum mean squared error criterion. We demonstrate the ability of the approach in tracking fatigue crack growth in an aluminum cruciform specimen. Several different types of short duration waveforms were transmitted and signals were received from multiple transducers at various stages of fatigue. Crack estimation results are presented showing the benefit of incorporating waveform design into the monitoring procedure.

8694-35, Session 9

Vehicle live-load effects evaluation of stay cable based on SHM

Chengming Lan, Univ. of Science and Technology Beijing (China)

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.

8694-36, Session 9

Real-time bridge scour monitoring with magnetic-field strength

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Scour was responsible for most of the U.S. bridges that collapsed during the past 40 years. The maximum scour depth is the most critical parameter in bridge design and maintenance. Due to scouring and refilling of river-bed deposits, existing technologies face a challenge in measuring the maximum scour depth during a strong flood. In this study, a new methodology is proposed for real time scour monitoring of bridges. Smart rocks with embedded magnets are deployed around the foundation of a bridge as field agents. As scour gradually develops, a smart rock continually falls into the bottom of the increasing scour hole and thus provides engineers with the maximum scour depth information with magnetic field strength measurements over time. This paper will summarize the findings from various calibration and validation tests with smart rocks in open channel flumes at Turner-Fairbank Highway Research Center. First, the critical flow velocities that initiate the movement of smart rocks with various sizes and densities were characterized in a small flume. They provide critical information for the design of smart rocks. Second, calibration tests with embedded magnets in rocks were conducted in the small flume to understand the magnetic field strength change with distance and orientation of magnets. Third and lastly, smart rocks were deployed around two model piers tested in an open channel flume with sands. Scour tests were conducted for a period of at least 90 minutes. The magnetic field strength was correlated with the increase of scour depth over time. Test results indicated that properly designed smart rocks in terms of size and density always fall into the bottom of a scour hole. They remain at the bottom of the hole and provide critical information in the process of scour development. At various time instances, the scour depth information can be retrieved from the magnetic field strength measured from the smart rocks.

8694-37, Session 9

Placement/delivery evaluation of nanocomposite for robot supported nondestructive rehabilitation of concrete bridge decks

Giri Venkiteela, Matthew Klein, Husam Najm, Perumalsam N. Balaguru, Rutgers, The State Univ. of New Jersey (United States)

Results reported in this paper deals with the evaluation of flow characteristics of nano-composites developed for nondestructive rehabilitation of bridge decks using robots. The composites have been evaluated for strength and durability characteristics and the next crucial part is to deliver these composites to micro cracks and delaminations. This is a part of ANDERS project at Rutgers University dealing with automated nondestructive evaluation and nondestructive rehabilitation of transportation infrastructures using robotics. Penetration ability of the composites was evaluated using concrete blocks to simulate field conditions. Promising formulations were injected into cracks using different types of equipment that are currently used in the field for repairs. An experimental setup was built to study the flow characteristics through the cracks in real time using video equipment. Rate of flow, pressure needed, wetting of surfaces, incorporation of entrapped air and ease of filling the entire crack were studied. In addition, fitting and injection types for the automation of repairing process were also identified. The results show that nano composites can be successfully be delivered to small cracks using currently available equipment. Details of the experimental setup, flow characteristics, comparison of various equipment and recommendations for choosing the equipment and fittings will be presented.

8694-38, Session 9

In-situ health monitoring on steel bridges with dual-mode piezoelectric sensors

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Current routine inspection practices for bridge health monitoring are not sufficient for timely identification of areas of concern or are incapable of providing enough information to bridge owners to make valuable informed decisions for maintenance prioritization. Continuous monitoring is needed for long-term evaluation from an integrated sensing system that would act as a monitoring and early warning alarm system that is able to effectively communicate the information from the bridge directly to the bridge owners for potential and immediate response. Due to the variety of deterioration sources and locations, there is currently no single NDE method that can detect and address the potential sources globally.

To address the need of this urgent highway bridge health monitoring, a joint venture research has been initiated under the NIST Technology Innovation Program by incorporating a novel and promising sensing approach based on piezoelectricity together with energy harvesting to reduce the dramatic uncertainty inherent into any inspection and maintenance plan. One approach to damage detection and classification has been focused on the use of piezoelectric sensors (PES) at both active (ultrasonic NDE) mode and passive (acoustic emission) mode on steel bridge. The acoustic emission (AE) method has been shown the best potential for global bridge health monitoring while active sensing will provide additional quantification process. Two types of the PES have been studied to provide fundamental principles for their applications to steel bridges. Extensive laboratory investigation was performed supported by a theoretical modeling analysis. A prototyped system has been demonstrated to show how the PES sensors are used for the dual mode damage detection and quantification on representative structures.

8694-39, Session 9

Cyber-infrastructure design and implementation for structural health monitoring

Gwendolyn W. van der Linden, Abbas Emami-Naeini, SC Solutions, Inc. (United States); Yilan Zhang, Jerome P. Lynch, Univ. of Michigan (United States)

Structural Health Monitoring of large-scale bridges requires collection, storage and processing of large amounts of data, and must provide distributed concurrent access. In this paper we report on the progress of the design and implementation of a cyber-infrastructure system that is currently being field-tested on a long-span bridge in California and a short-span bridge in Michigan. This system provides remote access to sensor data acquisition systems, data analysis modules, and human operators. The implementation is based on an object-oriented data model description and makes extensive use of code generation to allow for the rapid development and continued improvement of the system. Currently the system provides storage of raw and processed sensor data, finite element models, traffic data, links to PONTIS data, reliability modeling data, and analysis results. Apart from the ubiquitous read/write access, the system also includes an event system that allows data consumers to be triggered by the arrival of new data. In addition to essential backup/restore facilities, the system also includes import/export tools that can migrate data between versions, which is very useful in keeping pace with the continuous improvements that are being made in the design and implementation of the cyber-infrastructure system. The system also provides introspection, as the data model is made available by means of an 'inspector' client interface, which allows the development of generic client tools that can dynamically discover the data model, and present a corresponding interface to the user. Currently available user-interfaces include an editor GUI application, and a read-only web application.

8694-40, Session 9

Integrated monitor and warning system for the Jeremiah Morrow Bridge

Mehdi Norouzi, Jason Kumpf, Victor J. Hunt, Arthur J. Helmicki, Univ. of Cincinnati (United States)

Over the past years, several different algorithms for measurement-data interpretation and structural evaluation have been proposed and implemented by various researchers but in general, there is no current reliable standardized method that can be applied to bridges for detection of abnormal behavior by interpreting measurement data. In this paper, a methodology for integrating a monitor and its warning system with results from both truckload tests and structural analysis is presented for the Jeremiah Morrow Bridge. Wireless data collection system, data cleansing and archiving procedures, Prediction model using Principal Component analysis and capacity rating based upon truckload test results for the instrumented members are detailed. The truckload test and monitored responses document the "normal" or expected behavior of the structure to traffic and environment, respectively. A warning system is then designed upon a threshold technique which minimizes the probabilities of false alarms and the missed detection of critical events based upon the capacity rating. Past results of the implemented system for the Jeremiah Morrow and other bridges are discussed. Alarm scenarios are reviewed based upon the collected historical data from the monitors and generated warnings. Finally, detectability and detection time of the algorithm are compared with linear regression methods.

8694-41, Session 9

Arch bridge suspenders damage detection based on GA optimized BP neural network

Junliang Hu, Quansheng Yan, Shiping Huang, Hengbin Zheng, Zhou Chen, South China Univ. of Technology (China)

Suspender damage detection research to a concrete-filled-steel-tube (CFST) tied arch bridge is proposed. When suspenders of arch bridge damaged, the inner force of suspenders are redistributed. Back-propagation (BP) neural network(NN) is introduced to carry out damage detection. Apply genetic algorithm (GA) to optimize the initial weights and thresholds of BP NN to improve calculation efficiency . Suspenders' inner force difference are taken as structural damage detection(SDD) feature index after suspenders damaged to identify damage location. The results show that the damaged suspenders identification have a good effect in the case of different damage extent and prove the feasibility and practical of this method.

8694-42, Session 9

Monitoring lower limit states in bridge structures

Mohammed M. Ettouney, Weidlinger Associates, Inc. (United States); Sharada Alampali, Prospect Solutions, LLC (United States)

Bridges managers employ, directly or indirectly, numerous types of limit states. These limit states can be physical, such as different states of stresses / strains in a bridge girder or degree of deterioration in a bridge deck. They can also be operational such as traffic volume, budgetary constraints, or bridge inspection operations. Perhaps one of the most studied limit state is the failure state, which is usually defined as the state when demand exceeds capacity. Even though failure state is paramount; sole concentrating on it might not be the most efficient management approach. The vast majority of bridge limit states are far below failure state. It is equally important to understand limit states below failure state. As such optimal decision can be made at different limit states. Making the right decisions at states lower than failure state can also prevent a failure state, or at least provide ample warning before bridge conditions reach failure state.

8694-43, Session 9

Uses of WIM data in bridge risk management

Mohammed M. Ettouney, Margaret Tang, Ryan Anderson, Weidlinger Associates, Inc. (United States)

Weigh in Motion (WIM) of traffic have been an invaluable method in monitoring traffic over the highways for many years. The information provided by WIM helps in decision making and research regarding pavement and bridge designs as well as planning, enforcements and administration of traffic. This paper investigates using WIM in the emerging area of risk management of bridges.

Risk management is composed of several components. These includes, but not limited to: risk assessment, risk acceptance, and risk monitoring. Risk assessment involves quantifying risk, risk acceptance involve the decision of whether the assessed risk is acceptable, and risk monitoring involves the techniques regarding real time, or near real time, of in-field and objective measurements (as opposed to theoretical / computational) risk assessment.

8694-61, Session 10

Finite element model calibration of a RC building based on seismic response trends from long-term monitoring

Faheem Butt, Piotr Omenzetter, The Univ. of Auckland (New Zealand)

This paper presents a study of seismic response trends and model updating based on those trends for a three storey reinforced concrete (RC) building monitored for a period of more than two years. The building is instrumented with five tri-axial accelerometers and a free-field tri-axial accelerometer is also installed at some distance from the building. For evaluation of seismic response, the state-of-the-art time domain N4SID system identification technique was used taking into account the soil-structure-interaction (SSI) under a wide range of earthquake magnitudes. Trends of variation of seismic response were developed by correlating the peak response acceleration (PRA) at the roof level with the identified frequencies and damping ratios. A general trend of decreasing frequencies was observed with increased level of response, while damping ratios were observed to have scattered values and no clear trend. To simulate the behavior of the building, a three dimensional finite element model (FEM) of the building was developed in which soil underneath the foundation and around the building was modeled using spring elements, and non-structural components (claddings, in-fills and partitions) were also included. The developed FEM was then calibrated using a sensitivity based model updating technique to produce a series of updated FEMs replicating the behavior of the building at different shaking levels. This enabled tracing how stiffness of structural and nonstructural elements and soil changes with shaking amplitude. It was concluded from the investigation that knowledge of variation of seismic response of buildings is necessary to better understand their behaviour during earthquakes, and also that soil and non-structural components have a significant influence on the seismic response of the building and these should be considered in models to simulate the real behavior.

8694-62, Session 10

The selection of spectral element polynomial orders for high-requency numerical wave propagation

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Understanding the propagating elastic wave characteristics in materials is a foundation for quantitative Nondestructive Testing methods based on wave propagation such as guided wave ultrasonics and acoustic emission. The conventional finite element formulation requires very fine meshing and small time steps to prevent the dispersion pollution at high frequencies. The spectral finite elements reduce the required degrees of freedoms and the computation of time integration for dynamic finite element models via using high order orthogonal polynomials to define the locations of nodal coordinates. In this study, the advantage of spectral elements over conventional finite elements for frequencies up to 400 kHz is demonstrated on plane stress model of a structural steel plate. The excitation frequency is varied from 60 kHz to 400 kHz. The Legendre orthogonal polynomials with the orders of 3, 4 and 5 are selected. The required h refinements (i.e. element size) to eliminate the numerical error for three polynomial orders are identified. The results provide a guide for selecting the element sizes for different polynomial orders and the time step for explicit time integration. The validity of the spectral element formulation is demonstrated via comparison with conventional finite element models.

8694-63, Session 10

Numerical predictions of visco-elastic properties and dynamic moduli of innovative pothole patching materials

Kuo-Yao Yuan, Wei Yuan, Jiann-Wen Ju, Jenn-Ming Yang, Wei H. Kao, Larry Carlson, Univ. of California, Los Angeles (United States)

As asphalt pavements age and deteriorate, recurring pothole repair failures and propagating alligator cracks in the asphalt pavements have become a serious issue to our daily life and resulted in high repairing costs for pavement and vehicles. To solve this urgent issue, pothole repair materials with superior durability and long service life are needed. In the present work, revolutionary pothole patching materials with high toughness, high fatigue resistance that are reinforced with nano-molecular resins have been developed to enhance their resistance to traffic loads and service life of repaired potholes. In particular, DCPD resin (dicyclopentadiene, $C_{10}H_{12}$) with a Rhuthinium-based catalyst is employed to develop controlled properties that are compatible with aggregates and asphalt binders. In this paper, a multi-level numerical micromechanics-based model is developed to predict the visco-elastic properties and dynamic moduli of these innovative nano-molecular resin reinforced pothole patching materials. Irregular coarse aggregates in the finite element analysis are modeled as three sizes of randomly-dispersed multi-layers coated particles. The homogenized properties of asphalt mastic, which consists of asphalt binder, cured DCPD and air voids, are theoretically estimated by the homogenization technique of micromechanics in conjunction with the elastic-viscoelastic correspondence principle. Numerical predictions of overall visco-elastic properties and dynamic moduli are compared with suitably designed experimental laboratory results.

8694-64, Session 10

Numerical study of structural change estimation in a rotor system based on change in resonance and antiresonance frequencies

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This study addresses the quantification of structural change in a rotor system based on extraction of resonance and antiresonance frequencies from frequency response functions (FRFs). Quantification of structural change refers to the estimation of magnitude and location of a potential fault in the structure which can take the form of local component wear, damage, debris deposition, etc. This is achieved by determining the change in both the resonance and antiresonance frequencies from several FRFs in comparison to baseline measurements. The resulting expression contains enough information to identify the structural dynamics in both the frequency and spatial domains and is then applied to a model updating routine utilizing an optimization algorithm. As a result, this methodology can be used non-intrusively with magnetic actuators and proximity sensors to excite and measure the structure's response and determine magnitude and location of a potential fault.

8694-65, Session 10

Numerical and experimental investigation of delamination clapping with meshfree methods and nonlinear acoustic techniques

Ettore Barbieri, Univ. of Oxford (United Kingdom); Michele Meo, Francesco Ciampa, Univ. of Bath (United Kingdom)

Some type of cracks and delaminations in composite materials are difficult to detect with linear ultrasonic measurements. Indeed, linear techniques are more effective for tensile loaded delaminations ("open

cracks") because crack faces act as internal boundaries reflecting and scattering the incoming signal. Therefore, for early stage detection where cracks are loaded in compression, or not loaded at all (closed cracks), since the signal is transmitted across the crack there is no observable change in the linear behaviour. However, closed cracks induce Contact Acoustic Nonlinearities (CAN), reflecting in the generation of sub-harmonics and higher order harmonics, which are detectable through nonlinear acoustic techniques.

From the modelling perspective, the dynamics of closed cracks pose two major challenges: firstly, the introduction of discontinuities in the numerical approximation and secondly, the self-contact interaction between the crack faces, its detection, and the prevention of spurious penetrating (or overlapping) displacements.

Advanced discretization methods for partial differential equations, known as Meshless Methods or Meshfree Methods, remove most of disadvantages of the traditional Finite Element (FE) techniques for fracture mechanics. Differently from FE, meshfree methods use corrected smooth kernels to approximate the displacements. Such kernels can be discontinuous, allowing the insertion of cracks within the shape functions without resorting to re-meshing techniques. Particularly, in this work we present a new enriched kernel for meshless methods for the numerical treatment of multiple arbitrary non-planar cracks in two and three dimensions. Self-contact is enforced through penalty methods that do not require the insertion of extra-nodes (or elements), nor matching or aligning meshes, and proves its effectiveness in an explicit time-integration scheme.

Numerical studies were conducted to investigate the interactions of acoustic/ultrasonic waves with the impact damage on composite plates with pulse-echo and pitch-and-catch-mode. Then experimental nonlinear contact acoustic experiments were conducted on a damaged carbon fiber-reinforced plastic laminate showing a good correlation with the numerical predictions, proving suitability of meshfree methods for the investigation of nonlinear interactions of acoustic/ultrasonic waves with delaminations.

8694-66, Session 11

Slotted patch antenna sensor for wireless strain sensing

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Strain sensing offers critical information for determining safety status of various engineering structures. In this research, a slotted patch antenna is designed as a wireless sensor for monitoring strain and crack on metallic structures. By introducing slots into the antenna configuration, antenna surface current is detoured. Because a longer traveling distance is provided for the current, footprint of the slotted patch antenna can be reduced to only one quarter of a previously designed folded patch antenna. Electromagnetic simulation shows that the antenna resonance frequency varies approximately linearly as the antenna sensor is under strain. The frequency variation is wirelessly interrogated and recorded by a reader, and can be used to derive strain/deformation. The slotted patch antenna sensor is entirely passive (battery-free), by exploiting an inexpensive off-the-shelf RFID (radiofrequency identification) chip. Operation energy of the chip is captured from interrogation power emitted by the reader. This paper first describes the slotted antenna sensor design. Electromagnetic simulation results on strain sensing performance are then presented, followed by experimental results on strain sensing. To thoroughly verify the sensor performance, tensile testing experiments are conducted for both small and large strain ranges.

8694-67, Session 11

Optimal sensor placement for structural health monitoring: A comparative study between the control engineering and civil engineering approaches

Gopichand Movva, Yan Wan, Shengli Fu, H. Felix Wu, Univ. of North Texas (United States)

Wireless sensor networks (WSNs) provide a cost-effective solution for modern structural health monitoring. In establishing WSNs, the design of sensor locations is critical to enable high-fidelity structural monitoring and to maintain effective sensor networking. In this paper, we investigate the optimal placement of wireless sensor nodes for better data acquisition and monitoring performance. A number of sensor placement methods have been widely used in civil engineering, such as effective independence (EI), modal assurance criterion (MAC), and enhanced versions of each. However, we find that these methods have several limitations. First, these methods are designed to best estimate mode shapes, but not modes and damping parameters, which are also important characteristics of civil structures. Second, these methods rely heavily on finite element models (FEMs), which may not be accurate due to structural tearing, lack of original design documentation, over-simplification, etc. On the other hand, control engineering approaches are developed based upon the estimation theory of general system dynamics, without consideration of the key parameters of interest in civil structures. To address the gaps between the two fields, we conduct a comprehensive study to unveil the pros and cons of each approach. In particular, we study a simple sensor placement procedure, based upon actuating a structure using an impulse input, and then maximizing the estimation performance of key structural characteristics from the response data, using the variety of control and civil engineering approaches. We envision that this study will fill the gap between the two fields, and provide optimal placement approaches that take advantages of the advances in both fields.

8694-68, Session 11

Implementation of a Compressive Sampling Scheme for Energy Efficiency in a Wireless Structural Health Monitoring System

Sean O'Connor, Jerome P. Lynch, Univ. of Michigan (United States)

Wireless Structural Health Monitoring (SHM) offers modular distribution of power and computational resources, as well as fast installation. Such advantages enable higher nodal densities than tethered systems resulting in increased spatial resolution. High nodal density comes at a cost though as huge amounts of data are generated, weighing heavy on power, transmission bandwidth, and data management requirements, often making data compression necessary. The traditional compression paradigm consists of high rate (>Nyquist) uniform sampling and storage of the entire target signal followed by some desired compression scheme prior to transmission. The Compressed Sensing (CS) framework however, combines the acquisition and compression stage thus removing the need for storage and operation of the full target signal prior to transmission. The effectiveness of the CS approach hinges on the presence of a sparse representation of the target signal in a known basis, similarly exploited by several traditional compressive applications today (e.g., imaging, MRI). Of interest here is the compressibility of acceleration response signals of the Telegraph Road Bridge (TRB), a multi-girder steel-concrete composite bridge located in Monroe, MI. Field implementations of CS schemes in wireless SHM systems have been challenging due to the lack of commercially available sensing units capable of sampling methods (e.g., random) consistent with the compressed sensing framework, often moving evaluation of CS techniques to simulation and post-processing. The research presented here describes actual implementation of a CS sampling scheme to the Narada wireless sensing unit and the energy efficiency observed in the deployed sensors.

8694-69, Session 11

Full-scale testing of civil structures using wireless sensing technologies

Zhenhua Huang, H. Felix Wu, Univ. of North Texas (United States)

Performing full-scale structural testing is an important methodology for researchers and engineers in civil engineering industry. The full-scale testing helps the researchers understand civil infrastructure's loading scenarios, behaviors, and health conditions. It helps the engineers verify, polish, and simplify the structural design and analysis theories. To conduct a full-scale structural testing, sensors are used for data acquisitions. Structural researchers and engineers use sensors to record various physical parameters of civil infrastructure and to convert these parameters to analog or digital signals. The physical parameters most often used to depict the property, behavior, or health condition of civil infrastructure include accelerations, velocities, displacements, positions, strains, and forces. In addition, temperatures, pressures, sound, flow rates, viscosities, optical radiations, and electromagnetic fields have been used as well. Based upon their application methodologies, sensors used for civil-infrastructure testing could be categorized into traditional contact sensors and remote (non-contact) sensors. Based upon their data communication strategies, sensors used for civil-structure testing could be divided into traditional cabled sensors and wireless sensors.

Wireless sensing technologies employ wireless communications. They can be wireless accelerometers, wireless strain sensors, wireless thermal sensors, and many other types of sensors with wireless communication functions. Compared to cabled sensors, wireless sensors can potentially significantly reduce implementation time and costs, thus facilitating deployment of a dense network of sensors for structural health monitoring (SHM).

This paper reviews the wireless sensing technologies for full-scale structural testing applications, especially focusing on the Illinois WSSN (wireless smart sensor network) package. It is expected to help structural researchers and engineers get familiar with the wireless sensing technologies and select the most effective wireless testing tools.

8694-70, Session 11

Experimental case studies on wireless and wired sensors

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Performing full-scale structural testing is one of important methodologies for researchers and engineers in civil engineering industry. To conduct a full-scale structural testing, sensors are used for data acquisitions. Based upon their data communication strategies, sensors used for civil-structure testing could be divided into traditional wired sensors and wireless sensors. Compared to cabled sensors, sensors that employ the wireless communication technology can potentially reduce implementation time and costs, thus facilitating deployment of a dense network of sensors for structural health monitoring (SHM). This paper experimentally evaluates the advantages and disadvantages of wireless sensors versus wired sensors. Accelerometers are selected for case studies since they are one of the most widely used sensors in civil infrastructure testing, primarily in system identification and SHM. Three different accelerometers studied in this paper include the low-frequency piezoelectric wired accelerometer, the force balance triaxial accelerometers, and the wireless smart sensing network sensor board based on the MEMS technology. These sensors were compared during a series of tests, which include force vibration testing of a laboratory scale steel frame, field ambient vibration testing of a building connection bridge, and full scale field monitoring of a 65-m high wind turbine tower vibration. The complete testing procedure (instruments deployment, data acquisition, and data processing) shows the advantages and disadvantages of different types of sensors. It is expected that the results of this study can help structural researchers and engineers get familiar with the wired and wireless sensing technologies and select the most effective testing instruments.

8694-44, Session 12

Multilayer transfer matrix characterization of complex materials with scanning acoustic microscopy

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A multilayer structured thin film system, such as a biomedical thin film, MEMS (Micro Electric Mechanical System) /NEMS (Nano Electric Mechanical System) devices, and semiconductors, is widely used in various fields of industries. To non-destructively evaluate the multilayer structured thin film system, a mechanical scanning acoustic reflection microscope (hereinafter simply called "SAM"), has been well recognized as a useful tool in recent years. Especially, V(z) curve method is used to characterize the very small area of the system

In this study, V(z) curve simulation software for simulating the multilayer structured thin film system has been developed. In the software, the Thompson-Haskell method is applied to solve a reflectance function. All input and output interfaces are built as GUI for users' convenience. To ensure the reliability of the simulation, series of experiment are implemented, and the results are compared with the simulation results. For the specimen, Silicon (100) is used as a substrate. Titanium (thickness: 10 nanometer) and Gold (thickness: 100 nanometer) are deposited respectively.

Further, surface acoustic wave (hereinafter simply called "SAW") velocities are calculated from the simulated V(z) curve and compared to those measured from the experiments. They are agreed very well. Thus, the reliability of the simulation software is confirmed.

8694-45, Session 12

Damage investigation of single-edge notched beam tests with concrete specimens using acoustic emission techniques

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The Acoustic Emission (AE) techniques acquire and analyze the signals emitted from the deformation or fracture of materials under external loading. In this study, the AE techniques with statistical analysis were used to study the damage process of single-edge notched beam (SEB) tests with normal strength concrete (NSC) and ultra high performance concrete (UHPC) specimens. The SEB tests with the lab-prepared NSC and UHPC specimens were conducted by employing a clip-gauge controlled servo-hydraulic testing system and an AE damage detection system. It was found that the cumulative AE events with respect to the crack mouth opening displacement (CMOD) or the crack tip opening displacement (CTOD) correlate to the mechanical loading of the specimens. A Weibull rupture probability distribution was proposed to quantitatively describe the mechanical damage behavior under the SEB test. A bi-logarithmic regression analysis was conducted to calibrate the Weibull damage distribution with detected AE signals and to predict the damage process as a function of the crack opening displacements. The calibrated Weibull damage functions were compared among NSC and UHPC specimens with different notch depths and locations. More AE damage events were detected for the specimen with larger notch-depth at the beginning of the damage process due to a higher initial stress concentration factor KI. The offset-notched specimen also produced more AE damage events due to shear damage effects. The results indicate that the calibrated Weibull rupture probability functions with AE event data can be applied to study damage processes under mechanical loading for brittle materials such as concrete.

8694-46, Session 12

Hexagonal air-coupled sensor array for advanced impact echo testing

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The main objective of this study is to develop a hexagonal air-coupled sensor array for the IE that includes a solenoid-driven impact source at the center and six air-coupled sensors with parabolic acoustic reflectors at vertices of a hexagon. The resulting hexagonal sensor array will be used as a part of an air-coupled impact-echo device for delamination detection in concrete bridge decks. First, the study was conducted on a series of 2D and 3D finite element (FE) models that include both solid concrete plate and air domains. A series of parametric studies was conducted to determine the optimal sensor-and-source configuration in a hexagonal sensor array. The main variables were the rim angle and the width of the acoustic reflectors, and location of air-coupled sensors. Furthermore, numerical simulations using 3D FE models, including delamination defects in concrete decks, were conducted to develop an innovative signal interpretation algorithm of IE results from the developed hexagonal air-coupled sensor array. Next, validity of findings from theoretical studies was verified using experimental studies in laboratory. Finally, the results clearly demonstrate that the advanced air-coupled sensor array significantly improves test speed and accuracy of signal interpretation of IE test results. This will increase the feasibility of air-coupled sensing in actual impact echo testing on concrete bridge decks.

8694-47, Session 12

Designing 2D arrays for SHM of planar structures: a review

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2-D ultrasonic phased arrays, due to their beam-steering capability and all azimuth angle coverage are a very promising tool for SHM of plate-like structures using Lamb waves (LW). Linear phased arrays that have been proposed for that purpose produce mirrored image characterized by azimuth dependent resolution, which prevents unequivocal damage localization. 2D arrays do not have this drawback and they are even capable of mode selectivity when generating and receiving LWs.

In this paper we propose a consistent methodology for three-step, theoretical, numerical and experimental investigation of diverse 2D array topologies in SHM applications. In the first step, the theoretical evaluation is performed using frequency-dependent structure transfer function (STF), which enables theoretical investigation of array performance in a dispersive medium for a predefined tone-burst excitation.

A dedicated tool for numerical simulations is proposed for the evaluation of 2D array beampattern in a specific structure. The simulations are performed using local interaction simulation approach (LISA), which enables time-efficient 3D simulations of LWs propagation.

Using scanning laser vibrometer is proposed for experimental verification, in a setup where LWs, excited by the PZT transmitters of the investigated array are sensed in multiple points corresponding to the locations of the 2D receiving array elements.

For illustration, beampatterns of three symmetrical 2D topologies, i.e., circular, star-shaped and spiral-shaped, are examined in the paper and compared in terms of their beam-width and side-lobes level. The effect of apodization applied to the array elements will be also investigated.

8694-48, Session 12

An ultrasonic wave-front with propagation direction dependent frequency

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The use of phased array methods are commonplace in ultrasonic applications, where controlling the variation of the phase between the narrowband emitters in an array facilitates beam steering and focusing. An approach is presented here, whereby all emitters in a 1 dimensional array are pulsed simultaneously, with a controlled bandwidth to emit a 2 dimensional wave. The key result is that one can generate a smooth, continuous wave-front emitted from the array, over a large solid angle, whose frequency varies as a function of angle to the array. Analytic and finite element models created to simulate this phenomena have been validated with experimental results using ultrasonic waves in metal samples. This pulsed approach provides a rapid means of flooding a region of space with a wave-front, whereby any wave that scatters or reflects off a body to a detector will have a distinct arrival time and frequency. This is a general wave phenomena with potential applications in radar, sonar and ultrasound.

8694-49, Session 12

The method to process ambient test data for unscaled flexibility identification

Jian Zhang, Southeast Univ. (China)

Flexibility identification using impact test data is meaningful for structural deflection prediction however impact test of civil infrastructures is expensive. Ambient test is easy to carry out but generally only produces basic modal parameters. In this article, a method is proposed to identify un-scaled flexibility from ambient data. It is derived that magnitudes of the frequency response functions (FRFs) estimated from the impact and ambient test data have a linear relationship in each mode, but the magnitude ratio in each mode is different. The way to calculate the magnitude ratio is proposed, thus un-scaled flexibility can be identified for un-scaled deflection prediction. Examples illustrates that the proposed method is effective to identify un-scaled flexibility from ambient data and the identified results are meaningful for structural damage detection and safety evaluation.

8694-50, Session 12

Overall evaluation light-weight composite pressure vessel with alloy liner by acoustic emission and Bragg grating

Junqing Zhao, Xiaodong He, Rongguo Wang, Wenbo Liu, Harbin Institute of Technology (China)

Light-weight carbon fiber composite pressure vessel with inner thin-wall aluminum alloy liner has main problem of local buckling during manufacture and working process. The approach of acoustic emission and Bragg grating are adapted to monitoring the light-weight composite vessel under water pressure. Two channels of acoustic emission were bonded to before dome and cylinder to monitoring the performance of the vessel withstanding maximum 4.5MPa water pressure during loading, maintaining and unloading. Meantime electric strain gauges were attached to aft dome and cylinder of the outer surface by hoop and meridian direction respectively to test the vessel behavior. Ten Bragg sensors were arranged corresponding with the strain gauges position in order to monitor the vessel behavior. Analysis indicated Bragg sensors can evaluate outer surface behavior of the vessel with pressure and fit well with strain gauges. AE character parameters analysis illustrated the local buckling of inner thin-wall liner.

8694-71, Session 13

Structural noise reduction in lock-in thermography imaging of composites by time-domain reconstruction and spatial slope correction

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Lock-in thermography is a popular thermal non-destructive testing (TNDT) technique which like other active thermographic techniques, requires an external heating stimulus, preferably on a blackened surface. It is however, not immune to non-ideal situation like non-uniform heating and surface emissivity variation.

The phase image helps to reduce the effect of surface emissivity variation to some extent, but is inadequate in case of large variations. For example, reflecting surface patches on a poorly blackened metallic sample cannot be treated with phase image alone.

Further, structural noise can significantly interfere with the process of defect detection, as in the case of carbon fibre composite materials.

This paper proposes an image reconstruction algorithm for off-line reduction of such artifacts arising from internal structure and surface emissivity variation of the test piece. Additionally, the proposed algorithm enables lock-in thermography tests in transient regime, and removes temperature gradients due to non-uniform heating.

The proposed algorithm works in five steps -- 1) DC trend removal by time domain polynomial fit, 2) phase and amplitude image extraction, 3) time domain video reconstruction, 4) optimal frame identification, and 5) heating non-uniformity correction by 3D polynomial fit.

The algorithm is successfully demonstrated on a carbon fibre test piece, having 6,mm back drilled holes at various depths ranging from 0.25,mm to 2,mm in steps of 0.25,mm. The algorithm has also been deployed on a poorly blackened mild steel test piece having reflecting surface patches.

8694-72, Session 13

A comparison of thermal responses of CFRP composites due to low energy impact and defect growth due to post-impact vibration using infrared thermography

Sri Naga Pavan Addepalli, Kelvin E. Donne, Swansea Metropolitan Univ. (United Kingdom); Ian R. Cooper, TWI Ltd. (United Kingdom); Owen Williams, Swansea Metropolitan Univ. (United Kingdom); Benjamin Dutton, TWI Ltd. (United Kingdom)

Carbon Fibre Reinforced Polymers (CFRP) are used increasingly as primary structural components in aircraft due to their excellent strength-to-weight ratio and corrosion and fatigue resistance. Detection of low-energy impact damage occurring on such materials using conventional and advanced Non-Destructive Testing (NDT) methods is an enormous challenge. Research shows that the heat produced by a CFRP composite during impact can be captured with an infrared camera operating at high frequencies (900Hz). This study used infrared thermography to monitor the material condition of 3mm and 6mm thick CFRP samples before, during and after impact. A number of 120mmxl240mm CFRP samples were made using a 120GSM unidirectional carbon prepreg material in a hot press at a temperature of 120°C, a pressure of 2 Tonnes and a curing cycle of 60 minutes. These samples were subjected to impact testing at energies ranging from 7J to 20J using modified charpy and drop testers. High speed visual and infrared cameras captured the event and heat produced during impact on the impact and non-impact side respectively. The impacted samples were then inspected using a pulsed thermography system and the damage was recorded. The samples were then subjected to vibrations using a shaker and the defect growth was monitored using the infrared camera alongside a Laser Doppler Vibrometer (LDV). The samples were inspected again using the pulsed thermography system. Results were then correlated to provide a unique understanding of defect morphology from initial impact through the growth period due to vibration.

8694-73, Session 13

Non-destructive evaluation of photovoltaic cells using Photothermal beam deflection technique

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Photothermal (PT) techniques offer large range of methods by which the materials can be evaluated non-destructively. PT techniques for thermal NDE were first developed around 1980 and have ever since been in use for a wide range of spectroscopic and imaging applications [1, 2]. Photovoltaics (PV) is one of the most promising future energy technologies, but dearth of techniques for non-destructive evaluation and testing poses a large barrier, impeding high performance and cost effective solutions. PT techniques are based on detection of heat generated from the samples due to non-radiative deexcitation processes [3]. Light absorbed by the solar cell is converted into electrical energy, but not all light absorbed is converted to useful current and most of the light absorbed is lost as radiative and non-radiative emission into the surroundings.The photovoltaic conversion efficiency is thus limited by photothermal and photoluminescence conversion efficiency. Thus the intensity of the PT signals is proportional to the conversion efficiency of light into heat and inversely proportional to all other photoinduced energy conversion processes [4].

In this work we use photothermal beam deflection technique (PTBD) in the skimming configuration for measuring the transport properties of thin film solar cell layers. The principle and advantageous of this technique have been reported earlier [5]. This paper reports on the use of this technique for NDE of photovoltaic cell parameters like series resistance, optimum load resistance and efficiency. PTBD is found to be a simple and reliable tool for characterization of PV devices. The measured values of the electrically measured characteristics agree well with those reported in literature. Transport properties of the p and n layers making the cell measured using PTBD correlate well with the open circuit voltage, short circuit current measurements of the cell. PTBD technique being a non-destructive tool and measurements being made under open circuit conditions, it was applied to analyse partially completed solar cells as well, yielding information about every process in fabrication sequence. Thus through this work we establish PTBD as a potential tool for effective monitoring of the industrial processes of device fabrication.

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8694-74, Session 14

Imaging and detection of cracks in metallic structures with Eddy current sensors

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In this paper, we will we will focus on the modeling of electromagnetic systems, in the aim of using it in an inversion scheme. The purpose will consists in imaging cracks with eddy current sensors, through an estimation of the conductivity of the piece of metal under test.

In order to achieve a realistic and reliable imaging technique, the first step consists to build an instrument that is capable of creating eddy currents in a given direction and at a given frequency in the material under inspection. To that purposes, an original Eddy Current (EC) imaging device was developed at the SATIE laboratory. The device uses an inducer able to generate a uniformly oriented EC with the material, and a linear magneto optical imaging film which actually translates the surface magnetic map into light intensity, detected through an optical setp up and a CCD camera in a stroboscopic framework

The basic imaging process required the knowledge of a direct model, which can be used afterwards in an inversion scheme. The authors used a relatively new developed technique, called 'Distributed Points Source Method' (DPSM) to model a simplified EC device. Our model was then used to build a global inversion scheme based on a multi frequency approach.

In the last part of the paper, the inversion scheme will be tested with imported images obtained with cracks with different shapes and different depths.

8694-75, Session 14

Multiple defect interpretation based on Gaussian processes for MFL technology

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Magnetic Flux Leakage (MFL) technology has been used in non-destructive testing for more than three decades. There have been several publications in detecting and sizing defects on metal pipes using machine learning techniques. Most these literature focus on isolated defects, which is far from the real scenario.

This study is towards generalization of the interpretation of the leakage flux in the presence of multiple defects based on simulation models, together with data-driven inference methodologies, such as Gaussian Processes (GP). An MFL device has been simulated using both COMSOL Multiphysics and ANSYS software followed by prototyping the same models for experimental validations.

Multiple circular defects of a certain depth were introduced on a cast iron pipe sample and both radial and axial components of the leakage field have been measured. It was observed that both axial and radial components differ with different defect configurations. We propose to use GP to solve the inverse model problem by capturing such behaviors, i.e. to recover the profile of a cluster of defects from the measurements from the MFL device. The data was used to learn hyper parameters of the GP model with squared exponential covariance function and automatic relevance determination to solve this regression problem.

Extensive quantitative and qualitative evaluations are presented using simulated and experimental data that validate success of the proposed non-parametric methodology for interpreting the profiling of clusters of defects with MFL technology.

8694-76, Session 14

A novel methodology to determine needle position for DC potential difference method to evaluate quenching depth from surface

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DC potential difference method are simple and fast non destructive testing method.

It measures voltage between two points on surface touched by each needle.

In some kind of engineering structural member, neighborhood of iron surface is required to have higher hardness than normal iron's one.

To meet this demand, quenching process is a popular process to make iron hard from surface and quenching depth is important parameter to be ensured in target member after process.

Because quenched iron increases its resistance by 20%, D.C.potential method is able to be used for evaluating quenching depth.

However output voltage was insensitive for change of deep quenching depth over 5.0mm, measurement would fail over 2.0 mm with improper needle array probe in reality.

We developed a novel methodology to determine needle positon to improve its applicability over 5.0 mm depth which is demanded in some member.

In this methodology, needle position are optimized for cost function that is voltage gradient to quenching depth.

Throughout this optimization, (1) an analytical expression of surface voltage which are obtained solve Laplace equation in three dimensional space. (2) CAS system (Maple / MAXIMA) . are invoked.

Experimental data shows good coincidence to those numerical computation, and monotone increasing property of voltage to depth are kept up to 10 mm quenching depth.

Proposed needle positions have made DC potential difference method possible to evaluate quenching depth over 5.0 mm.

8694-51, Session 15

Acoustic emission remote sensing of thermal protection system performance with elastic waveguides

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This paper will describe measuring the performance of thermal protection system (TPS) materials during high heat flux loading with acoustic emissions passed through an elastic waveguide. TPSs are critical components onboard space vehicles that undergo hypersonic atmospheric reentry maneuvers. Detecting TPS breakdown during highly energetic heating events is nontrivial due to the temperatures involved – often in excess of 1000 °C. Many sensors cannot tolerate such conditions. Previous studies indicated that it is possible to detect different types of thermal heating conditions on different TPS materials via waveguided acoustic emissions. The test facility is a laboratory-based plasma torch that operates in a partial vacuum to apply high heat loading on cylindrical samples of TPS material approximately 20 mm in diameter and 30 mm long. The sample chuck attaches to an elongated rod with an internal water cooling line and extends through the wall of the vacuum chamber. This rod is the acoustic emission waveguide. Elastic events generated by the intense heating on the sample travel down the waveguide to an acoustic emission sensor placed outside of the hot vacuum chamber and in normal room conditions. Statistical pattern recognition methods tease out the different test conditions from the voluminous acoustic emission data. This work extends these preliminary proof-of-concept tests by a more detailed study of the sensing technique and waveguide performance and uses the measurements to better understand different thermal loading environments on different TPS materials.

8694-52, Session 15

Digital image correlation and distortion correction for creep deformation measurement of high temperature components

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Creep is one of the most serious high temperature damage mechanisms, and its measurement is of crucial importance in maintaining the safe operation of power plants. Optical techniques especially digital image correlation (DIC) seems the only practicable technique that can be applied in-situ. This paper presents a new high temperature DIC system for creep measurement. Telecentric lens is used to acquire sequential images of a test piece at high temperature. Due to air flow and temperature gradient, the grey level of every pixel in the images tends to change randomly over time. This results in image distortions which must be corrected before accurate strain measurement can be made using DIC technique. To this end, an Adaptive Image Filtering (AIF) algorithm is developed. It is based on probability of intensity distributions, and has the advantage of suppressing image distortion while maintaining spatial resolution of the original images. After AIF, an optimal image is formulated to represent each set of sequential images which are acquired over different periods of time. DIC is used to calculate the strain between different images pairs. Preliminary results from controlled high temperature (600-700°C) experiments on P91 steel samples demonstrated the effectiveness of the technique and algorithm

8694-53, Session 15

LiDAR scan and smart Piezo layer combined damage quantification

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Large deformations of structures are difficult to quantify due to the external deformation and the internal residual stress distribution. LiDAR uses rays of laser beams to measure position data that produces a point cloud that provides a 3-dimensional description of the deformed. Piezoelectric (PZT) smart layer generates internal stress distribution using actuator/sensor network that generates and receives high frequency wave signals that permeate through the interior of a structure. The severity or quantity of the damage is illustrated by a graduated color scale and adjustable threshold value. This paper suggests the combination of the two technologies to provide a full-field imaging of the damaged state of a structure and reports the results of an experiment done on a 16 inch x 16 inch aluminum plate subjected to five damage scenarios. In order to effectively analyze the results, the images for from each sensor system were superimposed. Frequencies that depicted the best interpretation of damage in the direct path (PZT) images were superimposed with the 3-dimensional LiDAR images. Four damage scenarios were imposed on an aluminum plate including saw cuts at different depths using an electric saw. The final damage is a severe bending of the plate. The bending of the specimen produced an image that located the most severe damage directly under the left hand portion and directly above the right hand portion of the bend. The results can be presented in three-dimensional imagery to best illustrate the full condition of the damage.

8694-54, Session 15

Bolted-connection modeling and validation through laser-aided testing

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Bolting is a commonly used connection method for extending structural members' length. Bolted flange plate connections are widely employed in high-rise facility structures, such as light masts, transmission poles, and wind turbine towers. Complex connection behavior plays a significant role in the overall dynamic characteristics of a structure by directly influencing the natural frequencies, mode shapes, and responses to external excitation. A finite element (FE) modeling study of a bolt-connected square tubular steel beam is presented in this paper. Various modeling techniques, including a 3D solid model and a simplified spring model, were explored for the bolt joint simulation. Modal testing was performed in a controlled laboratory condition to validate the FE model, developed for the bolted beam. A small shaker was used to excite the suspended beam and two commercially available laser Doppler vibrometers, a portable single point digital vibrometer and a scanning vibrometery system, were used simultaneously to measure structural vibration. The single-point laser vibrometer was used as a reference while the scanning laser acquired vibration data. A series of tests were conducted with variable bolted connection states; the bolts being set to different pressure states to simulate possible loosening damage. This study is one of a group of on-going efforts to marshal knowledge associated with detecting damage on bolted structures. Vibration monitoring, in conjunction with numerical modeling of the structure, is proposed for assessing structural integrity based on a proper evaluation of the connection conditions.

8694-55, Session 15

Full field displacement measurement by double symmetrical illumination with diode lasers through a pair of double exposure reflection holograms

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Compact phase stepping interferometer for shape and full field displacement measurement in static and in "real time" operation mode is presented. Double symmetrical illumination of the object in two orthogonal planes with diode lasers, emitting in NIR (790 nm and 830 nm), through a pair of double exposure reflection holograms of a reference plane is applied. Diode lasers without collimators and spatial filters are used directly for reconstruction of the reference planes and for object's illumination through the holograms. Phase stepping is introduced simply by precise increments of the diode lasers current. By introduction of removable sinusoidal phase gratings and removal of the holograms, the system operates as a single-shot fringe projection profilometer. The proposed system is very stable against external noise, produced by vibrations, temperature changes, air flows, as well as against the influence of object's "rigid body" motion. The first, second and mixed derivatives of the components of the displacement vector could be used for calculation of the in-plane normal strain, shear strain, in-plane rotation, as well as out-of-plane rotation (tilt), stresses and bending moments. Precise information for displacement vector's components and their derivatives are essential for quality control, failure prediction and early detection of critical zones with abnormal mechanical behavior of loaded objects, due to voids, cracks, fatigues and other stress concentrators. The developed system is compact and suitable to perform measurement in "real" time operation mode, which is essential for measurement of composite and other materials with non linear mechanical response.

8694-77, Session 16

Nondestructive Examination for Light Water Reactor Sustainability: Needs and Research Priorities

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In the United States, an initial 40 year operating license is granted for nuclear power plants with the opportunity to apply for multiple 20 year license extensions. Ten reactors have already entered the first phase of long term operation (LTO) (operation between 40 and 60 years) and nearly all of the remaining reactors have already received their first 20 year license renewal or have applications pending. The Light Water Reactor Sustainability (LWRS) program is a U.S. Department of Energy effort aimed at further extending the lifetime of currently operating nuclear power reactors as part of an overall strategy to ensure future energy security. The focus of R&D under this program is to address the technical challenges that are expected to be life-limiting. One of the technical pathways in the LWRS program is focused on light water reactor (LWR) materials. Materials degradation in passive components is considered a potentially significant challenge for ensuring the safe operation of plants as they enter advanced phases of LTO; the ability to monitor and correctly interpret the condition of passive components is considered key to mitigating the consequences of aging degradation. A recent series of workshops was held to identify the nondestructive examination (NDE) needs for LTO and define a research roadmap to address these needs. To facilitate roadmap development, passive components in LWRs were further categorized into cables, concrete, reactor pressure vessels, and piping. This paper will summarize the outcomes of these workshops and describe the resulting roadmaps.

8694-78, Session 16

Development of an automated scanner and phased array ultrasonic testing technique for the inspection of nozzle welds in the nuclear industry

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Regular in-service inspection is important to verify the integrity of welded nozzle sections in the nuclear industry. Nozzle sections can be susceptible to crack growth due to thermal fatigue and stress corrosion. Early detection of cracks is therefore essential to ensure the continued safe operation of the facilities. In order to reduce the time and cost of such inspections there is a need to develop a system capable of performing a full inspection of nozzles without the need to change probes. The aim of this project was to design an inspection system that is able to achieve the following: reduce the inspection times, improve defect detectability and sizing, and reduce human intervention, which will reduce workforce radiation uptake. The developed automated system reduces the requirement for complex robotic manipulation and consequently reduces the size and cost of robotic deployment systems. This paper will present the inspection technique development and ultrasonic simulation using CIVA that was carried out to determine the most appropriate phased array probe and its detection capabilities. The parameters that are assessed are the beam propagation through the material, the beam coverage and the focusing characteristics of the beam as well as the defect response at critical areas of the nozzle. Furthermore, the developed automated inspection system and its functionalities will be presented together with experimental results from nozzle mock up samples with simulated defects at the nozzle to vessel weld.

8694-79, Session 16

Design, fabrication, and testing of YCOB high-temperature acoustic emission sensor

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Passive sensors have been incorporated in many industries for the purpose of health monitoring in structures. Although they are used so frequently, high temperature sensors in applications up to and exceeded 1000°C have many limiting factors, such as lifetime, chemical incompatibilities, and complexity. This temperature range is often reached in the energy, aerospace, and automotive fields, all of which have a vital need for health monitoring. Acoustic emission (AE) monitoring is a valuable tool in health monitoring because of the acoustic wave emissions that are associated with fatigue of structures and moving machinery. Piezoelectric sensors have shown promising results as AE sensors, but are often hindered by the loss of electric properties above temperatures in the 500-700°C range. Yttrium calcium oxyborate YCa4O(BO3)3 is one of the most promising new materials due to its high resistivity at high temperatures, and its relatively stable electromechanical coupling and piezoelectric properties across a broad temperature range. In this paper, a piezoelectric acoustic emission sensor will be designed, fabricated, and tested with YCOB single crystals for use in high temperature applications. An acoustic wave generated by a transducer outside of the furnace will propagate through an alumina rod into the furnace where the YCOB acoustic emission sensor is located. Charge output of the YCOB sensor will be collected using a lock-in charge amplifier. Sensitivity and frequency response will be investigated across a temperature range from room temperature to 1000°C.

8695-1, Session 1

Monitoring of corrosion damage using high-frequency guided ultrasonic waves

Paul Fromme, Univ. College London (United Kingdom)

Corrosion develops due to adverse environmental conditions during the life cycle of a range of industrial structures, e.g., offshore oil platforms, ships, and desalination plants. Both pitting corrosion and generalized corrosion leading to wall thickness loss can cause the degradation of the structural integrity. The nondestructive detection and monitoring of corrosion damage in difficult to access areas can be achieved using high frequency guided waves propagating along the structure from accessible areas. Using standard ultrasonic transducers with single sided access to the structure, guided wave modes were generated that penetrate through the complete thickness of the structure. The wave propagation and interference of the different guided wave modes depends on the thickness of the structure. Laboratory experiments were conducted and the wall thickness reduced by consecutive milling of the steel structure. Further measurements were conducted using accelerated corrosion in a salt water bath and the damage severity monitored. From the measured signal change due to the wave mode interference the wall thickness reduction was monitored. The high frequency guided waves have the potential for corrosion damage monitoring at critical and difficult to access locations from a stand-off distance.

8695-2, Session 1

Characterization of Lamb wave attenuation mechanisms

Daniel Schmidt, Deutsches Zentrum für Luft- und Raumfahrt e.V. (Germany)

This study investigates the attenuation mechanisms of Lamb wave propagation fields in order to describe the acoustic response of the actuator-sensor system.

In a first step the attenuation of different Lamb wave modes are experimental measured by air-coupled ultrasonic scanning techniques. Different plate materials, such as aluminum and quasi-isotropic CFRP (Carbon fiber reinforced polymer), are used. As a result, the attenuation of the A0 and S0 mode in a frequency range of 25 to 1000 kHz is measured.

In a next step an analytical model based on higher order plate theory is developed. With this model the dispersion diagrams as well as the damping characteristic of the plate materials are calculated. The solutions are compared with experimental data. Moreover, the dispersion diagrams are compared to the exact analytical solutions of elastic wave propagation, which is calculated by the transfer matrix method. The limitations of the higher order plate theory compared to the exact solution are discussed. Based on the experimental and analytical data the various attenuation mechanisms such as geometric spreading, absorption, leakage and dispersion are characterized for different Lamb wave modes.

Finally, the attenuation mechanisms are considered in the calculation of Lamb wave mode tuning curves.

8695-3, Session 1

Structural health monitoring and damage prognosis in composite repaired structures through the excitation of guided ultrasonic waves

Sofia Pavlopoulou, Keith Worden, Constantinos Soutis, The Univ. of Sheffield (United Kingdom)

The interest in composite repair technologies has been recently increased following the wide applications of composite materials in aerospace industry. Bonded repair patch technology provides an alternative to mechanically fastened repairs with significantly higher performance. The work here demonstrates two case studies: a woven composite panel repaired with an external composite patch and a woven composite panel with a scarf repair that minimises discontinuities and provides smoother surface. In the first case, piezoelectric (PZT) transducers were surface bonded and the propagation of the symmetric and anti-symmetric Lamb waves modes were investigated while the panel was subjected to fatigue loading. In the second case, piezoelectric transducers were utilized in order to excite low frequency Lamb waves while the panel was tested under static tensile loading. Along with Lamb wave testing, additional techniques were used to monitor the extent of the developed damage such as 3-dimensional Digital Image Correlation, X-ray radiography and optical microscopic analysis. All signals in both cases were further processed with outlier analysis and linear and non linear principal component analysis in order to develop an appropriate damage prognosis strategy. The current work identifies the problems of the traditionally used novelty detection approaches and proposes solutions through the concept of principal curves and appropriate feature extraction techniques.

8695-4, Session 1

Lamb Waves in a Honeycomb Composite Sandwich Plate

Fabrizio Ricci, Univ. degli Studi di Napoli Federico II (Italy); Ajit K. Mal, Himadri S. Samajder, Harsh K. Baid, Univ. of California, Los Angeles (United States)

Honeycomb composites are used in many aircraft, aerospace and structures due to their high stiffness to weight ratio and other desirable properties. However, composite materials in general are susceptible to internal damage that can occur during manufacturing and/or service of the structure resulting in significant loss of their load carrying capacity. Thus safe operation of such defects critical structures requires careful monitoring to detect, characterize and repair any emerging or existing hidden damage in their primary components during the life of the structure. Ultrasonic waves are widely used to detect damage in both metallic and composite structures, and the analysis of their interaction with defects gives important information on the state of health of such structures. In particular, guided Lamb type waves are being studied intensively for applications in wide area inspections. Effective use of ultrasonic waves requires a clear model-based understanding of their characteristics as they propagate in the structure of interest. Such an understanding is currently lacking for honeycomb composites due to the geometrical complexity and paucity of published work in this general area. A detailed study of ultrasonic guided waves propagating in a honeycomb sandwich plate consisting of an aluminum honeycomb core and woven composite face sheets is carried out in this paper. A coordinated analytical, numerical and experimental work is used to characterize the material properties of the sandwich structure, to determine the propagation characteristics of the guided waves and the response of the plate to localized dynamic loads representative of surface mounted transducers. The results of this study should be useful in developing reliable NDE methods for the detection of hidden defects in sandwich structures.

8695-5, Session 1

Phased array design for optimized directivity behaviour in guided wave applications

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Guided Lamb waves in the ultrasonic range have potential for structural health monitoring of thin structures, e.g. for the detection of impact damages which may cause delamination in carbon fibre reinforced materials. For the emission of guided waves piezoelectric transducers can be used which are applied to the surface of the structure.

By using a phased array of transducers a directivity pattern for the inspection of a limited area on the structure can be created with common beam forming algorithms. Line arrays require only a small number of transducers but the main lobe is generated on both sides of the array which means an excitation towards an unwanted direction is produced.

In this contribution a 2D array design is introduced which tends to emit only one main lobe towards the direction of interest. The concept basically utilises two parallel line arrays. Both arrays emit signals with a single burst. The signal emitted by the second line array is meant to suppress the unwanted lobe of the main array by out-of-phase superposition. This requires an appropriate timing of the emission of the signals of the single transducers.

The feasibility of the concept has been studied by simulation. Practical experiments on CFRP sheets have been carried out with array layouts of up to sixteen single piezo transducers. A PC-controlled electronics system has been used for the actuation of the transducers. Emission and directional behaviour of the Lamb waves on the structure has been monitored with a Laser scanning vibrometer.

8695-6, Session 1

Detection of impact damage in composite panels using guided ultrasonic waves

Bibi Murat, Paul Fromme, Univ. College London (United Kingdom)

Composite materials such as carbon fiber reinforced panels offer many advantages for aerospace applications, e.g., good strength to weight ratio. However, impact during the operation and servicing of the aircraft can lead to barely visible and difficult to detect damage. Depending on the severity of the impact, fiber breakage or delaminations can be induced which reduce the functionality of the structure. Efficient structural health monitoring of such plate-like components can be achieved using guided ultrasonic waves propagating along the structure and covering critical areas. However, the guided wave propagation in such anisotropic and inhomogeneous materials needs to be understood from theory and verified experimentally to achieve sufficient coverage of the structure. Using noncontact laser interferometer measurements the guided wave propagation in carbon fiber reinforced panels was investigated experimentally. Impact damage was induced in the composite panels and the guided wave scattering at the damage measured and quantified. Good agreement with theoretical wave propagation predictions was found and barely visible impact damage in composite panels detected.

8695-7, Session 2

Structural Health Monitoring of Bridges using Digital Image Correlation

Christopher Nonis, Christopher Niezrecki, Tzu-Yang Yu, Univ. of Massachusetts Lowell (United States); Timothy E. Schmidt, Trilion Quality Systems (United States); Shafique Ahmed, Che-Fu Su, Univ. of Massachusetts Lowell (United States)

Due to the aging civil infrastructure (i.e. bridges), there is a critical need for monitoring and assessing structural integrity of large scale structures. According to the ASCE, in 2008, the average bridge in America was 43 years old and 161,892 bridges were structurally deficient or obsolete. Currently, bridge health is assessed primarily using qualitative visual inspection, which is not always reliable because some damage is difficult to detect or quantify visually. Traditional sensors such as strain gages, and displacement sensors, have been recently used to monitor bridges. These sensors only measure at discrete points, making it difficult to detect damage that is not in the proximity of the sensor or is difficult to interpret. To rectify this drawback, this paper presents results of using three dimensional digital image correlation (DIC) as an approach for bridge structural health monitoring.

3D DIC is a non-contact, full field, optical measuring technique that uses digital cameras to measure surface geometry, displacement, and strain. DIC can be used for monitoring by imaging a bridge periodically and computing strain and displacement from images recorded at different dates or operating conditions. In this paper, DIC is shown to locate non-visible cracks, quantify spalling, and measure bridge deflection. These techniques are first demonstrated on a three-foot reinforced concrete beam in the laboratory. Field measurements are also made on three full-scale bridges. This paper discusses challenges and solutions to implementing DIC on large structures in the field. The results reveal that DIC is an effective approach to monitor the integrity of large scale civil infrastructure.

8695-8, Session 2

Real-time structural health monitoring of live loads on a flat commercial roof

Ok-Youn Yu, Stacy Moore, Appalachian State Univ. (United States)

Deployment of wireless monitoring systems provides real-time data to address safety issues and the concerns of structural loading. Processes of early damage detection using wireless networks are increasingly being used to guide the decision-making process in risk management in the aging stock of existing buildings. Data attained in the analysis of typical building styles will have great scientific value in estimating changes in structural performance due to redesigned building uses. The Department of Technology and Environmental Design at Appalachian State University, NC, USA, is in the process finding a dedicated solar lab space for its Appropriate Technology Program, which has been a highly recognized for its research and educational efforts over the last 20 years. The program currently combines classes and lab space into a single room, which does not adequately meet the academic needs of the students and program. One location that could help meet these needs is the flat roof on Katherine Harper Hall. Here students would not have to wheel their undersized projects through the doors of the building to search for a sunny workspace, which is tough to find given the steeply sloped and highly shaded nature of the site. In this research project, the following topics are addressed: [1] Safety - The development of an early warning system to address safety issues due to live structural loading associated with the installation of solar collectors, rack equipment, students and instructors on top of an existing roof; [2] Wireless Monitoring Systems - Sensors are mounted to beams which measure and relay real-time data by radio to personnel via a computer network who can use the information for active load monitoring and future research. There is an increased interest in sensing technologies to meet the challenges in the engineering and construction fields. These technologies will help us better monitor and evaluate structural performance and health.

8695-9, Session 2

Applications of inter-digitized transducers (IDTs) for structural health monitoring (SHM) of bridge structures

Jeong-Kwan Na, Sean T. Gleeson, Edison Welding Institute (United States)

Ultrasonic surface wave generating inter-digitized transducers (IDTs) have been designed, fabricated and applied to a simulated critical component of bridge structures, which represents part of steel bridge structures. Goals of the current investigation are determining the minimum number

of IDT sensors required to achieve the maximum monitoring coverage over a given gusset plate design as well as the size and the optimum operating frequency. These sensors can be customized depending on SHM applications. Various sizes of sensors ranging from several centimeters to several millimeters with resonance frequencies between 100 KHz and 3 MHz are tested. IDT sensors operating at 1 MHz with the overall physical dimensions of 15 mm x 17 mm were found to give the best coverage with a minimum number of sensors. A second test component investigated in this work is a dog-bone shaped fatigue test specimen with two wing-like attachments fillet welded perpendicularly. The main goal for this fatigue testing is to find out how early in the fatigue process a failure in the fillet welds can be detected with ultrasonic surface waves. Changes in the amplitude of surface waves are monitored for this study and an indication of welded parts separating from the main dog-bone shaped piece detected from the result of fatigue test. From a close examination of the welded section, no visible separation of wing-like parts has been noticed, especially near the weld toes. Detailed discussions on the analysis of ultrasonic surface signals are given in this work.

8695-10, Session 2

Site-Specific Live Load Factor Calibration for Weigh-in-Motion Sites with especially heavy traffic volume

Hua Zhao, Hunan Univ. (China); Shiyong He, Guilin Economy Construction Investment Cooperation (China)

The selection of appropriate live load (LL) factor for different type of heavy vehicles plays an essential role in the assessment of existing bridges, especially for the sites with ADTT over 5000. The LL factors in the AASHTO Load and Resistant Factor Rating (LRFR) Manual are based on Ontario load data and thought to be representative of bridges nationwide with similar traffic volumes. However, for evaluation of existing bridges, it will be more accurate and reliable to apply site-specific information, rather than rely on generalized information, to characterize the local uncertainty. Following the methodology for developing site-specific LL factors in the provisions of the LRFR Manual, LL factors for two weigh-in-motion (WIM) locations in Alabama with heavy traffic volume over 5000 were calibrated in this paper. WIM Data was collected throughout the year and in both travel directions to account for possible seasonal and directional variations. Different WIM data collection windows were also analyzed to determine the minimum required collection window to achieve statistically valid results. WIM records were categorized based on the unique truck permitting conditions in the state. The process for LL factor calibration maintained the nationally accepted structural reliability index for evaluation. The calibrated site-specific LL factors demonstrated that the analysis of WIM data in Alabama resulted in lower LL factors for both two sites than those presented in the LRFR Manual. It is recommended that Alabama DOT apply these lower LL factors to more accurately represent the load rating of bridges with especially heavy traffic volume.

8695-11, Session 2

Damage identification utilizing dynamic deflection of bridge structure under vehicle loading

Zhen Sun, Yozo Fujino, The Univ. of Tokyo (Japan)

Method utilizing dynamic deflection for damage identification of bridge structures under vehicle loading is proposed. Damage is modeled as local reduction of flexural rigidity. Vehicle model moving at constant speed is analyzed with Newmark method in Matlab, incorporating the effect of road surface roughness and vehicle-bridge interaction. Road surface profile is generated with power spectral density functions. Bridge model is established in Finite Element software ABAQUS. Interaction between vehicle and bridge is realized through a global iteration procedure, which obtains the interaction force on bridge from dynamic analysis of vehicle model in Matlab, then input to the bridge model in ABAQUS. On the other way, displacements at different contact points from bridge FE model are extracted and incorporated in vehicle model input, along with road surface roughness function. Iteration is performed until compatibility at contact points is satisfied, which ensures the same displacement between vehicle and bridge at the contact points. The dynamic deflection is utilized to locate the damage. The vehicle passes through every section of the bridge, therefore the response will include the information when the vehicle is applied on the damage part. The damage causes larger deformation and nonlinearity in the time history of the dynamic deflection response. Once the damage is identified in time history of dynamic deflection, it can be transformed to space domain to locate the damage. This proposed method is verified by numerical study. Influences of vehicle speed, road surface condition and sensor location on damage identification are discussed.

8695-12, Session 2

Structural Health Monitoring of a Large Span Cable Structures based on FBG sensors

Yuxin Zhang, Shanghai Normal Univ. (China)

As one of the most important invention in measurement fields in the 20th century, the technology of FBG has been greatly developed, and it has been the advanced research and applications in many areas. In this paper, a new SHM(Structural Health Monitoring) technique for large span cable structure based on FBG sensors is proposed. In this technique, FBG sensors are installed on the two sides of anchor head of cables instead of being installed directly on cable. The relationship between wave length change of FBG sensors and cable tension change is calibrated in cable production factory during the production period of cables. The calibration considering several upload and download cycles is conducted and analyzed to study the technique's availability. The results by using one side data, two sides data and the average data of two sides are compared to study the eccentricity effects of installation. Finite element analysis is conducted to decide the optimal sensor position. Other factors related to the technique are also introduced such as the sensors' installation requirement and skills, the effects of temperature and the practical application effects. The paper can provide helpful reference for the SHM of large span cable structures.

8695-13, Session 3

Damage detection in reusable launch vehicle components using guided ultrasonic waves and 3-D laser vibrometry

Wieslaw J. Staszewski, AGH Univ. of Science and Technology (Poland); David Barnoncel , EADS Astrium (France); Jochen Schell, Polytec GmbH (Germany); Patrick Peres, EADS Astrium (France)

Reusable Launch Vehicles are often used in space applications to guarantee space exploration with reduced costs. These structures often use components from newly developed materials. It is inevitable that reliable inspection methods will be required for quality control and maintenance of such structures to avoid potential damage. Recent years have shown many applications of guided ultrasonic waves for structural damage detection. It appears that Lamb wave are the most widely used guided ultrasonic waves for structural damage detection. Various methods have been developed for Lamb wave generation and sensing. The approach based on non-contact laser vibrometry is particularly attractive for monitoring of large plate-like structures.

This paper describes some initial results from evaluation tests based on Lamb waves for damage detection of Reusable Launch Vehicles composite components. Low-profile, surface-bonded piezoceramic transducers were used for Lamb wave generation. Non-contact measurements of Lamb wave responses were taken by a laser

vibrometer. The results presented in this paper demonstrate the great potential of the method for quality inspection and structural damage detection of space composite structures.

8695-14, Session 3

Effect of Uncertainty in Material Properties on Optimal Layout of Sensor Network for Achieving Highest Probability of Damage Detection in Structures

Kuldeep P. Lonkar, Vishnuvardhan Janapati, Fu-Kuo Chang, Stanford Univ. (United States)

Structural health monitoring (SHM) based on acousto-ultrasound method has emerged as a promising technique for inspection of structural damage. Diagnostic stress waves are generated by piezoelectric actuators. While traveling through the structure, these waves interact with it; and give us the structural information at the sensors. Diagnostic algorithms are then used to detect, localize, classify, and quantify the damage. The detection capability of a given SHM system strongly depends not only on its algorithm, but also on the sensor-actuator density, their distribution, the hardware sensitivities, and uncertainties in the material properties of sensors and structure.

Recently, the authors have developed a spectral element method based simulation tool, Piezo Enabled Spectral Element Analysis (PESEA), to accurately model acousto-ultrasonic waves in complex structures. PESEA is further integrated with an analytical tool based on genetic algorithm to get an optimal sensor layout for a given structure to achieve maximum probability of damage detection (POD). However this deterministic approach does not address the key issue of the sensitivity of the sensor network to the variation in material characteristics of a real structure. The aim of this paper is to understand how the uncertainties in material properties of the sensors, adhesive, and the structure itself affect the POD for a given sensor network.

In this study, the above-mentioned challenge is overcome by the application of non-deterministic analyses. An investigation is performed using Monte Carlo method along with PESEA to quantify the variability in sensor signals due to uncertainty in material properties, and how it influences the POD. The variability in the sensor signals is then incorporated in the sensor network optimization tool. This paper will include results from the optimization tool using the non-deterministic approach. Sensor network will be optimized for a complex metallic structure for both accurate damage detection and localization. The paper will also include experiments to validate the proposed method.

8695-15, Session 3

SHM of Composite Structures Using Ultrasonic Guided Waves

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Advanced composites are being increasingly used in aircraft and aerospace structures. Despite their high structural efficiency, composite materials are often susceptible to hidden defects that may appear during their manufacturing and/or service of the structure. This paper is concerned with the detection and characterization of damage in plate like composite structures before they grow to a critical size. A careful theoretical, numerical and experimental analysis is first carried out on isotropic and anisotropic plates to identify the behavior of the transducers used to generate surface loads and record the signals during the experiments. The theoretical results are compared with those obtained from an explicit finite element (FE) code for their mutual verification, showing excellent agreement. This allows using FE models for more practical cases, for which the geometric and material complexities of actual structures present practical difficulties in direct analysis of wave propagation data using theoretical constructs only.

A methodology for a nearly automatic damage identification and localization based on the interaction of guided waves with damages in composite structural components is then described. The structure is assumed to be instrumented with an array of actuators and sensors to excite and record the waves propagating across the damages. A damage index, calculated from the measured waveforms at each sensor location in a previous (reference) state and the current state, is introduced as a determinant of structural damage. The method is based on the well known fact that the characteristics of the recorded waveforms are modified by the presence of emerging and growing defects in the vicinity of the array. This is particularly true for guided waves, which are strongly affected by delaminations and other hidden defects in their propagation path. The application of the damage index techniques is given form different structures and materials, including different experimental set-up where different sensors and waveforms are considered.

8695-16, Session 3

Predictive Modeling of PWAS-Coupled Shear Horizontal Waves

Ayman M. Kamal, Bin Lin, Victor Giurgiutiu, Univ. of South Carolina (United States)

This paper discusses shear horizontal (SH) guided waves that can be excited with shear type piezoelectric wafer active sensors (PWAS). The paper starts with a review of the state of the art in SH waves modeling and their importance in non destructive evaluation (NDE). This is followed by basic sensing and actuation equations of shear-poled PWAS transducers with appropriate electro-mechanical coupling coefficients. The electro-mechanical impedance of the SH-PWAS transducer is studied. The equations for shear stress transfer between PWAS and the structure are developed. The amplitudes of shear horizontal wave modes are normalized with respect to the wave power; normal mode expansion (NME) method is used to account for superpositioning multimodal SH waves. Modal participation factors are presented to show the contribution of every mode. Model assumption includes: (a) straight crested guided wave propagation; (b) evanescent waves are ignored; and (c) ideal bonding between PWAS and structure with shear load transfer concentrated at PWAS tips. Power and energy transfer between PWAS and the structure is analyzed in order to optimize sensor size and excitation frequency for maximum wave energy production for a given source. The paper ends with summary, conclusion and suggestion of future work.

8695-17, Session 3

Lamb waves in disbonded sandwich structures

Fabrizio Ricci, Univ. degli Studi di Napoli Federico II (Italy); Ajit K. Mal, Harsh K. Baid, Univ. of California, Los Angeles (United States)

Ultrasonic waves are widely used to detect damage in both metallic and composites structures, and the analysis of their interaction with defects gives important information on the state of health of such a structures. In honeycomb sandwich structures the geometrical complexity and the presence of certain irregularities such as the skin-celled core and disbonding, make the prediction of wave propagation using only theoretical approaches very difficult, except in highly idealized models.

In this paper ultrasonic wave propagation in a sandwich plate is investigated using theoretical, numerical and experimental approaches. The sandwich plate consists of two 1.78 mm thick woven composite skins and an aluminum honeycomb core of thickness 12.7 mm with an equivalent cell diameter of 5.5 mm. Due to the relatively low frequencies used in this work, both materials are assumed to be transversely isotropic with a common symmetry axis normal to the plate. For the damaged case, a 25.4 mm long disbond at the skin-core interface is assumed

to be present. In the experiments, the elastic waves are generated by broadband PZT transducers located on the plate surface and recorded by identical transducers placed at different locations on the surface near the disbonded region. As a consequence of the interaction between the propagating waves and the disbond, the signals recorded by the transducers are distorted relative to the baseline (i.e. no damage case). The simulations are carried out using the finite element codes, ABAQUS and LS-DYNA, for a two dimensional model of the problem in an effort to understand these features and to predict other expected features of the interaction process.

8695-18, Session 3

A new temperature compensation method for guided wave-based structural health monitoring

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When guided wave is used to monitor the health condition of complex structures, the measured signals are often far too complex to directly interpret. The simple but effective damage detection way is to subtract a signal captured during the operational life of the structure from that captured in a health state. However, guided waves are sensitive to changing operational and environmental conditions. This study proposes a new method combining optimal baseline selection and adaptive linear neuron network (ALNN) to effectively compensate the temperature effect. The experiment of guided waves propagating under changing temperatures (-40°C~80°C) is conducted on the stiffened composite plate to summarize some guidelines. This study focuses on three issues: (a) Establishment of temperature compensation standard; (b) Parameters design of compensation filter; (c) Determination of temperature gradient of baseline signals. The key is how to obtain the filter parameters under all temperatures. The procedure is described as follows. Step 1: the compensation standard is established; Step 2: the temperature gradient is adjusted accordingly as threshold; Step 3: The measured signal and the baseline signal are normalized and then input into ALNN to train the parameters of compensation filter; Step 4: The obtained parameters are optimized through minimizing the quadratic sum of the error between the measured signal and the reference signal within the entire time domain; Repeat above steps to obtain all the filtering parameters under all temperatures. Finally, experiments are also carried on the composite plate subjected to changing temperature to illustrate the feasibility of the proposed method.

8695-19, Session 4

Automated Extraction of Damage Features through Genetic Programming

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Robust damage detection algorithms are the first requirement for development of practical structural health monitoring systems. Typically, a damage decision is made based on time series measurements of structural responses. Data analysis involves a two-stage process, namely feature extraction and classification. While classification methods are well understood, no general framework exists for extracting optimal, or even good, features from time series measurements. Currently, successful feature design requires application experts and domain-specific knowledge. Genetic programming, a method of evolutionary computing closely related to genetic algorithms, has previously shown promise as an automatic feature selector in speech recognition and image analysis applications. Genetic programming evolves a population of candidate solutions represented as computer programs to perform a well-defined task such as classification of time series measurements. Importantly, genetic programming conducts an efficient search without specification of the size of the desired solution. This preliminary study explores the use of genetic programming as an automated feature extractor for two-class supervised learning problems related to structural health monitoring applications.

8695-20, Session 4

Technological challenges of developing wireless health and usage monitoring systems

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Health usage monitoring systems (HUMS) are being incorporated into an increasing number of applications, e.g. monitoring safety critical components in civil, aerospace, mechanical and other structures. A good example is the use of HUMS in monitoring transmission and drive train components on rotary-wing aircraft operating in extreme environments. These transmission HUMS have enjoyed success in predicting the deterioration of components, however, current system implementations rely on high-bandwidth hardwired sensors and significant data processing capability to perform feature extraction and classification, limiting the locations where they can be installed. To extend HUMS capability into new application areas, such as wind turbine blades or helicopter rotor head components, and other applications impossible to hardwire, the functionality of HUMS needs to be implemented within a wireless sensor network (WSN) . The power, processing and packaging constraints of a WSN present many challenges.

This paper initially considers the performance requirements of a conventional wired HUMS and contrasts this with that available from state-of the art WSN components. Technical issues related to power supply, sensor technologies, signal conditioning, damage detection and prognostic algorithms for low power microprocessors, robustness and data integrity on wireless radio are discussed. The paper further considers different approaches reported in the literature to overcome system limitations, such as the use of intelligent sensor nodes which perform local signal processing and transmit only reduced dataset. Finally a WSN architecture for HUMS is suggested along with operational methodology, and preliminary test results to illustrate the capability of real system components.

8695-21, Session 4

Integrated Non-destructive Approach for Damage Detection and Quantification in Structural Components

Prashanth A. Vanniamparambil, Jefferson Cuadra, Eric Schwartz, Antonios Kontsos, Ivan Bartoli, Fuad Khan, Drexel Univ. (United States)

Reliable damage detection and quantification is a difficult process because of its dynamic and multi-scale nature, which combined with material complexities and countless other sources of uncertainty often inhibits a single non-destructive testing (NDT) technique to successfully evaluate the extension of deterioration in critical structural components. This talk presents an integrated structural health monitoring approach (ISHM) for effective damage identification relying on the intelligent integration of the Acoustic Emission (AE), Guided Ultrasonic Waves (GUW) and Digital Image Correlation (DIC) methods. The proposed system has been validated by testing composite specimens, seven-wire steel strands and partially grouted concrete walls and is based on the cross-correlation of heterogeneous damage-related NDT features.

Conventional AE monitoring relies on damage monitoring by evaluating multiple extracted and/or computed features as a function of load/time. In addition, advanced post-processing methods including mathematical algorithms for statistical analysis and classification have been suggested to improve the robustness of AE in damage identification. Unfortunately, such approaches are often found to be unsuccessful, due to challenging environmental and operational conditions, as well as when used on actual c structural components, such as bridge cables and composite panels. This talk presents the framework for successful correlation of AE features with GUW and mechanical parameters such as full field strain maps, which can provide a route towards actual cross-validated damage assessment, capable to detect the initiation and track the

8695-22, Session 4

Error analysis of the extended Kalman filter applied to the simultaneous localization and mapping problem

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In the simultaneous localization and mapping (SLAM) problem, a robotic system acquires a map of its environment while simultaneously localizing itself relative to this map. A commonly utilized solution to the SLAM problem is based on the extended Kalman filter (EKF). Given observations and control inputs, the EKF calculates the posterior probability of the robot pose and map. The EKF estimates the mean and the associated error covariance of the robot pose and map features by using nonlinear motion and observation models. In this article, asymptotic stability of the EKF estimation errors is studied. Furthermore, the dependence of the error convergence on the observability property of the nonlinear system is also investigated. The efficacy of the EKF is studied both for the cases when kinematic and dynamic models are used to represent the robot motion. It is anticipated that the comparison in the EKF performance for kinematic and dynamic robot models will provide important insights into estimator design.

8695-23, Session 4

Corrosion monitoring system for aircraft structures

Giovanni F. Nino, QUEST Integrated, Inc. (United States)

With the increasing age of current military aircraft fleets, there is a need to increase structure reliability and availability while reducing maintenance costs. Usually, these structures operate in severely corrosive environments that overtime can compromise the integrity of the vehicle. To reduce this risk, comprehensive corrosion control programs are used to detect and mitigate any corrosion damage. Unfortunately, the costs of these programs are on the top maintenance expenses for the military or airlines in the case of civil aircrafts. One way to reduce the costs without compromising the structural integrity is by installing a sensing system to monitor corrosion in critical areas of the structure (hot spots).

In this paper, we will present an embedded sensor network for on-ground interrogation to monitor corrosion in the inner structure of the F15 wing trailing edge hinges. The current inspection procedure for this area requires an expensive disassemble operation that removes the upper wing skin every time. The embedded system assesses the state of the most sensible component in the structure by monitoring its condition for corrosion using guided waves. The interrogation process is performed by a handheld tool placed outside of the aircraft, it assesses the presence of corrosion and measures material loss in the structure. Acoustic Finite Element simulations and experimental tests were used to identify the proper system configuration and to validate the design. The sensing network, as well as the communication interface, is delivered as a kit for easy installation on the aircraft structure. Finally, it can be noted that the technology presented on this paper can be used to monitor and assess corrosion on “hot spots” not only on aircraft but also on pipeline structures among others

8695-24, Session 4

A design method research of an extensometer on extreme conditions

Jiuhong Jia, East China Univ. of Science and Technology (China)

Structural health monitoring is an emerging technology, which could improve the safety and maintainability of process industry, such as petrification, power generation, metallurgy, et al. However, there is few kind of sensing devices that can be used in extreme environment for long time monitoring. In order to solve this problem, an extensometer with two shoulders is designed and the mechanisms of deformation amplifier are analyzed. Moreover, the errors of the right circular flexure hinge are assessed and the ratio equation of the bridge-type displacement amplification mechanism is deduced. And then an extensometer basing on deformation amplifying mechanism is designed, and the theoretical equation is verified by FEM.

8695-25, Session 5

Nonlinear Guided Waves in Solids under Constrained Thermal Expansion.

Claudio Nucera, Francesco Lanza di Scalea, Univ. of California, San Diego (United States)

Propagation of nonlinear guided waves is a field that has received an ever increasing interest in the last few decades. They are excellent candidates for nondestructively interrogating long waveguide like structures since they conveniently combine high sensitivity to structural conditions (typical of nonlinear parameters), with large inspection ranges (characteristic of wave propagation in bounded media). Nonlinear wave propagation in solids has been classically studied using finite strains theory. According to this framework a system of nonlinear PDEs is required to mathematically describe nonlinear phenomena such as acoustoelasticity (wave speed dependency on state of stress), wave interaction, wave distortion, higher harmonics generation, and so on. This work introduces a novel physical model aimed at predicting nonlinearity in constrained waveguides characterized by infinitesimal (ideally zero) strains subjected to thermal variations. Interatomic potentials are employed to explain the origin of nonlinear effects under constrained temperature changes. These potentials highlight at least a cubic dependence on strain of the residual strain energy that is stored in the material due to the prevented thermal expansion. The cubic relationship between strain energy and strain produces second-harmonic generation of propagating elastic waves. This principle is validated experimentally for longitudinal bulk waves propagating in a steel block under constrained thermal excursions.

8695-26, Session 5

Monitoring ageing of Alkali Resistant Glass fiber reinforced cement (GRC) using Guided Ultrasonic Waves

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Glass fiber reinforced cement (GRC) is a composite made of Portland cement mortar and alkali resistant (AR) fibers. AR fibers are added to Portland cement to give brittle cement additional flexural strength, and toughness. However, with aging the glass fibers are deteriorated and as a result the improvement in the mechanical properties of GRC resulted from the fiber addition disappears. It is investigated here if the glass fiber deterioration and weakening of GRC can be monitored using ultrasonic

guided waves. As a GRC specimen ages and becomes weaker its degree of nonlinearity changes. This change in nonlinear behavior of the material can be monitored by propagating ultrasonic guided waves through the specimen. In this study, dynamic signatures of aging are identified in GRC and emphasized in nondestructive evaluation of GRC.

8695-27, Session 5

Fatigue Crack Detection using Guided Waves Nonlinear Modulation

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This paper presents a fatigue crack detection technique based on nonlinear modulation created by two mixing guided waves. Two independent input signals are generated using two surface-mounted PZT transducers; a high-frequency probing signal and a low-frequency pumping signal in the range of 10 to 100 kHz. Corresponding guided wave responses are measured by additional PZT transducers installed on a specimen. Similar to existing vibro-acoustic modulation techniques, the "sidebands" near the frequency of the probing signal are observed at the presence of crack. The uniqueness of this study lies in that (1) only the sidebands frequency components are isolated from measured raw signals by changing the input signal phases, (2) nonlinearity caused by the structural system is separated from additional inherent nonlinearity resulted from the measurement hardware system, (3) the frequencies of the probing and pumping signals are swept to increase crack detectability, and (4) a simple but effective damage classifier is proposed for autonomous monitoring. Actual fatigue cracks in thin and thick aluminum plates are successfully detected using the proposed technique in a laboratory setup.

8695-28, Session 5

Higher harmonic generation in a hollow cylinder for structural health monitoring

Yang Liu, Cliff J. Lissenden, Joseph L. Rose, The Pennsylvania State Univ. (United States)

Effective condition based maintenance founded on structural health monitoring depends on early detection and characterization of material damage. In a number of important instances the appearance of macroscale damage such as a crack occurs too late in life to make useful maintenance decisions. However, in metallic materials macroscale crack growth is usually preceded by microstructural evolution. For example, localized increase in dislocation density leads to microcracks, which link up to form fatigue cracks. In addition, void nucleation and coalescence along grain boundaries lead to creep-driven cracks. It is well known that lattice anharmonicity leads to the generation of higher harmonics when an ultrasonic wave is propagating, thus enabling correlation with microstructure evolution. Here, the generation of higher harmonics in a hollow cylinder are examined analytically, numerically, and experimentally. Analytical modeling and numerical simulation are used to guide experiments on a segment of tubing. The investigation is limited to axisymmetric primary modes, but both longitudinal and torsional type modes are considered. These primary modes have been shown to only generate longitudinal modes that are internally resonant (i.e., the amplitude of the higher harmonic increases linearly with propagation distance). It is well documented that internal resonance requires the primary and secondary wave fields to be synchronized and to have nonzero power flux. These considerations enable selection of both longitudinal and torsional primary wave fields that generate internally resonant second harmonics. The parallel to higher harmonics generated in plates is discussed. Experimental results using magnetostrictive transducers in a pitch-catch mode are presented.

8695-29, Session 5

A Hybrid Characterization Method for Fatigue Damage Using Nonlinear Lamb Waves and Piezoelectric Sensor Networks

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Nonlinear Lamb waves are highly sensitive to the microscopic plasticity-driven fatigue damage and are particularly suitable for damage detection in geometrically complicated structures to which the access is limited. A characterization method for fatigue damage in plate-like structures was established based on the nonlinear Lamb waves in conjunction with the use of a piezoelectric sensor network. A dedicated finite element (FE) modeling technique was developed, accounting for various sources of nonlinearities in the structure with fatigue damage. An acoustic nonlinearity parameter was introduced for quantifying the nonlinearity of captured Lamb waves. Piezoelectric sensor networks were constructed to quantitatively characterize the damage, using both i) the higher-order harmonic features of time-domain wave signals, including the time of arrival of the second-order harmonics; and ii) the correlation between the acoustic nonlinearity parameter and various sensing paths in the sensor network. A hybrid diagnostic imaging algorithm was further proposed, able to present the characterization results in intuitive diagnostic images. The approach was experimentally verified on a fatigue-damaged aluminum plate, showing reasonably good accuracy. Compared to the existing nonlinear ultrasonics-based inspection techniques, this proposed approach uses a permanently attached sensor network that well accommodates automated online health monitoring, and more significantly, it introduces the linear concepts to the signal processing of nonlinear Lamb waves, endowing the approach with a capacity of quantitative characterization of fatigue damage.

8695-30, Session 5

Nonlinear Elastic Imaging of low-velocity impact damage in Composite Structures using an Inverse Filtering approach

Francesco Ciampa, Michele Meo, Univ. of Bath (United Kingdom)

Developments in carbon fibres reinforced plastic (CFRP) materials have allowed a radical advancement in lightweight aerospace applications. Indeed, laminated composite structures can be tailored to display desired properties in specific directions and areas, such as high stiffness and strength. However, these components are sensitive to low velocity impact damages that can considerably degrade the structural integrity and, if not detected, they can result in loss of control and catastrophic failures of the vehicle.

Literature provides a quantitative number of diagnostic imaging methods that can continuously provide a detailed image of the structural damage. This paper presents a nonlinear Structural Health Monitoring (SHM) imaging method, based on ultrasonic guided waves (GW), for the detection of the second order nonlinear signature in a reverberant CFRP composite structure caused by a low velocity impact. In particular, this research study extends a recent published work by the same authors on the detection of the third order source in a composite sandwich panel, due to the presence of hysteretic material behaviour.

The proposed technique, based on a combination of second order phase symmetry analysis (PSA) with chirp excitation and inverse filtering (IF), is applied to a number of waveforms containing the nonlinear impulse responses of the medium. Phase symmetry analysis was used to characterize the second order nonlinearity of the structure due to delamination, by exploiting its invariant properties with the phase angle of the pulse compressed chirp signals. Then, the IF approach was applied to a number of waveforms stored into a database containing the experimental second order transfer function of the structure. Unlike other ultrasonic imaging methods, the present method allows achieving

the optimal focalization of the nonlinear source in the spatial and time domain, by taking advantage of multiple linear scattering and a small number of receiver sensors. In addition, this methodology does not require any baseline with the undamaged structure for the detection of the nonlinear source.

8695-31, Session 6

Detection, localization and energy quantification of shocks on mechanical structures using elastic energy flow estimators from piezoelectric sensors bonded on the structure.

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Detection, localization and energy quantification of impacts on a mechanical structure remains a major expectation in many themes, including that of structural health monitoring (Health monitoring). The most concerned areas are undoubtedly aeronautics and aerospace where the use of more frequent composite structures makes their health monitoring and control essential for obvious reasons of performance and safety. Locating, detecting and estimating the shock energy and the time history of the shock events will allow a better risk management of structural damages (breakage, delamination, deformation ...). The central objective of this work focused on the impact detection by estimating the elastic energy induced flow (Poynting vector) during the shock. These estimators are derived voltages provided by piezoelectric elements bonded to the structure. By meshing the structure with these piezoelements, it becomes possible to estimate the power flow (Poynting vector) all over the whole structure and relate this information to the shock characteristics (location, energy). The theoretical approach is complex and requires a comprehensive understanding of various couplings Anyway, these technique, because of its easy implementation and low demand in computing resources, constitutes an interesting proposal for future passive impact detection techniques. The energy consumption to compute the estimators (location, energy) being low, the system could be self-powered from the structure vibrations.

8695-32, Session 6

Numerical and experimental characterization of scattering in damaged composite plates

Matteo Carrara, Massimo Ruzzene, Georgia Institute of Technology (United States)

In this paper, we investigate the scattering behavior of defects in composite plates. Scattering coefficients are of great importance for the estimation of wave-damage interaction, for the interpretation of recorded Lamb wave signals, and for the development of novel signal processing strategies. The anisotropy of composite laminates makes modeling of wave propagation and the numerical estimation of scattering coefficients particularly challenging.

The paper studies numerical models of wave propagation in composites, and evaluates their predictive ability. These evaluations rely of full wave field measurements on selected composite plate specimens, through which information on dispersion and directionality of propagation are conveniently extracted. In addition, filtering in the frequency/wavenumber domain allows the extraction of scattered wave fields and the estimation of the scattering coefficients. Comparisons between numerical and experimental data highlight modeling challenges, illustrate mesh-driven directional propagation, and suggest an effective strategy for the estimation of the scattering coefficients through tests and FE modeling.

8695-33, Session 6

Reliable predictions of micro-cracks from macro-scale responses

Sonjoy Das, Sourish Chakravarty, Univ. at Buffalo (United States)

A stochastic multi-scale based approach is presented in this work to detect the signatures of micro-anomalies textit{from} macro-level response variables. By micro-anomalies, we primarily refer to micro-cracks of size 10--100~$mumathrm{m}$ (depending on the material), while macro-level response variables imply, e.g., strains, strain energy density of macro-level structures of typical size often varying at the order of 10--100~m. These micro-anomalies are not discernible by naked eyes. Nevertheless, they can cause catastrophic failures of structural systems due to fatigue cyclic loading that results in textit{initiation} of fatigue cracks. Analysis of such precursory state of internal damage evolution, before a macro-crack visibly appears (say, size of a few cms), is beyond the scope of conventional crack propagation analysis, e.g., fracture mechanics. The proposed work is likely to fill this gap and an extension of an earlier work by Das. In the earlier work, macro-level (continuum) constitutive properties (e.g., constitutive elasticity tensors) of heterogeneous materials were constructed within a probabilistic formalism based on random matrix theory, maximum entropy principle, and principles of minimum complementary energy and minimum potential energy. The effects of micro-cracks are now incorporated into the continuum material properties within the present formulation by extending the previous work. Distinct differences are observed in the macro-level response characteristics depending on presence or absence of micro-cracks, thus opening up the possibility of detecting micro-cracks from experimental measurements of macro-level response variables.

8695-34, Session 6

FPGA based hard- and software platform for ultrasound measurement systems and its application to time of flight measurement and phase sensitive ultrasound microscopy

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The ongoing development of ultrasonic load and structural health monitoring schemes, as well as ultrasonic imaging, require sophisticated measurement equipment to fulfill the ever increasing demand for speed and real-time capability.

Commercially available off the shelf devices, e.g. digital storage oscilloscopes and arbitrary function generators, have been accommodated for this purpose with good success in the past, but their adaption to new applications is limited by the lack of information that their manufacturer is willing to provide, as well as by the manufacturer's rights on his intellectual property. We therefore developed a versatile hard- and software platform which is individually adaptable to a variety of ultrasound measurement tasks and also covers time critical auxiliary functions like the control of mechanical scanners etc. The essential point is that we possess all intellectual property on the hard- and software, including the source code of the FPGA configuration, with no restrictions by rights of others.

The concept is centered on a field programmable gate array (FPGA) accomplishing the common tasks of computer interfacing and digital signal generation and processing, which is complemented by application specific circuitry for digital to analog resp. analog to digital conversion, and digitally controlled analog signal processing. Extensive advantage is taken of reusable components, both software and electronic layout.

To demonstrate the capability and flexibility of our platform concept, two measurement systems that were developed on base of it are presented in detail: A device acquiring the transport time of ultrasound by chirped pulse compression and correlation techniques with 1 ps temporal resolution, and a phase sensitive ultrasound microscope working with sine bust signals of 1.2 GHz excitation frequency.

8695-35, Session 6

Autonomous self-building blocks

Wei-Chih Wang, Univ. of Washington (United States) and National Cheng Kung Univ. (Taiwan)

In this paper, we represent the development of a new modular moving platform as smart structure. The design contents several modular self-configure block which is integrated by controller, extended arm and magnetic latch. The platform could reconfigure by using connection and disconnection of magnetic latch from each module depends on different applications. To provide the hardware strategy, we present the mechanical design of self-configure modules, latch mechanism of Halbach array, wireless microcontroller controller system, sensors and motor drive. Some of the basic block functions to show robotic modules that can reconfigure themselves to take on a variety of forms are demonstrated.

8695-36, Session 6

Analysis of wave propagation In rib-stiffened and isogrid panels for structural health monitoring techniques

Benjamin S. Cooper, Andrei N. Zagrai, New Mexico Institute of Mining and Technology (United States)

As the use of structural health monitoring for aircraft becomes prevalent and the need for health monitoring systems for space vehicles rises, the versatility and robustness of structural health monitoring techniques becomes paramount. Satellite structures used for commercial and defense applications are very complex. Simplified approximations to satellite panels and components will yield undesirable errors in many damage identification techniques, particularly those that consider time of flight for elastic waves. Rib-stiffened and isogrid panels are such examples of structural satellite components. Preliminary evaluations of health monitoring techniques, which relied on a simple flat plate approximation of stiffened structure, reveal unsatisfactory results. Further investigations have been made into the effect which ribs have on wave propagation. Conclusions have been drawn concerning the modifications necessary in structural health monitoring algorithms to include the effect of ribbed and isogrid panels on wave propagation and time of flight calculations.

8695-37, Session 7

Structural dynamic characterization of small-scale multipurpose payloads using conventional and fiber optic sensors

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Structural dynamic characterization is important for ensuring reliability and operability of spacecraft payloads in harsh environments. During the launch, a structure experiences dynamic loads, including acoustic excitation. Conventional sensors are used to infer structural dynamic characteristics. Limitations of conventional strain sensors include low frequency band, susceptibility to electromagnetic interference, and use of multiple wires. To mitigate these deficiencies, an innovative fiber optic strain measurement system is considered to obtain strain distribution at specific locations on a payload. Theoretical models are suggested and compared with results of experimental testing. Limitation of analytical model is discussed and comparison with a numerical model is presented. The research addresses usability of presented models in determining dynamic response of a payload and variation due to distribution of components. It is proposed that discussed experimental and theoretical procedures can be used in determining structural performance for a variety of missions.

8695-38, Session 7

Life cycle strain monitoring of composite airframe structures by FBG sensors

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In this research, a life cycle health monitoring technology for composite airframe structures based on strain mapping is proposed. It detects damages and deformation harmful to structures based on strain mapping by fiber Bragg grating (FBG) sensors through their life cycles including the stages of molding, machining, assembling, operation, and maintenance. FBG sensors are suitable for life cycle strain monitoring because reflection spectrum of FBG sensor is determined by the strain applied to its grating section, which makes it possible to measure the strain change since the sensors were installed in structures. In this paper, a life cycle strain monitoring test of CFRP structures was conducted. FBG sensors were embedded in spherical-shell-shaped specimens and monitored the strains which arose in the stages of molding, machining, assembling, and operation. In the molding stage, the strains of the specimen cured under uniform temperature distribution were compared with those of the specimen cured under stepped temperature distribution. Two results showed the different tendency reflecting curing temperature distributions, which confirms the validity of measured thermal strains. Moreover, strain change measured under differential pressure, which simulated operational load in flight, showed reasonable agreement with calculation. These results demonstrate that the strain which arises in composite structures can be monitored through their life cycles by FBG sensors embedded in the structures in molding stage.

8695-39, Session 7

Structural health monitoring of concrete elements with embedded arrays of optical fibers

Sergei Khotiaintsev, Alfredo Beltrán-Hernández, Juan González-Tinoco, Gerardo Aguilar-Ramos, Univ. Nacional Autónoma de México (Mexico)

We present an optical-fiber sensor system for structural health monitoring of concrete elements, such as beams and columns. The system employs arrays of conventional optical fibers embedded in the elements as crack sensors. Experimentally, we have tested twelve different types of optical fibers for this role, as well as several embedding techniques. With some of these, the survival rate of the optical fibers embedded in concrete was as high as 80%. The loss of some fibers during the embedding process was acceptable provided that the number of fibers in the array was redundant. The optical transmission of all fibers in the array was monitored in a time-division multiplexed mode at a sufficiently high repetition rate, in a KHz range. It allowed us to monitor large optical fiber arrays quasi-continuously. A sharp decrease in the optical transmission of one or more optical fibers indicated the development of a crack in the element subjected to mechanical load. The system successfully detected the initiation and propagation of cracks in concrete elements subjected to progressively increased mechanical load. In this work, we address the relation between the mechanical properties of the optical fibers and their behavior in the present application. Also, we present considerations that lead to rational system design. This system can be used in mechanical testing for the detecting and mapping of cracks in concrete elements. Due to the simplicity of the operation principle and relatively low cost,

this system can also find applications in structural health monitoring of critical elements of civil infrastructure.

8695-40, Session 8

High temperatures health monitoring of the condensed water height in steam pipe systems

Shyh-Shiuh Lih, Yoseph Bar-Cohen, Hyeong Jae Lee, Mircea Badescu, Xiaoqi Bao, Stewart Sherrit, Nobuyuki Takano, Patrick N. Ostlund, Jet Propulsion Lab. (United States)

A health monitoring of the height of condensed water in steam pipe systems was developed to ensure the safety of the operation of the Consolidated Edison of New York steam pipe system. The monitoring system needs to measure the height of the condensed water thru the pipe wall while operating at temperatures as high as 250oC. The system needs to make measurements in real time and the method that was developed uses ultrasonic waves to determine the height from the reflected signals in pulse-echo generated and received by a piezoelectric transducer. A breadboard is developed that consists of a pulser/receiver, high temperature transducer, and a GUI/ filtering/autocorrelation code that determine the water height in steam pipes. A series of tests were performed to examine the developed system and the issues that were encountered with the transducers have been addressed. In preparation to perform field tests in manholes, a mounting strap was developed and lessons learned are documented to reduce the probability of system failure. This paper reports the results of the study towards establishing a practical health monitoring systems.

8695-41, Session 8

Change in Time of Flight of Longitudinal (axial symmetric) modes due to Lamination in Steel pipes

Umar Amjad, Chi H. Nguyen, Ehsan Mahmoudabadi, Tribikram Kundu, The Univ. of Arizona (United States)

Investigations with the aid of longitudinal guided waves in cylindrical structures have been regularly studied for non-destructive evaluation (NDE) and structural health monitoring (SHM). While earlier works concentrated on the amplitude reduction of the propagating waves due to structural anomalies in this work the change in time of flight is investigated. Longitudinal (axial symmetric) modes are excited by a PZT (Lead Zirconate Titanate) transducer for detection of any fluctuation or change in the surface of a steel pipe. To observe the small change in TOF due to lamination on the surface of a steel pipe, cross-correlation technique is used to attain a higher temporal resolution. Appropriate dispersion curves are calculated for the careful study of the propagating modes. The experimental technique and results are presented in detail in the paper.

8695-42, Session 8

Characterization of traffic loads on buried pipeline for life-cycle monitoring and management of municipal distribution system

Suzhen Li, Xinliang Li, Tongji Univ. (China)

Health monitoring of pipeline structures, which can provide a fast and reliable decision-making tool for life-cycle management of municipal distribution system, has attracted many interests in recent years. For the convenience of distribution and construction, most pipelines are buried under urban main roads frequently carrying heavy traffic. Vehicle load is one dominating factor that influences the structural condition of pipelines in long-term service. By integrating the framework of structural health monitoring (SHM), this paper develops an intelligent knowledge system for characterizing and modeling traffic loads in view of condition evaluation and residual life assessment of underground pipeline. Considering a pipe between two crossings or ends of a road, the strain sensors are first attached onto its outside surface of at least two cross sections. Data acquisition and wireless transmission is implemented via RTU (Remote Terminal Unit). For a certain vehicle, its axle weight and speed are estimated by comparing the pipe structural responses at different locations. Lane loads regarding traffic flow are characterized based on the data processing in a statistical way. A field test is conducted for a gas pipe buried under a main road to verify the feasibility and effectiveness of the proposed system.

8695-43, Session 9

Localization of defects in irregular waveguides by dispersion compensation and pulse compression

Luca De Marchi, Alessandro Marzani, Marco Miniaci, Univ. degli Studi di Bologna (Italy)

In this work a pulse-echo automatic procedure suitable to locate defect-induced reflections in irregular waveguides is proposed. An irregular waveguide is composed by a sequence of segments with different dispersion properties (uniform straight and curved geometry, different cross-sections, tapered portions, different materials, etc.).

In particular, the proposed signal processing extracts the distance of propagation of a guided wave traveling in an irregular waveguide by means of a two steps procedure. First, a Warped Frequency Transform (WFT) is used to compensate the dispersion of the guided wave due to the traveled distance in a portion of the waveguide that is assumed as reference. Next, a pulse compression procedure is applied to remove from the signal processed with the WFT the group delay introduced by the remaining portions of the waveguide.

In our approach, the group delay is numerically calculated as a summation of group delays that the wave ideally experiences propagating in a sequence of waveguides with progressively changing cross-sections. Thanks to this pulse compression procedure the actual distance traveled by the wave echoes can be revealed. Thus the proposed signal processing strategy extends pulse-echo defect localization procedures based on guided waves to irregular waveguides. Since the processing is based on Fast Fourier Transforms, the algorithm can be easily implemented in real time applications for structural health monitoring. The potential of the procedure is demonstrated and validated numerically by simulating and processing Lamb waves propagating in different tapered waveguides.

8695-44, Session 9

Adaptive unscented Kalman filter (UKF) for acoustic emission (AE) source localization in noisy environment

Ehsan Dehghan-Niri, Alireza Farhidzadeh, Salvatore Salamone, Univ. at Buffalo (United States)

This paper proposes an adaptive Unscented Kalman Filter (UKF) algorithm for Acoustic Emission (AE) source localization in plate-like structures in noisy environments. Overall, the proposed approach consists of four main stages: 1) feature extraction, 2) sensor selection based on a binary hypothesis testing, 3) sensor weighting based on a well-defined reliability function, and 4) estimation of the AE source based on the Unscented Kalman Filter (UKF). The performance of the proposed algorithm is validated through pencil lead breaks performed on an aluminum plate instrumented with a sparse array of piezoelectric sensors. To simulate highly noisy environment, two piezoelectric transducers have been used to continually generating high power white noise during

testing. The results show the capability of the proposed algorithm for in-flight Structural Health Monitoring of metallic aircraft panels in highly noisy operational situation.

8695-45, Session 9

Guided waves-based damage localization in riveted aircraft panel

Tomasz Wandowski, Pawel Malinowski, The Szewalski Institute of Fluid-Flow Machinery (Poland); Wieslaw M. Ostachowicz, The Szewalski Institute of Fluid-Flow Machinery (Poland) and Gdynia Maritime Univ. (Poland)

In this paper the investigation of a Structural Health Monitoring method for riveted thin-walled aircraft panel is presented. The concept is based on the guided elastic wave propagation phenomena. This type of waves can be used in order to obtain information about structure condition and possibly damaged areas. In reported investigation piezoelectric transducer was used to excite guided waves. Measurement of the wave field was realized using laser scanning vibrometer that registered the velocity responses at defined points on the structure surface. This non-contact tool allowed to investigate phenomena related to wave propagation in considered aircraft element. Due to high complexity of the element baseline measurements were taken before measurements for component with the introduced discontinuity. Signal processing procedures were developed in order to visualize the interaction of elastic waves with specimens components (rivets, stiffeners, etc.). In the second stage of research the signals gather by laser vibrometry method were input to the damage detection algorithms. Signal processing methods for features extraction from signals were proposed. These features were applied in order to detect and localize the presence of damage. In the first step damage detection was based on full wavefield measurements. In this way it was possible to obtain amplitude contrast between region with discontinuities and without them. In the second step a point-wise damage detection was conducted. It was based on several laser measurement points treated as sensors. The results of damage detection were compared with each other and conclusions were drawn.

8695-46, Session 9

Signal processing for the inspection of immersed structures

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The non destructive inspection of immersed structures is gaining popularity as it keeps costs at minimum avoiding unexpected and costly failures. In this paper we present a non-contact laser/immersion transducer technique for the inspection of underwater structures. In particular, a laser operating at 532 nm is used to excite leaky guided waves on an aluminum plate immersed in water. The plate possesses a few damages in terms of holes and notches. An array of immersion transducers is used to detect the propagating waves. A signal processing based on continuous wavelet transform and empirical mode decomposition is utilized to extract features that are associated with the presence of damage. The experimental results show that the proposed system can be used for the inspection of underwater waveguides.

8695-47, Session 9

Design of a low-power structural monitoring system to locate impacts based on dispersion compensation

Alessandro Perelli, Carlo Caione, Luca De Marchi, Univ. degli Studi di Bologna (Italy); Davide Brunelli, Univ. degli Studi di Trento (Italy); Alessandro Marzani, Luca Benini, Univ. degli Studi di Bologna (Italy)

The objective of this study is to develop an embedded ultrasonic structural monitoring system for impact localization in plate-like structures.

The procedure exploits signals sampled in passive mode by 4 sparse conventional piezoelectric transducers and a STM32F4 board, with ARM Cortex-M4 micro-controller (MCU), which is used to implement the processing framework.

The approach is based on guided waves dispersion compensation procedure, which is achieved by means of the warped frequency transform.

Procedures based on dispersion compensation are usually applied to active monitoring techniques, as they require the knowledge of the impact time to effectively compensate the waves dispersive behaviour.

This problem is exceeded through the cross-correlation in the warped frequency domain which is achieved performing a Non-Uniform FFT on the acquired signals, followed by the cross-correlation and then applying a traditional inverse FFT.

By cross-correlating the signals related to the same event acquired by different sensors, the difference in travelled distances (DDOA) can be determined and used to locate the impact via hyperbolic positioning.

The localization algorithm is implemented in the STM32F4 board whose ADCs sample 4 input channels in double mode with 250 kHz maximum frequency and data are collected with DMA; when the input threshold is exceeded the trigger is sent and the MCU performs the algorithm.

The performances are analyzed in terms of DDOA accuracy and power consumption in each step of the algorithm.

Results show the effectiveness of the proposed implementation with 30 mA mean current consumption during the elaboration and 3.3 voltage reference.

8695-48, Session 9

quantitative monitoring of 2-dimensional damages using envelop locating curves

Chaoliang Du, Xinlin P. Qing, Yishou Wang, Commercial Aircraft Corp. of China, Ltd. (China)

Damage monitoring is of great concern to manufacturers as well as maintenance personnel for significantly improving safety and reliability of aircrafts. Delamination and corrosion are amongst the most interested types of damages the industry want to detect for composites and metals correspondingly. In plate structures, these damages could all practically be treated as 2-dimensional damages. Many progresses have been made on monitoring the location of the aforementioned damages; however, to monitor the size of these damages is still very challenging. It is known from dynamic theory that elastic waves will be scattered or reflected at the interface of two different media. Thus scattered or reflected waves will be generated at the boundaries of damages. By analyzing these scattered or reflected waves, the boundaries of these damages could be determined, then, not only the location, but also the size of these 2-dimensional damages can be given. In this study, to get as exact monitoring results as possible, two types of locating curves are used: the curves acquired by pitch-catch mode and the curves acquired by pulse-echo mode. By taking the inner most locating curves, the boundaries of the damages could be given. Experimental results showed that the size of an elliptical 2-dimensional damage could be given quite well with as few as 3 sensors, and with 4 or more sensors, more exact monitoring results could be obtained.

8695-49, Session 10

Smart Materials for High Power Applications *(Invited Paper)*

Shujun Zhang, Hyeong Jae Lee, The Pennsylvania State Univ. (United States)

High power piezoelectric materials have been used for a wide range of applications, including ultrasonic motors, transformers and medical ultrasonics. Recently, ultrasound has attracted attention for medical diagnostic imaging and therapeutic applications, such as acoustic radiation force impulse (ARFI) imaging and ultrasound-guided high intensity focused ultrasound (HIFU) therapy, which require probes capable of both high quality diagnostic imaging and radiating high acoustic power (force) into tissue. Currently, high power applications are limited by the internal power dissipation, which will generate heat and increase hysteretic effects resulting in thermal instability. Thus, piezoelectric materials with high mechanical quality factor Q (inverse of mechanical loss, closely related to the heat generation under high level vibration), large electromechanical coupling factor kij (associate with the bandwidth of the transducer) and high dielectric constant (figure of merit [FOM] k•Q) are desired to meet the requirements of advanced high power electromechanical applications. However, mechanical Q or electromechanical coupling/piezoelectric coefficient/ dielectric constant can be enhanced only at the expense of each other. Therefore, modified piezoelectric materials were surveyed in this article to optimize the FOM for high power applications, including polycrystalline ceramics, single crystals and composites.

8695-50, Session 10

Piezoelectric Thick Films for High Frequency Biomedical Ultrasonic Transducer Applications *(Invited Paper)*

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High frequency ultrasonic imaging has been extensively used for imaging of eye, blood vessel, skin and small animals. Fabrication of the transducers, which is the most critical component of the ultrsound imaging system, becomes challenging especially when very high frequency is required. Conventional lapping-and-dicing method with bulk piezoelectric materials will no longer be feasible. However, Piezoelectric thick films are good candidate materials to fabricate high frequency ultrasound transducer. This paper presents the latest development of high-frequency ultrasonic transducer and arrays with high-quality piezoelectric thick films.

Piezoelectric (shch as PZT, PMN-PT, PZT-PMN-PT) thick films were successfully prepared with a composite sol-gel solution. Film quality was enchanced by infiltration of PZT sol-gel into composite films and optimization of PZT powder to PZT sol-gel mass ratio in composite solution. Over 80 MHz single element transducer and linear arrays were fabricated with the PZT thick films. To fabricate the kerfless array, an insulating layer of Si_3N_4 was first patterned onto PZT films to leave an opening for the working area of the linear arrays. One major problem with the kerfless arrays is their large crosstalk. To decrease the crosstalk, the array elements have to be seperated. Inductively coupled plasma-Reactive ion etching based dry etching was selected to etch the PZT thick films into kerfed arrays. The 36-elements linear array shows -6dB bandwidth of 60% and insertion loss of around -40 dB with center frequency of 80 MHz, respectively. In addition, silicon lens transducer by MEMS technology for high frequency transducer application will be introduced.

8695-51, Session 10

Quantitative acoustic evaluation of materials: devices and applications of single crystal PCMUT technology

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In this paper, new results regarding nondestructive evaluation (NDE) of materials using a 35MHz piezoelectric composite-based micromachined ultrasound transducer (PCMUT) array are presented, as well as the extension of this technique to lower frequencies for quantitative biomedical evaluation. The former application has the capability to improve resolution for better defect detection in structures, improving both safety and reliability, whereas the latter provides the ability to apply similar techniques to evaluation of bone tissue in vivo. Through a combination of domain engineering and micromachining of single crystal PMN-PT, the transverse length extensional mode was used to develop a single element transducer with more than 4 octaves of bandwidth. This can be used towards characterization of bone loss and restructuring in osteoporosis or microgravity environments.

Results from the PCMUT array show that an imaging depth greater than 20mm is achievable with a proper delay pattern, and when performing C-scans, structural defects such as cracks are evident in the sample material. Results from resolution characterization will also be discussed. A machined phantom with structures of known dimensions was used to evaluate array performance.

The wide bandwidth of the domain engineered transducer was used to perform measurements similar to acoustic spectroscopy on bone tissue samples, and comparison between materials from 300kHz to 7MHz shows distinct differences. Initial comparisons between bone measurements made with commercial devices and this transducer will also be shown. This technology shows promise as a single measurement tool for non-ionizing, quantitative evaluation of biological structures

8695-52, Session 10

Analytical model of planar LiNbO3 plate with four-layer structure of inversion layer

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High frequency broadband ultrasonic transducers are attractive in high-resolution ultrasonic imaging technique. The planar LiNbO3 single crystal plate with polarization inversion layer can be excited to generate the even harmonic vibrations in thickness extension mode which is available for high frequency broadband ultrasonic transducer design. K. Nakamura et al. experimentally examined the dependences of the inversion layer thickness in the Z-cut LiNbO3 inversion layer plate on the heat treatment conditions, such as temperature, time and atmosphere. C. Z. Huang et al. has proposed an analytical model of a multilayer ultrasonic transducer with two-layer inversion layer structure according to the previous publications. However, some fine structures in the planar inversion layer plate have been ignored.

8695-53, Session 10

Design, fabrication and test of a small aperture, dual frequency ultrasound transducer

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States); Di Wu, Beijing Jiaotong Univ. (China)

High resolution ultrasound medical imaging requires high frequency transducers, which inevitably result in penetration depth reduction because of high loss in two-way-loop at high frequency. To obtain high resolution imaging with reasonable penetration depth, a dual frequency transducer was designed for contrast imaging. A 35MHz receiving transducer with aperture of 0.6mm x 0.5mm was integrated into a 5MHz transmitting transducer with aperture of 0.6mm x 3mm. With more than 2MPa pressure at 5MHz transmitted into tissue with contrast bubbles, broadband acoustic waves can then be generated upon the excitation of microbubbles. The high frequency component of the nonlinear response from microbubbles will be received by the 35MHz transducer for high resolution imaging at a relatively large depth since the penetration depth of acoustic waves is enhanced by reducing the wave propagation path at high frequency to one-way-loop only. In the characterization, the prototyped transducer showed the ability of transmitting more than 3MPa pressure at 5MHz, with an input of 5-cycle burst at 194Vpp, which is high enough to generate non-linear oscillation of microbubbles. The pulse-echo test showed that the -6 dB bandwidth of the 35MHz transducer is 34.4% and the loop sensitivity is -38.3 dB without matching. The small aperture, dual frequency ultrasound transducers developed in this paper are promising for high resolution ultrasound medical imaging.

8695-54, Session 11

Implementation of a novel imaging technique in an existing structural health monitoring system

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In this paper, a novel imaging technique is assessed with a structural health monitoring (SHM) system based on an array of piezoceramic sensors and actuators for in-plane inspection. The imaging approach used in this system is based on the time-of-flight (ToF), and the knowledge of the velocity of ultrasonic waves in the structure. While this technique assumes non-dispersive wave propagation, the proposed imaging technique exploits the dispersion of waves as it is based on the phase velocity. The signal measured at a given sensor is correlated with a theoretical prediction of a propagated burst in the structure and, combining the results for multiple sensors, an image of the reflectors in the structure is obtained. This paper presents the implementation of the novel imaging technique in an existing system, including considerations for physical access to the signals and their conditioning. The performance of the existing imaging approach is compared with the novel imaging technique proposed for three test cases. The first assessment is conducted on a simple aluminum plate where magnets are used to simulate a defect. Then, the assessment of the novel imaging techniques is conducted on riveted plates with simulated cracks of different lengths. The full assessment is finally conducted for the detection of an impact damage on a helicopter tail rotor. Imaging results are presented for a number of damage detection scenarios on these structures. The novel imaging technique is shown to improve imaging localization, resolution and robustness, while allowing fast implementation.

8695-55, Session 11

Guided Ultrasonic Wave Propagation through Inaccessible Damage in a Folded Plate using Sensor-Actuator Network

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Rapid localization and virtual imaging of damages in complex structures like folded plate can help reduce the inspection time for guided wave based NDE and integrated SHM. Folded plate or box structure is one of the major structural components for increasing the structural strength. Damage in the folded plate, mostly in the form of surface breaking cracks in the inaccessible zone is a usual problem in aerospace structures. One side of the folded plate is attached (either riveted or bonded) to adjacent structure which is not accessible for immediate inspection. The sensor-actuator network in the form of a circular array is placed on the accessible side of the folded plate. In the present work, the circular array is employed for scanning the entire folded plate type structure for damage diagnosis and virtual imaging of hot spots. The method employs guided wave with relatively low frequency bandwidth of 100-300 kHz. Change in the wavelet coefficient with respect to a baseline signal is used to construct a quantitative relationship with damage size parameters. Detecting damage in the folded plate by using this technique has significant potential for off-line and on-line SHM technologies. By employing this technique, surface breaking cracks on inaccessible face of the folded plate are detected without disassembly of structure in a realistic environment.

8695-56, Session 11

Damage Detection in Composite Structures with Multi-Path Guided Wave Imaging

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Ultrasonic guided waves offer a promising mechanism to perform rapid and reliable detection of damage in large, plate-like structures. Distributed arrays of permanently attached, inexpensive piezoelectric transducers are perhaps the most cost-effective approach to large-area monitoring; however, the received signals can be very difficult to interpret. Complex composite structures compound this problem due to the anisotropic propagation environment and large number of echoes and reverberations that result from features such as stiffeners, ribs, cut-outs and fasteners. The elliptical guided wave imaging algorithms traditionally used to perform damage detection and localization require knowledge of the propagation velocity and rely on direct path propagation between sensors and areas of inspection. Consequently, these algorithms become more difficult in composite structures since the propagation velocity and amplitude are directionally dependent, and they can completely fail in complex structures if direct path propagation cannot be ensured. This work describes the concept of multi-path guided wave imaging. The imaging algorithm uses experimentally estimated Green's functions to leverage the multi-path echoes and reverberations, which simultaneously improves imaging performance and reduces the number of required sensors. Neither a priori knowledge of the propagation velocity nor direct path propagation are required with this new imaging algorithm, and therefore multi-path guided wave imaging is ideally suited for complex composite structures. Experimental data from a CFRP specimen is used to demonstrate the multi-path guided wave imaging algorithm and compare performance to state-of-the-art elliptical imaging methods.

8695-57, Session 11

Evaluation of the Lamb Waves Approach to Detect Simulated Damage in a Orthogonal Plane of the Sensor Network Surface for Corrosion Detection Application

Fernando Dotta, Leandro B. Ceresetti, Embraer-Empresa Brasileira de Aeronautica SA (Brazil)

Non-destructive testing methods for rapid and reliable corrosion detection in complex metallic assemblies are an on-going challenge due to practicalities of inspection and geometric complexity. Corrosion damage, unlike the fatigue damages are almost impossible to determinate where or when it will affect the structures, the current engineering methodology only can determinate the susceptible areas for corrosion. In this scenario is most difficult to chose the structures to monitoring and place sensors all susceptible areas is not practical.

This work demonstrates the evaluation of the Lamb Waves approach in order to detect and locate simulated damages in a aluminium alloys place orthogonally from sensor network surface. The testing were performed using a typical aeronautical specimen configuration and Direct Image Path from Acellent Technologies The experimental results indicate the Lamb Waves technique is high accurate and it is shown a promising application to detect corrosion damage. This study is part of a set study of several SHM Technologies, like CVM (Comparative Vacuum Monitoring), EMI (Electro-Mechanical Impedance), AE (Acoustic Emission), LW (Lamb Waves). Those studies are under EMBRAER's R&D program.

8695-58, Session 12

On the self-powering of SHM techniques using seismic energy harvesting

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To extend the operating lifetime of vehicles and particularly aircrafts as well as reducing maintenance costs, there has been a growing interest in the design of wireless structural health monitoring (SHM) systems. The classic solution is to use the batteries for powering such devices. However, their limited lifespan and recycling issues propel the research on supplying the electrical energy from ambient sources. Vibration-based piezoelectric harvesters are one of the prominent options in this domain because of their good adaptability, integrability, low maintenance and long lifetime.

In the literatures, the piezoelectric harvester is predominantly modeled as a lumped single-degree-of-freedom (SDOF) mass-stiffness-damper system. However, in some practical applications, there is a mechanical-mechanical coupling effect between the harvester and the host structure, which can not be realized with a SDOF model. This mechanical-mechanical coupling effect will induce an additional damping of the host structure during the energy conversion. In the paper, we propose a two-degree-of-freedom (TDOF) model to describe the tradeoff between the damping effect on the host structure and the harvested power for several mass ratios (harvester mass to host structure mass) cases. Experimental results presented to validate the theoretical modeling show that the harvester effect is not negligible on the host structure for a mass ratio as small as 0.02 when the output power is optimized, yielding a damping effect on the host structure of more than 3 dB.

The impact in terms of harvested power will also be discussed in terms of self-powered, wireless SHM techniques viability.

8695-59, Session 12

Axial stress determination using Impedance-based method and its application on the thermal stresses measurement in Continuous Welded Rail

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This paper presents the current investigation in UCSD on the feasibility of using an impedance-based Structural Health Monitoring (SHM) technique in monitoring the Continuous Welded Rail (CWR). Being welded to form uninterrupted rails that are several miles long, the CWR has been widely used in the modern rail industry since 1970s. However, the almost total absence of joints for expansion of CWR would create the potential of buckling with high temperature and breakage in cold environment due to the rail thermal stresses. The objective of this research is to utilize the capability of the impedance method in identifying the neutral temperature or zero-stress state in CWR. The principle of Electromechanical Impedance (EMI) is to utilize high frequency structural vibration through a piezoelectric transducer to detect changes in structural point impedance due to the presence of change of structural integrity or in-situ stress. In practical CWR monitoring, the rail track structure being monitored is undergoing changes due to the effect of thermal stress and the environmental factors. Based on this assumption, three sets of experiments were conducted: the influence of axial stresses on the EMI signature was studied with an axial loading test on a rectangular section of steel milled from a 136lb RE rail; the temperature effect on the proposed method was investigated with heating-cooling cycle test on an unconstrained 136lb RE rail; the third test to simulate the monitoring scenario as expected in the field was conducted with heating-cooling cycle test on constrained 136lb RE rail testbed in UCSD. The low-cost impedance measurement system was built and applied to collect EM signatures during the test whose performance was verified by the standard impedance analyzer. During the analysis, both the real and imaginary parts of the EM signatures were studied since both the stress and temperature would have different influence on the signatures compared with defect detection. The temperature effects on the piezoelectric materials and structures were investigated and the corresponding temperature compensation algorithm would be applied on the application. The final result illustrates that the proposed impedance-based method would be promising to characterize the thermal stress in CWR.

8695-60, Session 12

Experiment study on structure damage detection using a higher-order resonant circuit

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Taking the use of the electromechanical characteristics of piezoelectric, admittance-based structure health monitoring method is an effective method to detect damages. Under a certain voltage excitation, the mechanical damages can be detected by monitoring the current change from the piezoelectric transducer. Based on the electrical-mechanical analogy and the series tuned mass damper theory, a higher-order circuit has been designed to increase the signal-to-noise ratio of the current measurement and the detection sensitivity to damages. The experiment study on the admittance-based damage detection method with a higher-order resonant circuit is carried out in this paper. The damage detection performance of higher-order circuit is compared with that of first-order resistive circuit and that of second-order inductive circuit. The influence of electrical components on damage detection sensitivity and the influence of inaccuracies of electrical components due to temperature drift on damage detection ability are also studied. The results show that the designed structure health monitoring method with higher-order circuit has higher signal-to-noise ratio and higher sensitivity to damages than the first-order resistive circuit and the second-order inductive circuit. Optimal electrical components, i.e., resistors, inductors, and capacitors, are found in the experiment study. It also indicates that the admittance change due to damages is very sensitive to the inaccuracies of electrical components. We find that if the accuracies of electrical components are not high enough, it is difficult to distinguish the admittance change caused by small damages from that caused by inaccuracies of electrical components due to temperature drift. Therefore, it concludes that higher damage detection sensitivity requires higher accuracies of electrical components.

8695-61, Session 12

Multiscale analysis of wave-damage interaction in two and three dimensional isotropic plates

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In this paper a geometric multiscale finite element method (GMsFEM), recently developed by the authors, is applied to the analysis of wave propagation in damaged plates. The proposed methodology is based on the formulation of both two- and three-dimensional multi-node (or multiscale) elements capable of describing small defects without resorting to excessive mesh refinements. Each multiscale element is equipped with a local mesh that is used to compute the interpolation functions of the element itself and to resolve the local fluctuations of the solution near the defect. The computed shape functions guarantee the continuity of the solution between multiscale and conventional elements. This allows using an undistorted discretization in the uniform portion of the domain while limiting the use of multiscale elements only in the vicinity of the damaged area. In this article the method is applied to evaluate the reflection coefficients due to cracks of different size and orientation in an otherwise homogeneous plate. Also, numerical simulations of wave-damage interaction are used to compute the scattering diagrams associated to three-dimensional defects in isotropic plates.

8695-62, Session 12

Acoustic emission crack detection of railway turnouts using FBG sensing technology

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Railway turnouts are the weakest components of a high-speed ballastless track system. Fatigue cracks may occur in the railway turnouts suffering from the cyclic loadings by high-speed trains, and therefore it is of great significance to continuously monitor the health condition of the railway turnouts and promptly detect the fatigue cracks at the crack initiation stage. It is well-known that acoustic emission (AE) signals are generated when fatigue cracks initiate and propagate. Detecting the AE signals with a high-frequency nature could help identify the fatigue cracks and their locations. Currently the majority of AE crack detection methods are based on the piezoelectric sensors and seldom on the fibre Bragg grating (FBG) sensors which have great potential to be an alternative of the traditional electrical sensors because of their salient advantages such as anti-electromagnetic interference, multiplexing capability, excellent durability, etc. In this study, a novel method for AE crack detection by use of the FBG sensing technology is proposed and applied to monitor the fatigue cracks of railway turnouts. A railway turnout with man-made cracks is used to validate the effectiveness of the proposed method. FBG sensors are glued on different locations of the tested railway turnout. As a comparison study, piezoelectric (PZT) sensors are glued adjacent to the FBG sensors. AE signals derived from the crack growth are generated by knocking the rail-tracks with a hammer. Based on the collected field test data from the impact experiments, it is observed that FBG sensors are competent to detect AE signals originated from the cracks and have a higher signal-to-noise ratio in comparison to the PZT sensors. Additionally, the crack locations are also identified through statistical analysis of the AE signals from different FBG sensors glued on different locations of the railway turnout. The experimental results demonstrate that the proposed method is promising in accurately identifying the fatigue cracks and their locations on the railway turnout.

8695-63, Session 13

Numerical simulation for damage interaction of guided waves in composites

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Composite structures are used extensively 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.

Predicting the damage using failure analysis is more complex for composite structures because of the material being non-isotropic. GW can be instrumental in overcoming this difficulty, as GW can be sensitive to specific defects in terms of both location and size of the damage by controlling the testing parameters. To get a better understanding of the GW interaction with damages in composite structures, in the proposed paper, numerical simulations based on LISA will be implemented for simulated damages with incremental complexities. We will begin with a relatively simple damage to the composites like a through hole, followed by notches and delaminations. Preliminary validations will be carried out against finite element simulations and they will be followed by experimental validation using laser vibrometry.

8695-64, Session 13

Modeling of guided waves for detection of linear and nonlinear structural damage

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This paper presents an analytical approach to modeling guided Lamb waves interacting with linear and nonlinear structural damage. The modeling of guided waves interacting with damage is important because analytical model and parametric studies help us understand and interpret diagnostic wave signals for damage detection. Beside their multi-mode and dispersive nature, guided waves interacting with damage involve complicated phenomena such as wave transmission, reflection, mode conversion, and frequency modification.

The analytical model is constructed in frequency domain based on the concept of plate transfer function. Lamb waves generated by piezoelectric wafer active sensors (PWAS) propagate into the structure, interact with linear and nonlinear damage, carry the damage information with them, and are picked up by the sensing PWAS transducer. Structural damage is modeled as a new wave source, where guided waves are transmitted, reflected, mode-converted, and frequency modified (second and third order harmonics included). The total wave energy is distributed to different wave packets and components by the transmission, reflection, and mode conversion coefficients; energy balance among all the wave packets is enforced. Complex amplitudes are used to represent both magnitude and phase information. Multi-mode Lamb waves are discussed for high frequency and thick plate applications. Structural damping is accounted for by the use of complex stiffness parameters. Parametric studies are carried out on different damage types of various severities. Case studies comparing the analytical model with finite element simulation and experiments are done. The paper finishes with summary, conclusions, and suggestions for future work.

8695-65, Session 13

A coupled SAFE-BEM formulation for modeling leaky waves in waveguides of arbitrary cross-section surrounded by isotropic media

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Advanced Non-Destructive Evaluation and Structural Health Monitoring applications based on ultrasonic guided waves require mathematical tools capable to predict dispersive data for waveguides with generic geometric and mechanical characteristics. Well acknowledged analytical and semi-analytical methods, such the Global Matrix Method and the Semi Analytical Finite Element (SAFE) method, respectively, have been developed over years. However, while the former is still limited to waveguides with standard cross-section geometry, the latter fails in problems involving energy leakage.

In this paper a Boundary Element (BEM) formulation is coupled to a SAFE scheme in order to extend the capabilities of SAFE formulations to the computation of leaky guided waves. In particular, the SAFE is used to model both the mechanic and geometric characteristics of the waveguide, while the BEM is exploited to represent the external (unbounded) surrounding isotropic domain. Complex cross-section waveguides with boundary corners, as well as Cauchy singular integrals typically involved in BEM formulations, are treated using a regularization procedure.

The final dispersive wave equation for the leaky waves results in a nonlinear eigenvalue problem where the complex wavenumbers appear implicitly. The problem is efficiently solved by means of a Contour Integral Algorithm that does not require initial guesses of the solutions and derivative operations, providing at the same time good performances for parallel computing. The reliability of the proposed method is demonstrated by means of some numerical applications of practical interest.

8695-66, Session 13

Modeling of ultrasonic guided waves using the finite cell method

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The interest in online monitoring of lightweight structures with ultrasonic guided waves is steadily growing.

Thus, an increasing demand for efficient numerical simulation tools is to be seen. In order to decrease the maintenance costs and the downtime of airplanes significantly the aeronautic industry is a driving force in developing such Structural Health Monitoring (SHM) systems. Due to the complexity and dimensions of these applications conventional linear or quadratic pure displacement finite elements are not appropriate. The required mesh density results in enormous computational costs when wave propagation problems are considered. Higher order finite element method approaches (p-FEM, SEM etc.) seem to be the most viable choice to reduce the numerical costs. Since the application of carbon/glass fiber reinforced plastic (C/GFRP) or sandwich materials is steadily increasing conventional discretization techniques pose different problems. It is almost impossible to mesh these heterogeneous materials without gaining a prohibitively large computational effort. To circumvent this problem the authors propose to apply the Finite-Cell-Method (FCM). This higher order fictitious domain method shifts the meshing effort towards the adaptive integration of the finite element matrices. Thus, even the most complex structure can be discretized using a rectangular Cartesian grid.

The objective of the paper is to present an efficient method to simulate the wave propagation in heterogeneous materials utilizing the Finite-Cell-Method. Using this approach structures made of complex materials can be discretized efficiently. The functionality of the proposed scheme is demonstrated by studying Lamb wave propagation in a two-dimensional set up.

8695-67, Session 13

A guided wave approach for the detection of damage in a structure having elements with periodic damage

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A wave propagation based approach for the detection of damage in components of structures having periodic damage has been proposed. Periodic damage pattern may arise in a structure due to periodicity in geometry and in loading. The method exploits the Block-Floquet band formation mechanism , a feature specific to structures with periodicity, to identify propagation bands (pass bands) and attenuation bands (stop bands) at different frequency ranges. The presence of damage modifies the wave propagation behavior forming these bands. With proper positioning of sensors a damage force indicator (DFI) method can be used to locate the defect at an accuracy level of sensor to sensor distance. A wide range of transducer frequency may be used to obtain further information about the shape and size of the damage. The methodology is demonstrated using a few 1-D structures with different kinds of periodicity and damage. For this purpose, dynamic Stiffness matrix is formed for the periodic elements to obtain the dispersion relationship using frequency domain spectral element and spectral super element method. The sensitivity of the damage force indicator for different types of periodic damages is also analyzed.

8695-68, Session 13

Fully coupled electromechanical elastodynamic model for guided wave propagation analysis

Luke Borkowski, Kuang C. Liu, Aditi Chattopadhyay, Arizona State Univ. (United States)

Physics based computational models play a key role in the study of wave propagation for the purpose of structural health monitoring (SHM) and the development of improved damage detection methodologies. Due to the complex nature of guided waves, in particular Lamb waves, accurate and efficient computation tools are necessary to investigate the mechanisms responsible for dispersion, coupling, and interaction with damage. In this paper, a fully coupled electromechanical elastodynamic model for wave propagation in a heterogeneous, anisotropic material system is developed. The final framework provides the full 3D displacement and electrical potential fields for arbitrary plate and transducer geometries and excitation waveform. The model is validated theoretically and proven computationally efficient. Studies are performed on flat plates with surface bonded piezoelectric sensors to gain insight into the physics of experimental techniques used for SHM. Collocated actuation of the fundamental zeroth order Lamb wave modes is modeled over a range of frequencies and the relative energy of the modes is compared to demonstrate mode tuning capabilities. The displacement of the sensing surface is compared to the piezoelectric sensor electric potential to investigate the relationship between plate displacement and sensor voltage output. The manner in which piezoelectric actuation is modeled and the necessary stress-free boundary condition is imposed is shown to have a significant effect on the simulated wave speed and numerical stability. Since many studies, including the ones investigated in this paper, are difficult to perform experimentally, the developed model provides a valuable tool for the improvement of SHM techniques.

8695-69, Session 13

Damage analysis in composite structures using finite element method for SHM purposes

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Composites are becoming increasingly popular materials used in in aerospace industry, because they provide very high stiffness, high strength and reduced total mass. Damages such as fiber breakage, matrix cracking, delamination and disbond in composite structures are difficult to detect and may cause a catastrophic failure of structures. Structural Health Monitoring (SHM) offers an effective method to inspect the state of composite structures. But the damage modes are hard to be identified by SHM due to the complexity of signal interpretation. So damage features caused by different damage phenomena or modes need to be further analyzed by numerical simulation to provide some guidelines for monitor process of SHM. Guided wave for different damages simulated by the finite element method is presented in this paper. Different modes of damages (e.g. crack and delamination) are predefined at the same location. The guided waves are activated and received with different frequency in two ways of pitch-catch and pulse-echo. The response characterization of the damage in the form of crack or delamination is associated with propagation of guided elastic waves. The finite element models with crack and delamination are developed for quantitative analysis of different damage modes on elastic waves. The damage features that can distinguish different damage modes are extracted to form a feature database. Results of these simulations were compared with experimental ones to identify the damage mode. Finally, damage analysis is used to combine with the quantification of damage in SHM and calibrate elastic wave propagation from experimental data.

8695-70, Session 14

A flexible insert for wireless strain sensing

Irving J. Oppenheim, David W. Greve, Carnegie Mellon Univ. (United States); Antonia F. Chen, Univ. of Pittsburgh Medical Ctr. (United States)

We fabricated and tested (in a laboratory configuration) a flexible insert for wireless strain sensing in an intramedullary tibial nail. The nail is a thick-walled titanium tube with an anatomic bend, and our flexible insert was designed to be advanced into the hollow of the nail by a surgeon during the late stages of the fracture fixation process. The insert is a stainless steel rod, 170 mm long, with a part-circular section, roughly 4 mm wide and 2 mm deep that is slightly smaller than the hollow. A lithium niobate SAW device developed by our research team, with an operating frequency of 468 MHz, is bonded to the insert and demonstrates wireless strain sensing when the insert is bent.

We describe the mechanics of the flexible insert, which can be used for structural monitoring applications where conventional strain gauge installation and wiring would be impractical. Because of its flexibility, the insert can be advanced into an irregular channel, such as the hollow of a tibial nail, or a narrow access path drilled into a solid. The insert will bend elastically into a configuration with at least three points of contact with the host body. The insert will be prestrained (in bending) during installation and need not be anchored or bonded to the host body other than through contact. Bending strain in the insert will vary as the host body deforms. We analyze possible application examples, and we demonstrate strain sensing in a laboratory specimen.

8695-71, Session 14

Why may an atomic clock be needed for ultrasonic SHM with high temporal resolution?

Wolfgang Grill, Univ. Leipzig (Germany) and ASI Analog Speed Instruments GmbH (Germany); Gerhard Birkelbach, ASI Analog Speed Instruments GmbH (Germany)

Presented and discussed are wide band ultrasonic monitoring schemes and respective instrumentation suitable for structural health monitoring. Since temporal resolutions down to even 1 ps can be reached with the developed technology and since information on the structural health is deduced from observed time-of-flight data relating to travelling ultrasonic waves, calibration and precision of the temporal resolution can be crucial for the obtainable results. Shortcomings of usually available frequency standards and the possible need for standards with high resolution and stability are demonstrated, discussed, and examples are presented including an actual experimental demonstration.

Comment for this paper: Our co-operating partners and we have made the experience that neither the need nor the possibility to use and achieve high temporal resolution even down to 1 ps and in GHz SAM even down to 100 fs is understood or even believed and applications can be turned down due to this fact. The essential technical aspects are therefore to be published in connection with this publication.

8695-72, Session 14

Liquid viscosity measurement using super harmonic resonance

Wei-Chih Wang, Univ. of Washington (United States) and National Cheng Kung Univ. (Taiwan)

Viscosity sensors based on mechanical resonance, such as piezoelectric resonators, semiconduc¬tor resonators, vibrating wire resonators and our previously developed optical-fiber based resonator have gained popularity due to their simplicity of design and operation. They detect viscos¬ity by submerging an oscillating probe in the fluid of interest. Viscosity is measured by using the fact that the vibration amplitude of the probe is inversely proportional to the viscosity of the fluid. In practice, the vibration amplitudes are always kept sufficiently small in order to avoid nonlinear vibration effects. In this paper, however, nonlinear vibration is intentionally excited to improve the sensitivity of viscosity measurements, in par¬ticular super har¬monic resonance case. The results show that a nonlinear effect drastically improves sensitivity to viscous damping. Experimental results and several applications are also presented.

8695-73, Session 14

Carbon bed contamination detection and monitoring with piezoelectric wafer active sensors

Jingjing Bao, Victor Giurgiutiu, Univ. of South Carolina (United States); Gregory W. Peterson, U.S. Army Edgewood Chemical Biological Ctr. (United States); Miranda Duncan, Univ. of South Carolina (United States)

This paper describes the use of piezoelectric wafer active sensors (PWAS) to detect and monitor contamination in the carbon bed of filtration systems. We propose a novel approach based on the electromechanical impedance spectrum (EMIS) of PWAS transducers embedded into the carbon bed. PWAS EMIS is sensitive to structural mechanical impedance, hence can be used to detect pressure change of the carbon bed. PWAS can also be used as a simple resistance sensor to monitor the carbon bed resistance change during SO_2 contamination.

A preliminary model was developed to explain the PWAS-carbon bed interaction. Extensive experiments were performed to validate and verify the analytical predictions by the model. Specialized testing apparatus and procedures were developed for the experiments. Experimental results have shown that PWAS EMIS is sensitive to SO2 contaminations, and also able to detect pressure change in carbon bed. Significant temperature rise was detected in the carbon bed. The temperature effects on the PWAS EMIS need to be compensated. In a preliminary study, temperature effects was evaluated and compensated for the experimental results. Further study on the temperature effects and insulations are planned to account for the environmental factors.

8695-74, Session 14

Characterization in various contrasts representing material properties by microscopic acoustic imaging

Wolfgang Grill, Univ. Leipzig (Germany) and ASI Analog Speed Instruments GmbH (Germany)

Presented, compared, and discussed are various microscopic imaging principles based on SAM, PSAM, ultrasonic holography and tomography concerning the determination of material properties in up to 3 dimensions. The materials include deposits, homogeneous isotropic matter, crystals, and inhomogeneous structures. Comparisons to well established techniques as V(z) with or without phase contrast and medical imaging are presented and novel schemes are explained concerning their advantages and possible shortcomings. Examples for high resolution imaging with contrast relating to material properties including age contrast for single cells are presented.

8695-75, Session 14

Forward light scattering method for structural characterization of electrospun fibers

Wei-Chih Wang, Univ. of Washington (United States) and National Cheng Kung Univ. (Taiwan); Jin-Jia Hu, National Cheng Kung Univ. (Taiwan)

Electrospun fibers have been applied in numerous areas. In many of the applications, aligned fibers are desired for their specific properties. Recently, many different techniques have been developed to create aligned electrospun fibers. The direction of the fibers as well as the distribution of fiber orientations, in general, are analyzed by SEM which requires significant processing, thus increases time, and therefore costs. Currently we are examining these materials with forward light scattering in order to obtain fiber alignment and the distribution of fiber orientations. The proposed technique is slightly modified in the hardware and software from previous techniques to provide a more accurate and detailed mapping of the fibrous structure.

8695-76, Session 14

Spectroscopic ellipsometry investigation of gold nanoparticles embedded in PDMS for bio-sensing applications

Yia-Chung Chang, Mohammad T. Yaseen, Academia Sinica (Taiwan)

In this work, biosensing capability of gold nanoparticles embedded in polydimethylsiloxane (PDMS) are investigated. Different sizes of gold nanoparticles are prepared and used to study the size effect on the samples response. The optical properties of the prepared samples are evaluated using the UV-Vis spectrophotometer to measure absorption spectra. We find that different size of gold nanoparticles gives different absorption spectrum. Besides, the spectroscopic ellipsometry is used to investigate the surface plasmon effect of this structure for various sizes of gold nanoparticles. The proposed structure could be a cost-effective scheme for biosensing applications.

Work supported by Academia Sinica and National Science Council of the Republic of China under Contract No. NSC 101-2112-M-001-024-MY3.

8695-119, Session PTue

Tissue characterization using acoustic wave tactile sensor array

Kyungrim Kim, Xiaoning Jiang, North Carolina State Univ. (United States)

Tactile perception of different types of tissue is important for the surgeon to perform the surgical procedures correctly and safely. Especially, for minimally invasive surgery (MIS) the surgeon should be able to perceive the location of the target tissue with limited perceptions. In order to distinct different tissue types, tissues can be characterized by electromechanical tactile sensors such as capacitive, resistive and piezoelectric tactile sensors. With a tactile sensing method, various parameters including force, pressure, displacement, stiffness, and softness have been used to identify a target tissue. In this study, tissue characterization using acoustic wave tactile sensor array is investigated. The acoustic wave tactile sensor array is able to detect the acoustic impedance change of target materials. Different tissues in human body have different properties including density, Young's modulus and acoustic impedance. In addition, abnormal tissues can have different density and elastic properties caused by the composition change compared to those of healthy tissues, which also leads to acoustic impedance difference. Therefore, the tactile sensor array is expected to distinct the abnormal or target tissue from normal tissues by means of detecting the acoustic impedance difference between them. The tactile sensor array used for the experiment was fabricated using a face-shear mode PMN-PT piezoelectric resonator which is highly sensitive to acoustic impedance of surface load. The proposed tissue characterization technique can be promising for the effective surgical process in minimally invasive surgery.

8695-120, Session PTue

Sensitivity-based optimal sensor placement for multi-type sensors

Xiaodan Sun, Gangling Hou, Zhenxu Wang, Harbin Engineering Univ. (China)

Integration of Multi-type senor data, which is mutual complementary, is a potential way to improve the accuracy and robustness of structural damage detection method. However, the effect of damage diagnosis based on multi-sensor data integration depends on the optimal sensor placement for multi-sensor data integration. Therefore, in the paper, an innovative optimal sensor placement based on sensitivity is proposed to determine the number and locations of three kinds of sensors including accelerometers, Fiber Brag Gauges (FBG), which are generally applied in vibration tests, and piezoelectric (PZT) sensors, which are commonly used in active sensing-based structural health monitoring. With considering the boundary effect of ultrasonic wave propagation and uncertainty caused by environment, the sensitivity-based object function to detect every possible damage location is established. Computational simulation on a simple-supported steel thin plate-like structure is implemented to evaluate minimum sensor number of accelerometers, FBG and PZT according to methods above. According to the optimal arrangements, general conclusions?such that the PZT is not suitable for placing on the boundary, are drawn. Finally, the optimal locations and number for three kinds of sensors are calculated.

8695-121, Session PTue

Bi-probability structural risk management method for bridge crane

Xiao Mei, Dashan Dong, Xinyuan Wang, Shanghai Maritime Univ. (China)

Bridge cranes, such as Quayside Container Cranes (QCC) were the most important equipments for ship-shore transport. The QCC was always operated all day and all night, meanwhile run speedily with heavy load. After a few years, cracks were found in structures, which damaged the structural health and also decreased the life of crane. Structural Health Monitoring (SHM) has emerged as a technology to detect the level of damage in structures. Yet it is not enough to just monitor the damage, it is also necessary to manage how important and what risk the damage presents. So that risk management should be conducted, in the case of a crane it could be a preliminary maintenance.

The QCC is a very bigger steel structural building, so it is difficult to conduct an overall check every day. How often should the structures be checked? Even if the cracks were found whether the structures should be maintained immediately? When did the crane structures reach the life to be scrapped? In order to achieve that, we will need to understand how the crane is working. Therefore, the concept Bi-probability is proposed, namely load probability and position probability. In the paper bi-probability structural risk management method is put forward, which is based on the Miner Linear Cumulative Damage theory (LCD) and Paris Law. The project will be carried out as follows: analysis real-time monitoring data, construct bi-probability stress cycle spectrum by rainflow counting method, and then give the inspection cycle of risk management. This method also can put into assess the maintenance decision for the in-service crane structures.

8695-122, Session PTue

Damage detection of transmission tower using ARX models and statistical quantification of error propagation

Gang Liu, Zongming Huang, Chongqing Univ. (China)

This study presents a damage detection method for transmission tower based on ARX models and quantification of error propagation under environmental and operational variability. The random responses of the tower under ambient excitation are transformed to free vibration response by random decrement technique. A cluster is built by several sensors and then the output of each sensor in the cluster is used as an input to the ARX (Auto-Regressive models with eXogenous input) model to predict the output of the reference channel in the same cluster. Parameters of ARX models and predict errors are both used as damage features to diagnosis damage. A statistical model is used to reduce the false alarm due to the uncertainty subjected by environmental, operational and measurement variability and quantification of error propagation in damage detection process is also addressed. The method is applied to the numerical data coming from simulating tower-line system in finite element software with random wind loads. It is shown that this method performs successfully to detect different damage cases and error propagation can be quantified well.

8695-123, Session PTue

Stress historical-log recording system based on ubiquitous mechanoluminescent sensing material

Nao Terasaki, Chaonan Xu, National Institute of Advanced Industrial Science and Technology (Japan)

A practical material that is mechanoluminescent (ML) in the elastic deformation region has been developed. The ML material can continuously emit high-intensity light under the application of mechanical stress. When dispersed on the structure, each particle acts as a sensitive mechanical sensor, while the 2-dimentional emission pattern of the whole assembly reflects well the dynamical stress and strain distribution. This provides a novel way of diagnosing the structural health, far more advantageous over the conventional point-by-point measurement method by use of a strain gage. It is possible to detect (or visualize) invisible defects and micro-cracks in small parts of machinery as well as to monitor the safety of huge constructions like bridges from shakes, damages and destruction.

On the other hand, however, not only the stress information at just each moment but also historical-log or integral of stress or fatigue crack growth are strongly required for practical use, from the view points of on-the-spot needs (reliability, a low price and easy-to-use) at the field of construction and structural maintenance.

Previously, we have reported the concept and demonstrative experiments on the “stress historical-log recording system”, consisting of the ML sensor and a photosensitive material.

In this study, we have investigated and successfully achieved the next points.

(1) Historical-log recording on fatigue crack growth

(2) Detection of crack mouth opening displacement on building and bridge in use.

(3) Development of stress historical-log recording paint.

8695-124, Session PTue

Non-contact measurement assessment of aerospace structures

Daniel Meisner, Andrei N. Zagrai, New Mexico Institute of Mining and Technology (United States)

Operation environment of engineered structures include transient and periodic loads that fatigue critical structural elements. To prevent structural failures, an efficient and inexpensive method of determining degree of structural deterioration is needed. Modern structural health monitoring (SHM) methods allow for extending structural life by analyzing continuous flow of information on structural condition and hence tailoring maintenance procedures. The majority of current SHM methods utilize piezoelectric transducers for transmitting and receiving elastic waves. Use of embedded or surface bonded piezoelectrics' requires a permanent bond to the host structure. Since quality of the bond is a dominant factor influencing sensor reading, it would be beneficial to eliminate the bond or at least reduce its influence on sensor reading. One option is to utilize magneto-elastic active sensors (MEAS) enabling electromagnetic generation and reception of elastic waves in conductive structures. By measuring MEAS response to harmonic input, magneto-mechanical impedance (MMI) of the structure may be obtained with correspondent mechanical and electrical contributions into the dynamic response. MMI may be measured in a non-contact setup, which in this study is coupled with laser-Doppler vibrometer (LDV) non-contact velocity measurements to validate structural dynamics. Various 2D and 3D structural geometries are considered in the experimentation. Experimental results are considered in verification of associated numerical and analytical models. MMI demonstrated capability to detect early-stage fatigue damage, that opens opportunities to predict material facture and crack development before onset of the catastrophic damage.

8695-125, Session PTue

Damage detection of a prototype building structure under shaking table testing using outlier analysis

Bong-Chul Joo, Young-Jun Yoo, Ki-Tae Park, Chin-Hyung Lee, Korea Institute of Construction Technology (Korea, Republic of)

The civil engineering community is becoming increasingly interested in monitoring structural behavior of civil infrastructure and in assessment of the structural performance. The demand has largely been driven by deficiencies in structural performance due to the aging of the infrastructure, excessive loading, and natural disasters such as an earthquake, a landslide, a typhoon and a tsunami. In this study, a structural health monitoring methodology using acceleration responses is proposed for damage detection of a three-story prototype building structure during shaking table testing. A damage index is developed using the acceleration data and applied to outlier analysis, one of unsupervised learning based pattern recognition methods. A threshold value for the outlier analysis is determined based on confidence level of the probabilistic distribution of the acceleration data. The probabilistic distribution is selected according to the feature of the collected data.

8695-126, Session PTue

Piezo-composites for energy harvesting from low-frequency noises

Xiaoming Zhou, Gengkai Hu, Beijing Institute of Technology (China)

We proposed a type of piezoelectric composites for energy harvesting from low-frequency noise environment. The composites are composed of metallic rings and discs placed on two surfaces of a clamped PVDF film. An equivalent discrete model is used to estimate the range of operating frequencies. Acoustic-structural coupled simulation is conducted to calculate electricity generated from PVDF films and analyze the vibration effects of the central discs and the outer rings. Numerical results show that the vibration modes can be tuned by changing the sizes of discs and rings. The first peak in harvested electricity at a lowest frequency corresponds to the resonant mode in which the ring and the disc vibrate in unison, while the second peak at a higher frequency is due to the resonant mode in which the larger block (the ring or the disc) vibrates while the other remains almost motionless. The two types of electrodes, namely the S-type and the U-type, are designed according to the two vibration modes. The harvesting efficiency of the designed piezo-composite has been improved by over 1000 times compared to that of the PVDF film fully covered by electrodes.

8695-127, Session PTue

Study on self-healing effect of concrete cracks based on microbial technique

Chunxiang Qian, Hui Rong, Southeast Univ. (China)

The self-healing effect of concrete cracks based on microbial technique were researched by the gauge for cracks width, scanning electron microscopy (SEM) and thermogravimetric analysis technology (TG) in this paper. The experimental results indicated that the concrete cracks could be fully filled by the microbial induced calcium carbonate precipitation afer cuing of 40 days. The quantities of microbial induced calcium carbonate reduced with the increasing of cracks depth. There was no calcium carbonate formation in the concrete cracks when the cracks depth is over 10 mm. In addition, the microorganisms could induce a large number of calcium carbonate formation away from the cracks surface of 1.5 mm. However, when the distance away from the cracks surface was over 1.5 mm, it could be found that the quantities of microbial induced calcium carbonate reduced with the incrasing of distance away from the cracks surface.

8695-128, Session PTue

Inverse problem solution in the identification of material elastic constants

Tadeusz Uhl, Wieslaw J. Staszewski, Lukasz Pieczonka, Pawel Packo, Lukasz Ambrozinski, AGH Univ. of Science and Technology (Poland)

Identification of the material constants is a key issue in the design and maintenance of structures and structural components. It is of interest for design engineers to know accurately the material data to be used in structural analysis. This knowledge is of major importance for the performance and safety of a designed structure. Another important aspect is the change of the material constants over time due to operational loads and environmental conditions. This changes may be localized or global and may serve as an indicator of structural health. Thus, constant monitoring of changes in the material constants may be an effective Structural Health Monitoring strategy. Currently, the identification of the material constants typically requires costly and time-consuming materials testing procedures that are frequently destructive in nature. Therefore, the methods for nondestructive, fast and accurate identification of the material constants are highly desirable.

The paper deals with material constants identification for metallic and composite materials. The approach is based on guided waves propagation and is nondestructive in nature. Experimental testing based on an array of piezoelectric transducers is combined with numerical modeling with use of the Local Interaction Simulation Approach. The two aspects are combined into a model based parameter identification problem. Physical and numerical experiments are used to determine the dispersion curves of propagating guided waves. The residual is defined based on the discrepancy between the measured and estimated dispersion curves for the fundamental guided wave modes. The method provides a means for directional and local material properties identification. The identification process may be performed in a short time the method may be applied for Structural Health Monitoring of plate-like structures.

8695-129, Session PTue

Study of nonlinear interaction of Lamb waves with breathing crack in an aluminium plate

Nitesh P. Yelve, Mira Mitra, Indian Institute of Technology Bombay (India)

Lamb waves are gaining popularity for nondestructive evaluation (NDE) of thin walled structures as they offer benefits such as built-in transduction, larger inspection ranges, and high sensitivity to small flaws. Conventional Lamb wave techniques based on the principles of linear ultrasonics, relies on measuring parameters such as attenuation, transmission and reflection coefficients. However, these parameters are sensitive to gross defects, where there is an effective barrier to transmission, whereas it is less sensitive to micro-cracks or crack initiation. On the other hand, nonlinear interaction of Lamb waves with defects, correlate the existence and extent of damage with the presence of additional frequency components in the output signal which are more sensitive to minute material inhomogenities. In the present study higher harmonic generation as a result of nonlinear interaction of Lamb waves with breathing crack in an aluminium plate is explored through finite element simulation in ANSYS. The nonlinearity parameter A_2/A_1^2, $A_1$and A_2 being the amplitudes of fundamental and second harmonics, is obtained for various transverse crack depths. The crack is modeled as a breathing crack using contact elements, which opens and closes as dilation and compression parts of the wave passes through it giving rise to contact acoustic nonlinearity (CAN). The nonlinearity parameter estimated from the analysis is found to be following a power law with varying crack depth. It shows that the nonlinear characteristics of Lamb waves can be effectively used for detecting and sizing the cracks with a fair accuracy.

8695-130, Session PTue

Advanced signal processing for high temperatures health monitoring of condensed water height in

steam pipes

Shyh-Shiuh Lih, Yoseph Bar-Cohen, Hyeong Jae Lee, Nobuyuki Takano, Xiaoqi Bao, Jet Propulsion Lab. (United States)

An advanced signal processing methodology is being developed to monitor the height of condensed water thru the wall of a steel pipe while operating at temperatures as high as 250oC. Using existing techniques, previous study indicated that, when the water height is low or there is disturbance in the environment, the predicted water height may not be accurate. In recent years, the use of the Hilbert transform technique has been shown to provide major improvements in signal analysis and has demonstrated to be a powerful tool for practical applications. A signal processing technique that is based on the Hilbert transform was developed and the determination of water heights at low levels was enabled. A series of tests and signal processing results have shown that the developed method provides a good capability for monitoring the height as well as the characterization of its disturbances (due to bulk or surface causes). To allow operating at 250oC the condensed water was simulated using silicon oil. The determined heights using time and frequency domain analyses will be described and discussed in this paper.

8695-77, Session 15

Guided wave propagation in carbon composite laminate using piezoelectric wafer active sensors

Matthieu Gresil, Victor Giurgiutiu, Univ. of South Carolina (United States)

The advancement of composite materials in aircraft structures has led to on increased need for effective structural health monitoring (SHM) technologies that are able to detect and assess damage present in composites structures. Piezoelectric wafer active sensors (PWAS) are lightweight and inexpensive transducers that enable a large class of structural health monitoring applications such as: (a) embedded guided wave ultrasonics, i.e., pitch-catch, pulse-echo, phased arrays; (b) high-frequency modal sensing, i.e., electro-mechanical impedance method; and (c) passive detection (acoustic emission and impact detection).

The focus of this paper is on the challenges posed by using PWAS transducers in composite laminate structures as different from the metallic structures on which this methodology was initially developed. After a brief introduction, the paper reviews the PWAS-based SHM principles. It follows with a discussion of guided wave propagation in composites and PWAS tuning effects. Experiments were performed on carbon fiber laminate, employing PWAS to measure the attenuation coefficient which is crucial in order to simulate the guided wave propagation. Expressions were derived from the Rayleigh damping model to compute the Lamb mode attenuation constants. Finally, the paper presents some experimental and multi-physics finite element method (MP-FEM) results on guided wave propagation in composite laminate specimens. The MP-FEM permits the input and the output variables to be expressed directly in electric terms while the two way electromechanical conversion is done internally in the MP_FEM formulation. The paper ends with summary and conclusion; suggestions for further work are also presented.

8695-78, Session 15

Examining the effect of delaminations and varying ply count on sensing ability for cfrp laminates embedded with terfenol-d

Jonathan Rudd, Dustin L. Spayde, Oliver J. Myers, Mississippi State Univ. (United States)

This paper examines the effects of delamination and ply variation on the sensing ability for magnetostrictive particles embedded in a carbon fiber reinforced polymer laminate. An analytical method is used to determine how delamination and ply variation affect the mechanical state and magnetic properties of the embedded terfenol-d particles. Numerical models are also used to simulate the effect of delamination and ply variation on the mechanical state. For the analytical method, the mechanical properties observed are the net strain and stress in a local particle section resulting from magnetostriction. A one dimensional load line equation and material property data are used to obtain approximate solutions. The magnitudes of the stress and magnetostriction drop in the laminates are observed. Based on the local mechanical and magnetic state, the magnetic permeability can be selected from experimental data. The analytical method reveals that the effect of a delamination is to reduce the resistance to particle actuation in a local area, which allows for variation in stress and magnetostriction magnitudes in damaged areas vs. non-damaged areas. This variation in the mechanical state subsequently affects the magnetic permeability, which changes the reluctance in the local particle layer. These results are compared to a numerical model of terfenol-d embedded in carbon fiber reinforced polymer laminate, which reveal a drop in stress and increase in magnetostriction in the delamination region. Finally, these results are projected to experimental results from health monitoring scans of carbon fiber reinforced polymer laminates with varied ply count from 2-14 plies, with delamination.

8695-79, Session 15

Experimental modal analysis for damage detection in composite plates using laser Doppler vibrometer

Anand Kumar, Harcourt Butler Technological Institute (India); Bishakh Bhattacharya, Indian Institute of Technology Kanpur (India)

The use of composites as structural material in critical and advanced applications is still lagging due to the lack of efficient and reliable damage detection methods which could ensure sustained reliability and well being of the structure over its planned service life. The use of advanced and precise optical measurement systems such as Laser Doppler Vibrometer is gaining in extracting vibration signatures for the purpose of damage detection as mass loading of the specimen due to sensors and actuators in embedded systems may be avoided. The dynamic responses of structure offer unique information on defects inside the structure. Changes in the physical properties of the structures due to damage alter the dynamic responses such as natural frequencies, modal damping and mode shapes. These changes in physical parameters can be extracted to estimate damages in the structure by experimental modal analysis. In the present work, dynamic responses of glass-epoxy composite laminates with different ply orientations are studied. Laser Doppler Vibrometer has been used to capture the vibration characteristics of dynamically excited healthy and delaminated composite laminates. Delaminations have been introduced in the laminates at different locations to simulate damage situations. The effect of delamination on modal characteristics (natural frequencies, modal damping and mode shapes) of the composite laminates has been analyzed for the purpose of damage detection, its location and severity. The first four natural frequencies recorded during experimental modal analysis for healthy laminates are compared with a standard FE software-ABAQUS. Perceptible changes in natural frequencies, damping and mode shapes are observed in all delaminated specimen during experimental modal analysis. Laminates with

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longitudinal and transverse direction fiber arrangements are more prone to these changes while cross ply laminates are only marginally affected. Experimental investigations show that a change in modal damping in a locality is a good indicator of potential delaminating site.

8695-80, Session 16

Nonlinear guided waves for neutral temperature measurement in continuous welded rails: results from laboratory and field tests

Claudio Nucera, Francesco Lanza di Scalea, Univ. of California, San Diego (United States)

Continuous Welded Rail (CWR) is used in modern rail construction including high-speed rail transportation. The absence of expansion joints in these structures brings about the risk of breakage in cold weather and of buckling in warm weather due to the resulting thermal stresses. 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 in-situ measurement of the rail Neutral Temperature in CWR. Currently, there is no well-established technique able to efficiently monitor the rail thermal stress, or the rail Neutral Temperature (rail temperature with zero thermal stress), to properly schedule slow-order mandates and prevent derailments. UCSD has developed a prototype (Rail-NT) for wayside rail Neutral Temperature measurement that is based on non-linear ultrasonic guided waves. Numerical models were first developed to identify proper guided wave modes and frequencies for maximum sensitivity to the thermal stresses in the rail web, with little influence of the rail head and rail foot. Experiments conducted at the UCSD Large-scale Rail NT Test-bed indicated a rail Neutral Temperature measurement accuracy of a few degrees. The first field tests of the Rail-NT prototype were performed in June 2012 at the Transportation Technology Center (TTC) in Pueblo, CO in collaboration with the Burlington Northern Santa Fe (BNSF) Railway. The results of these field tests were very encouraging, indicating an accuracy for Neutral Temperature measurement of 5 °F at worst, on both wood ties and concrete ties.

8695-81, Session 16

Elasto-acoustic coefficients relating to the time-of-flight of guided acoustic waves

travelling on aluminum structures and respective temperature coefficients

Hermann Klinghammer, Khurram S. Tarar, Univ. Leipzig (Germany); Mieczyslaw Pluta, Wrocław Univ. of Technology (Poland); Gerhard Birkelbach, Wolfgang Grill, Univ. Leipzig (Germany)

The dependence of the time-of flight of acoustic waves travelling over a distance of one unit length on the applied tensile stress and resulting strain is determined fort the accessible lower modes of Lamb waves and, to the extend possible, to results for SAW and bulk waves. The observations are compared to the results of modeling based on linear chains. The influence of temperature coefficients is discussed and methods to determine the temperature by the transport properties of guided waves even in the presence of stress or strain are presented. The obtained results are essential for the developed methods of integral structural health monitoring by monitoring of the time-of-flight of guided acoustic waves with high temporal resolution, reaching down to 10-6 of the time of one oscillation of the observed waves.

Comment: This new submission replaces an older doubly submitted and earlier by e-mail withdrawn paper

8695-82, Session 16

Temperature-independent localization algorithm using guided wave interrogation methods

Kevin Hensberry, Narayan Kovvali, Aditi Chattopadhyay, Arizona State Univ. (United States)

This paper examines the current challenges of using Lamb wave interrogation methods to localize fatigue crack damage in a complex metallic structural component in the presence of temperature variations. The goal of this research is to improve damage localization results for a structural component interrogated at an unknown temperature by developing a probabilistic and reference-free framework for estimating Lamb wave velocities. The algorithm developed for temperature-independent damage localization involves developing a model that can describe the change in Lamb wave velocities with temperature, the use of advanced time-frequency based signal processing for damage feature extraction, estimating the actual Lamb wave velocities from transducer signals, and a Bayesian damage localization framework with data association and sensor fusion. The proposed technique does not require any additional transducers on a component and allows the estimation of the velocities for the actual Lamb waves present in a component. Experiments to validate the proposed method were conducted using an aluminum lug joint interrogated with piezoelectric transducers for a range of temperatures and fatigue crack lengths. Experimental results show the advantages of using a velocity estimation algorithm to improve damage localization for a component interrogated at both known and unknown temperatures.

8695-83, Session 16

Studies of texture in nuclear graphites using laser ultrasonic line source measurements

James B. Spicer, Lindsey R. Lindamood, Johns Hopkins Univ. (United States)

Laser ultrasonic line sources have been used to study the ultrasonic properties of nuclear graphites. These materials exhibit varying degrees of porosity and texture that relate directly to the conditions imposed during material processing - extruded materials display significant texture while the anisotropy of molded materials is significantly lower. Both the texture (related to grain orientation) and porosity impact the long term performance of graphite under service conditions and methods are needed to assess the microstructural states of these materials during service. Laser ultrasonic measurements can be used to assess aspects of material microstructure by measuring longitudinal and shear wavespeeds as a function of propagation direction and polarization. While porosity-related effects are independent of propagation direction for materials with spherical pores, material texture (related to preferred grain orientation) produces anisotropic wave propagation effects.
In particular, propagation perpendicular to extrusion directions can produce shear wave birefringence effects that can be used to assess texture. Ultrasonic measurements in this work were made using laser ultrasonic methods that yield waveforms that can be interpreted using elastodynamic models for wave propagation in anisotropic materials. In particular, models for laser ultrasonic line sources in transversely isotropic materials have been used to simulate laser sources in nuclear graphites. The effects of optical penetration (related to material porosity) have been incorporated to produce synthetic waveforms that can be used to extract modulus information from experimental measurements. Current results hold open the opportunity for porosity and texture assessment using a limited set of ultrasonic measurements.

8695-84, Session 16

Temperature effect modelling of PZT transducers used for lamb wave propagation in damage detection applications

Piotr Kijanka, Pawel Packo, Wieslaw J. Staszewski, Tadeusz Uhl, AGH Univ. of Science and Technology (Poland)

Although damage detection using Lamb waves has been investigated for many years, real engineering applications are limited due to practical aspects related to implementation. Temperature effect is one of the major problems. It is well known that temperature variations influence Lamb wave propagation response parameters. In practice it is important to compensate for this effect. However, this often requires experimental tests. Numerical simulation can ease the task preventing multiple repetitions of unnecessary experiments. Simulated Lamb wave responses can be used to develop new methods for temperature compensation.

The effect of temperature variations on PZT transducer responses is investigated using finite element numerical modelling. The model takes into account temperature-dependent physical properties of low-profile PZT transducers and transducer bonding layers. The model is used to predict the S0 and A0 Lamb response in aluminum plate for the temperature range from -30 to +70 °C. The study shows relevant changes in Lamb wave amplitude response caused by temperature fluctuations. This approach can provide the basis for temperature compensation in ultrasonic guided wave damage detection systems used for structural health monitoring applications.

8695-85, Session 16

Cointegration and wavelet analysis based approach for Lamb wave based structural damage detection

Phong B. Dao, Wieslaw J. Staszewski, AGH Univ. of Science and Technology (Poland)

Lamb waves are often used in smart structures with integrated, low-profile piezoceramic transducers for structural damage detection and health monitoring. It is well know that the method is prone to contaminations from a variety of interference sources including environmental and operational conditions. The paper demonstrates how to remove the undesired temperature effect from Lamb wave data in order that structural damage can be detected precisely and reliably. The method is based on the cointegration method and wavelet analysis that are partially built on the analysis of non-stationary behavior of time-series. The key idea is that, instead of directly using Lamb wave data for damage detection, three approaches are proposed: (1) analysis of variances of wavelet coefficients on Lamb wave responses before cointegration (i.e. Lamb wave responses -> Wavelet decomposition -> Variances of wavelet coefficients), (2) analysis of cointegrating residuals obtained from the cointegration process of Lamb wave responses (i.e. Lamb wave responses -> Cointegration -> cointegrating residuals), and (3) analysis of variances of wavelet coefficients on Lamb wave responses after cointegration (i.e. Lamb wave responses -> Cointegration -> Wavelet decomposition -> Variances of wavelet coefficients). The method is tested on undamaged and damaged aluminium plates exposed to temperature variations. Small, medium, and large damage are presented in terms of a hole of 1, 3, and 5 mm diameter introduced in the center of plates, respectively. The experimental results show that the first approach is suffered from temperature variability and no damage can be detected; whereas the second and third approaches not only can detect the medium and large damage but also simultaneously isolate damage-sensitive features from temperature, i.e. temperature effects on Lamb waves are purged through cointegration. However in both cases, the small damage were not detected.

8695-86, Session 17

In vivo muscle length-force-joint angle relationship in quasi-static muscle action of biceps muscle

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Experimental findings of non invasive in-vivo monitoring are essential to study the diversity and evolution of musculoskeletal kinematics. In this paper we have presented the results that obtained from the uni-axial monitoring of the quasi-static dynamics of biceps muscle-belly with the custom developed ultrasonic caliper, together with the synchronously recorded applied external force and joint angle variations with the custom build ultrasonic force sensor and with resistive angle decoder respectively. The monitored muscle action includes the processes of active muscle contraction and relaxation in a closed path through initial isotonic contraction and then through eccentric (spring like) stretching. The technology applied here allows for observations of those processes and registration of their paths in the length-force-angle parameter space. That way of presentation reveals that at some conditions the closed-loop human cycles go along characteristic lines of well identifiable elementary processes. Presentation of these processes in the length-force parameters space allows for discussion of the mechanical energy expenditure during different muscle actions. Comparative studies of identical closed-loop muscle actions and the joint angle-force-length relationships of the muscle-tendon complex are presented. This synchronous monitoring also allows to quantify the joint torques and positions with high accuracy in living person..

8695-87, Session 17

Fully integrated MEMS based scanning endoscope with potential OCT application

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The proposed endoscope is aimed to develop a miniature MEMS based scanning endoscope that can eventually provide a real-time 3-D imaging and functional integration of high-resolution optical imaging techniques including optical coherence tomography (OCT). This paper presents the current status of our microfabricated SU8 cantilever beam scanner for endoscopic examination. The current design has improved performance with the implementation of a MEMS based electrostatic push-pull actuator as the scanner's foundation. This prototype features monolithic integration of the waveguide, actuator, and light source, and removes the dependence on external actuators used by the previous design. Fabrication of the SU-8 rib waveguide thickness was measured to be ~3.5μm as compared to ~50 to 100μm in our previous design, further improving our spatial resolution. By altering the system geometry, we have made coupling an optical fiber into the device easier and achieved ~95% coupling efficiency. The proposed rib cantilever waveguide design also allows a relatively large waveguide cross section (4μm in height and 20 μm in width) and broader band single mode operation (λ= 0.7μm to 1.3μm) with a minimum transmission loss (85% to 87% output transmission efficiency with Gaussian beam profile input). Our novel design provides a new means to create a 2-D raster scanning pattern using 1-D actuation, verified by transient finite element analysis. The scanner's line resolution and field of view have been optimized through a parametric study using modal and harmonic analyses. This paper describes the fabrication and testing of our MEMS optical scanner, which may find application in the area of endoscopy, where devices that minimize patient discomfort are needed.

8695-88, Session 17

Quantitative simulation of wave propagation in a human leg to support the ultrasonic non-invasive assessment of human bones

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The non-invasive assessment of bones via axial ultrasonic transmission techniques can be fully exploited only once the complexities of mechanical waves, generated by medical probes, are unveiled. To such aim, this paper presents a dedicated numerical strategy for a quantitative simulation of wave propagation in human bones. The proposed procedure overtakes the usually adopted bi-dimensional plate/cylindrical waveguide models taking into account the irregular geometry of the bone as well as the soft tissues and their damping role, typically neglected.

Starting from a computed tomography image of a human leg, first the proposed strategy builds a three-dimensional finite element (FE) mesh by converting voxels into elements. The procedure does not require any segmentation or further geometric interpretation of the bones and soft tissues (marrow, mussels, skin, etc.), and only the mechanical properties have to be provided via Hounsfield number density mapping.

Next, time transient analyses are performed to simulate how the waves travel along the bone. The FE code can timely handle simulations with hundred millions of elements in a standard PC desktop. Finally, the time transient responses are analyzed via a dedicated signal processing to highlight the time-frequency energy pattern of the guided waves that propagate along the bone. The proposed strategy can support research on ultrasonic non-invasive techniques based on stress wave analysis for the assessment of long bones.

8695-89, Session 17

Bio-penetrating near-infrared mechanoluminescent sensing material for on-site biomechanical measurement

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Inovative mechanoluminescent (ML) material emits light repeatedly in response to load even in elastic region. When dispersedly coted on a structure, each particle acts as a sensitive mechanical sensor, while 2-dimentional emission pattern of the whole assembly reflects well the dynamical stress distribution. Actually, so far, the ML sensing technique has been successfully applied to diagnosis of social structure, such as bridge, building, pipeline and so on. From viewpoint of on-site and early detection on stress concentration, however, not only the structures but also bio-body must be crucial target for health monitoring. To develop on-site bio-mechanical measurement system using ML sensor from outside of bio-body, we succeeded to achieve the next three points.

(1) Near infrared (NIR) light emitting ML material.

For detection of mechanoluminescence which emits inside bio-body from the outside, the ML wavelength should be in NIR region, around 700-900 nm from the viewpoint of bio-penetration property. Essentially, for the first time, we developed near NIR ML material, based on Eu^{2+} doped strontium aluminate ($SrAl_2O_4$:Eu) by co-doping additional emittive metal ion.

(2) Mechanoluminescence induced by ultrasonic wave irradiation.

We detected mechanoluminescence induced by ultrasonic wave, non-destructive and non-inversive wave for bio-body, and controlled the ML intensity by changing the power of ultrasonic wave.

(3) Detection of mechanoluminescence penetrated though bio-tissue.

We succeeded to detect the NIR-mechanoluminescence even through bio-body via bio-penetration.

These results show potential of the NIR-ML material as a good candidate for the diagnostic probe to visualize on-site biomechanical information from outside of body.

8695-90, Session 17

An electromagnetic-coil based nondestructive method demonstrating a screw-hole targeting of an intramedullary interlocking nail in long-bone surgery

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We report an electromagnetic-coil-based nondestructive method to target/locate screw holes of an intramedullary-interlocking nail in a bone during the surgical operation for a long-bone fracture. The method is an X-ray-free nondestructive approach addressing the over-exposure of radioactivity and machining difficulty of embedding a magnet into a nail caused by the conventional X-ray-imaging and magnetic-detecting approach, respectively. According to the method, we fabricate a targeting-system consisting of an emitting-coil, detecting-inductance, scanning-mechanism, and measurement electronics. When a voltage is applied to the emitting-coil attached on the inner/surrounding region of a screw-hole of a nail in a bone, a directional magnetic flux is generated by the emitting-coil due to the electromagnetic induction. The generated directional magnetic flux can penetrate the nail and bone. When the detecting-inductance outside the bone scans along the axial and angular directions of the nail/bone, different amount of the generated magnetic flux is detected by the detecting-inductance and subsequently converted to different induced-voltage response due to the electromagnetic induction. Through correlating the induced-voltage responses to the scanned axial and angular locations along the nail/bone, correlation curves for axial and angular targeting are plotted. Through analyzing the curves, a criterion for predicting the location of the screw-hole of the nail is established. When compared the predicted location with the actual location of the screw-hole, the maximum targeting error is 2 mm for targeting a screw-hole with a diameter of 5 mm. This shows the targeting-method is accurate and able to significantly simplify the screw-hole targeting procedure for the surgeon.

8695-91, Session 18

Study of an elastic metamaterial beam for broadband bending wave suppression

Rui Zhu, Guoliang Huang, Univ. of Arkansas at Little Rock (United States)

Vibration absorption in beams or pipe systems using local resonators has been investigated intensively. However, the resulting bandgap in a narrow bandwidth limits their practical engineering application. In the paper, an elastic metamaterial beam with multiple resonators is studied for the broadband bending wave suppression. First, a theoretical study of the metamaterial beam is performed for bending wave propagation. Based on the wave mechanism, a microstructure section design of the metamaterial beam is suggested. Finally, a metamaterial-based chiral beam is fabricated and experimental testing of the structure is conducted to validate the proposed wave function. This work can serve as a theoretical and experimental foundation for the metamaterial structure in a realistic loading environment.

8695-92, Session 18

High stiffness-high damping chiral metamaterial assemblies for low-frequency applications

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Stiffness and damping are conflicting requirements in many material systems. High stiffness is required in a wide range of structural components to provide sufficient robustness under demanding loading conditions. Simultaneously, a structure should be able to effectively mitigate shock and vibrations dynamically transmitted to it by the environment. While most conventional structures currently exhibit limited adaptability and damping capabilities, design strategies to simultaneously endow structural assemblies with high stiffness and high damping performance are proposed in this work. To this aim, a backbone structure suitable to meet stiffness requirements is combined with metamaterial inclusions able to provide fully-passive shock and vibration absorption. Viscoelastic resonant lattices with chiral topology are employed as inclusions, whose aim is to confine vibrational energy, pump it away from the backbone structure, and dissipate it through viscoelastic damping. The lattices are composed by an elastomeric matrix with the desired chiral shape, and stiff resonating inclusions are inserted at nodal locations. Both finite element simulations and experimental tests demonstrate that periodic chiral assemblies give rise to wide frequency bandgaps. Low-frequency tuning of the assembly for effective suppression of the first resonant mode of a backbone structure represented by an aluminum box-beam is demonstrated both numerically and experimentally. The considered lightweight inclusion is a chiral matrix realized with castable silicone rubber, featuring graded cylinder mass insertions. The proposed design methodology can be flexibly tailored to various frequency ranges and is applicable to both existing and novel structural components at different scales.

8695-93, Session 18

Novel split ring metamaterial for vibration control and structural health monitoring

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A novel metamaterial using split ring resonator is envisioned. Unlike traditional metamaterials multiple resonant frequencies were targeted to obtain by uniquely designed split rings embedded in polymer matrix. Purpose of such metamaterial is not only for creating simultaneous negative effective mass density and negative bulk modulus but also use them as a tuned structural health monitoring system. Frequency analyses have been performed to find multiple resonant frequencies, which is one of the most center focuses in acoustic metamaterial research. A new split ring metamaterial technique is proposed to find multiple resonant frequencies. The split ring metamaterial is made of a metal or piezoelectric sphere enclosed in metal circular ring. Two pairs of split circular rings and one spherical ring are placed symmetrically. In addition to circular split rings, two sets of elliptical split rings are also placed to enclose the aforementioned assembly. Rings are made of steel and two different types of epoxy resin are used to manufacture the complete unit cell. Alternate periodicity by mirroring the pattern has been introduced.

8695-94, Session 18

Actual working mechanisms of smart metamaterial structures

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Metamaterial structures are passive smart structures. This paper presents methods for modeling, analysis, and design of metamaterial bars and beams for broadband vibration absorption/isolation and reveals their actual working mechanisms. The proposed metamaterial beam (or bar) consists of a uniform isotropic beam (or bar) with many small spring-mass-damper subsystems integrated at separated locations along the beam (or bar) to act as vibration absorbers. For a unit cell of an infinite metamaterial beam (or bar), governing equations are derived using the extended Hamilton principle. The existence of stopband is demonstrated using a model based on averaging material properties over a cell length and a model based on finite element modeling and the Bloch-Floquet theory for periodic structures. However, these two idealized models cannot be used for finite beams (or bars) and/or elastic waves having short wavelengths. For finite metamaterial beams (or bars), a linear finite element method is used for detailed modeling and analysis. The concepts of negative effective mass and stiffness and how the spring-mass-damper subsystems create a stopband are explained in detail. The actual working mechanisms of the proposed metamaterial beams and bars are found to be based on the concept of conventional mechanical vibration absorbers.

8695-95, Session 18

Effective medium properties of acoustic crystals in two dimensions

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By using the multiple-scattering theory, we studied the low frequency effective medium properties of two-dimensional acoustic crystals consisting of cylindrical solid inclusions embedded in fluid hosts. We show that both the scattering property of a single scatterer and the effect of the lattice structure contribute to the effective medium. If the lattice has a four- or six-fold symmetry, the effective mass density is always isotropic regardless of the solid concentration and is independent of the lattice structure when the solid concentration is either low or high. For low concentrations, the contribution from the lattice structure cancels to zero and the effective mass density is the widely adopted dipole solution, whereas for high concentrations, the scattering of individual scatterers and the lattice effect interact in such a way that makes the effective mass density approaches the volume-averaged value asymptotically, which exhibits a universal exponent. In the intermediate regime, the effective mass density becomes structure dependent. If the lattice is a rectangle or rhombus, the effective mass density is anisotropic in general even in the leading order, in which the lattice effect is significant. For a rectangular lattice, the anisotropy is a result of the difference between the lengths of the basis vectors, and for a rhombus lattice, the anisotropy comes from the angle between the basis vectors. In all cases, the bulk modulus is always isotropic and satisfies the Wood's formula which is independent of the lattice structure. The analytic expressions are given and verified by the finite-element simulations.

8695-96, Session 18

Acoustic metamaterials: super absorbers for low-frequency sound

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It is well known that the attenuation of low-frequency sound has been a challenging task because the dissipation of materials in this regime is inherently weak. Here we show that by using thin elastic membranes decorated with designed patterns of asymmetric rigid platelets, the resulting acoustic metamaterials can absorb 86% of the acoustic waves at 170 Hz, with two layers absorbing 99% at the lowest and higher frequency resonant modes, where the relevant sound wavelength in air

can be three orders of magnitude larger than the membrane thickness. Finite element simulations of the resonant mode patterns and frequencies are in excellent agreement with the experiments. At resonances, the measured out-of-plane displacement profiles of the resonant modes show sharp discontinuities in the first-order spatial derivatives around the platelet perimeters, implying significantly enhanced elastic curvature energy is concentrated in these small volumes. For the lower frequency resonance this discontinuity is caused by the flapping motion of the two semicircular platelets that is symmetric with respect to the y axis, whereas for the higher frequency resonance it is caused by the large vibration of the central membrane region, with the two platelets acting as anchors. This thereby gives rise to strong absorption similar to a cavity system, even though the system is geometrically open. In particular, the overall energy density in the system can be two to three orders of magnitude larger than the incident wave's energy density.

8695-97, Session 18

Focusing Lamb flexural waves by designing an elastic metamaterial plate with variable microstructures

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In this paper, a thin elastic metamaterial plate with variable microstructures can be designed to bend and focus flexural A0 Lamb waves to a desired region on the plate and to use it as a low frequency elastic wave filter. The metamaterial strip serves as a "virtual convergencing lense" to bend and focus a set of A0 Lamb waves down to a point (or small region). Hyperbolic secant effective mass density profile of metamaterials is designed by changing the height of the microstructures to focus elastic waves to create a type of lens, which focuses structural wave energy. Aluminum cylinders with coated rubber are chose as microstructures because of its locally resonant mechanism (elastic metamaterial) for low frequency application while microstructures with periodic aluminum cylinders can only be performed at very high frequency range due to Bragg scattering mechanism (phononic crystals). Locally resonant and Bragg scattering induced band gaps are discussed as well.

Numerical simulations of Lamb waves in a metamaterial plate show that the design is effective at low and over a broad frequency range, 0-100kHz, because of the locally resonant mechanism, and traveling waves can be focused to the same region of the plate regardless of frequency. Besides, the first band gap of A0 Lamb wave appears around 100 kHz, so we can use this design as a low frequency elastic wave filter. Furthermore, the amplitude of Lamb waves around focusing region is increased several times in comparison with the amplitude from the source. This design has good potential applications in structural health monitoring since we are able to manipulate elastic wave by controlling and focusing elastic waves to a small region where the sensors are located.

8695-98, Session 18

Nonlocal effect of acoustic wave interaction with thin-plate metamaterial

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This work studies acoustic responses of thin-plates attached periodically with mass-spring resonators. In normally incident cases, the thin-plate structure can be well homogenized to metamaterial with negative dynamic mass. While for obliquely incident waves, effective material parameters can be dependent on incident angles, exhibiting the nonlocal effect. We analyze the thin-plate metamaterials with the infinite weight of the mass, which have negative effective mass below a cut-off frequency. It is found that the cut-off frequency, at which acoustic transmission is maximum, is correlated to incident angles when the wavelength is not much larger than the periodicity between mass-spring resonantors. As the result, the defined effective mass is related to incident angles, or parallel wavenumbers of incident waves. It is further found that the cut-off frequency shifts downwards with the increasing of the incident angle. The relation coincides very well with the dispersion curve of flexural waves in analyzed thin-plate structure. The result demonstrates that the cut-off frequency agrees with the eigenfrequency of flexural vibration, and incident waves of larger incident angle excite lower-order eigenmode of flexural vibration. The discovered nonlocal feature of thin-plate metamaterials would produce anomalous dispersion effect, used for acoustic wave manipulations.

8695-99, Session 19

Frequency-wavenumber filtering of nonlinear Lamb waves for detection and imaging of fatigue damage in aluminum plates

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This paper reports on the application of an ultra-high frequency (UHF) scanning laser Doppler vibrometer (SLDV) to enable the use of frequency-wavenumber domain signal processing techniques on nonlinear (higher harmonic) Lamb waves in aluminum plates subjected to fatigue damage. The formation of these higher order cumulative wave modes can be caused by material nonlinearities such as fatigue induced microcracks and plasticity. To date, studies of nonlinear elastic waves have typically utilized a combination of wedge transducers and/or custom laser interferometers to induce and measure the elastic waves. The main shortcoming of these experimental techniques is their low spatial resolution, which has precluded the use of frequency-wavenumber domain signal processing. The Polytec UHF-120 SLDV can take out-of-plane displacement measurements at up to 1.2 GHz with point spacing of less than 50 µm, making it an ideal tool for the investigation of higher harmonic nonlinear Lamb waves. Here, aluminum plates are subjected to cyclic loading at several different load levels, producing cracks from approximately 1 to 20 mm in length. Waves are induced using bonded piezoceramic transducers and measured in a dense grid using the SLDV. Resulting data are converted to the frequency-wavenumber domain via 2D and 3D Fourier transforms and subjected to a variety of filter techniques in order to detect and image the location and extent of fatigue damage.

8695-100, Session 19

Linear and nonlinear acoustic moment for structural health monitoring for compression loaded structures

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This work focuses on developing a methodology that uses both the linear acoustic moment and nonlinear acoustic moments of a given signal to help determine the damage present in a compression loaded specimen. The procedure was demonstrated on two compressively loaded alluminium plates and a rig was used that allowed the adjustment of the pressure . Two piezoelectric sensors were used to send and receive the input and output signals. The results showed that nonlinear acoustic moments (2nd and 3rd harmonic responses) responded less adversely to increases in pressure than that of the linear acoustic moment (1st harmonic). This was clearly seen as the rate of decrease in the above described compression loaded system for the nonlinear acoustic moments as pressure increased was smaller than that of the linear acoustic moment. The work provides a solid platform for the proposed acoustic moment method suggested, and an early hypothesis suggests

that the link between the linear and nonlinear acoustic moments can provide useful information about damage in compression loaded systems.

8695-101, Session 19

Nonlinear ultrasonic evaluation of fatigue damage of adhesive joints

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Ultrasonic NDE (nondestructive evaluation) is widely used in industries, and conventional NDE mainly focuses on the stage of appearance of macro-cracks and the coalescence and accumulation of these macro-cracks, where the physical information of wave propagation distance, sound speed, and attenuation, damping and scattering is employed. These physical parameters, however, are not sensitive enough to detect material degradation for mechanical/structural components. It is of great significance to develop an effective approach to nondestructively characterize material degradation. Nonlinear acoustic theory and the related experimental techniques have attracted considerable attention in recent years. Experimental results and physical models show that the material degradation is closely related to the nonlinear effects of ultrasonic waves.

In this paper, experimental evaluation of damage of an adhesive joint layer between two AZ31 magnesium alloy plates under low-cyclic fatigue loading is carried out by using longitudinal bulk ultrasonic waves. The well-defined acoustic nonlinear parameter based on the fundamental and second harmonics is measured. The results show that the nonlinear parameter increases with the increasing of loading cycle. A theoretical model with different tension and compression properties for the adhesive joint is developed. It is shown that the nonlinear parameter based on the theoretical model increases with the loading cycle in a similar way to the measured data. The present research is expected to provide a promising way for the characterization of adhesive joints damage effectively.

8695-102, Session 20

Strategies for guided wave imaging using two-element annular transducers

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Guided wave imaging methods using in situ piezoelectric disk transducers have been implemented by many researchers to localize damage in plate-like structures. Imaging is typically limited to one or two frequencies because of the need for reasonable mode purity and the limited ability of such transducers to achieve it. This limitation is due to the well-known mode tuning effect whereby mode purity is achieved only at frequencies where the transducer diameter is approximately half of the wavelength of the guided wave mode. In this paper the use of two-element annular transducers is considered, where each transducer consists of a disk surrounded by an annulus. If the two elements can be excited both together and individually, then there are more options for mode purity because of the different diameters. Furthermore, it has been previously demonstrated by Yeum et al. that mode purity can be achieved at additional frequencies via linear combinations of all possible signals from a pair of annular transducers [Wave Motion, 48, p. 358, 2011]. This paper explores the use of two-element annular transducers as part of a spatially distributed array and evaluates methods by which such arrays can be effectively utilized for improved localization of damage. Images are shown from aluminum plate specimens to illustrate the advantages that result from achieving mode purity at more frequencies than are possible with simple disks.

8695-103, Session 20

Aging effects on guided wave structural health monitoring sensor performance

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With the eventual push to implement structural health monitoring (SHM) methodologies and systems onto active duty aircraft, a realistic look at the effects of aging on a system's long term performance is required. This study investigates aging effects on lead zirconate titanate (PZT) bonded sensor packages used in a guided wave SHM laboratory experiment. Aging effects are quantified by computing the correlation coefficient between a reference waveform and test waveforms. The reference waveform is recorded from an initial healthy condition. Test waveforms are recorded periodically during the aging test. Three aging effects are considered: time (accumulated electrical fatigue of actuation PZT) effects, thermal cycling effects, and low stress mechanical cycling effects. The aging tests are designed specifically to avoid causing any damage to the host structure. Therefore, changes in the correlation coefficient value are attributed to aging effects. Waveforms are recorded at constant temperature to eliminate the need for post-processing of the waveforms to account for differences in wave speeds due to temperature variations. The results of the tests are mixed. Some sensors are stable over the duration of all tests, while other sensors test shows substantial changes, including clear trends of decreasing correlation coefficient values in the absence of structural damage.

8695-104, Session 20

Uncertainty quantification of a guided wave structural health monitoring system for composite bolted joints

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Assessing the robustness of a sensor system and the related predictions is a key step in structural health monitoring (SHM). In this paper, the SHM system under consideration uses macrofiber composite (MFC) sensors to generate ultrasonic guided waves for inspection of a composite bolted joint. Bolt bearing failure is introduced to a target hole through tensile loading. The MFC sensor-actuators are configured in a circular array around the target hole and used to send and receive the ultrasonic waves from many different directions. This strategy facilitates a scattering matrix approach to identifying the most effective actuation and sensing angles for damage detection. Multiple interrogation wavelengths are also utilized to study the effect of the wavelength relative to the size of hole being monitored. However, various other factors are expected to impact the ultrasonic signal and therefore the damage detection results. These factors are studied and their effects are quantified through the use of machine learning algorithms. Particularly, the position and orientation of each sensor is precisely measured through image processing techniques in order to quantify the effects of sensor misalignment. Finally, the sensitivity of the ultrasonic inspection technique to variation in each phenomenon is compared to better understand the most significant effects for damage detection.

8695-105, Session 20

Pressure mapping system based on guided waves reflection

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In this paper, guided wave interaction is used to develop a pressure mapping system for medical and touch-screen applications. The principle is based on interaction of guided waves in the presence of an added local mass and in the presence of a local pressure. For this purpose, piezoceramics are used for injecting guided waves into a thin structure and to measure the reflected waves due to the presence of an added mass or pressure. SHM imaging algorithms, based on Time-of-Flight (EUSR) or correlation (Excitelet), are implemented in order to obtain cartography of the reflections and deduce the presence, localization and intensity of local contact spots.

Analytical and numerical models are first derived to assess the critical parameters in order to maximize the reflection of guided waves (first order modes A0 and S0). It is shown that the sensitivity of the guided waves with respect to an added mass and pressure is highly related to the Young's modulus of the host structure. Then the implementation of the imaging process for real-time application is proposed. Finally, validation on a 0.5 mm thick plane aluminum plate prototype is addressed using 4 sensor / actuator pairs. It is observed that imaging of single pressure spot and multiple or extended pressure spots can be achieved using S0 mode around 300 kHz with a resolution of 0.5 mm. Extension in the case of more complex structures (curved shells, multilayer, complex shapes) is proposed using an experimental identification approach.

8695-106, Session 20

Wavelet best basis compressed sensing of ultrasonic guided waves

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A novel Compressed Sensing (CS) signal compression and reconstruction procedure is presented in this study for dispersive guided wave propagation analysis in passive structure health monitoring applications and it is compared with the classical Embedded Zerotree Wavelet (EZW) Algorithm with Huffman coding.

The proposed approach combines the Wavelet Packet multiresolution analysis, best basis selection and coefficients thresholding to generate a sparse but accurate time-frequency representation of the acquired dispersive signal, with the CS framework in order to compress the wavelet coefficients.

The mother wavelet choice is optimized to match the signal characteristics using lattice parameterization [Vaidyanathan Prentice-Hall 1993] which offers the opportunity to design orthogonal wavelet filters via unconstrained parameters.

In the reconstruction stage a modified CS Matching Pursuit algorithm is proposed since that the sparse coefficients are obtained through a best basis selection.

This approach is tested on experimental data obtained by passive excitation in a 1 m square aluminum plate and acquiring the dispersive signal with a conventional piezoelectric sensor.

The proposed framework is analyzed with a compression ratio between 40-80%; the performances are analyzed in term of percent residual difference and a threshold level sensibility study is performed.

Results show the improvement in signal reconstruction with the use of the modified CS framework respect to the EZW coding in particular with high additive noise in transmission.

In conclusion, CS applied to best basis wavelet coefficients and optimization of the mother wavelet through parameterization provides an adaptive approach for optimal signal representation for compression with low Signal-to-Noise Ratio.

8695-107, Session 20

Crack detection with Lamb wave frequency-wavenumber analysis

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Cracks are common defects in aluminum plate-like structural components that are in widespread use in aerospace, shipbuilding, and other industries. Ultrasonic detection using Lamb waves has proven to be an efficient method for crack detection and localization. Lamb waves have shown great potential for structural health monitoring (SHM) in plate-like structures. Attractive features include sensitivity to a variety of damage types and the ability to travel relatively long distances. Lamb wave propagation is described via a frequency-wavenumber relationship, manifesting dispersive and multimodal properties. When a mode passes through a damaged area, the wavenumber will be modified accordingly and can be used as a means for crack detection.

In this paper, we study Lamb wave propagation and crack detection using frequency-wavenumber analysis. The two dimensional Fourier transform converts time-space wavefield data into a frequency-wavenumber representation where various Lamb wave modes that propagate in different directions can be clearly discerned. A one dimensional scanning laser Doppler vibrometer is used to measure out-of-plane motion. Additionally, Lamb wave propagation is obtained through three dimensional Elastodynamic Finite Integration Technique (EFIT) simulation in terms of both out-of-plane and in-plane motions. Wavefield data obtained from a pristine aluminum specimen and a cracked aluminum specimen are processed and analyzed. Experimental and simulation data are then processed for frequency-wavenumber analysis and crack detection, respectively. The work presented here shows that experimental and simulated data yield comparable results and that damage can be detected as wavenumber changes at a selected frequency. This work shows the feasibility of using simulated data to aid in the development/optimization of Lamb wave based damage detection techniques.

8695-108, Session 21

Crack detection on wind turbine blade in an operating environment using vibro-acoustic modulation technique

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Wind farms have been constructed all over the world because the cost of wind power is low relative to other sources of alternative energy. To minimize the maintenance costs of wind farms, it is important to detect defects in wind turbine blades before these defects grow causing blade failure because it is less expensive to repair the blades when the defects are small.

In this paper, a method of detecting cracks on wind turbine blades using Vibro-Acoustic Modulation was investigated that uses active sensing with PZTs to probe for cracks in wind turbine blades as the blade is pumped in operation by the structural vibrations resulting from the turbine's operation.

The Vibro-acoustic response of a cracked blade was compared with the response of a healthy blade in the Vibro-Acoustic Modulation tests. The tests were conducted on a small wind turbine Whisper 100 operating in a wind tunnel. A swept signal was used as a probing signal instead of simple harmonic signal in an effort to obtain results that are independent of the blade frequency response function. A nonlinear index was extracted from the Vibro-acoustic data to quantify the degree of nonlinearity exhibited by the blade structure. The increase in this nonlinear index of the damaged blades that is demonstrated by the experiments suggests that the technique can detect the presence of the cracks in the blades.

8695-109, Session 21

Bolted joint loosening detection by using laser excitation

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The bolted joint widely used in mechanical products and structures frequently undergo loosening. Bolt loosening in some application can result in bolt failure. In this paper, the authors proposed a finite element model of a simple single bolt joint that undergoes loosening. The model was created using 3D solid elements and surface-to-surface contact elements between head/nut and flange interfaces. Pretension effects and contact behavior between flanges to be joined were also taken into account. The loose condition was given by applying a lower pretension force than normal and by changing the contact regions. Static structural analysis and frequency response analysis based on modal analysis were then carried out respectively using this model. The frequency response showed that the loosening condition changed the high frequency response significantly. The change had tendency to shift the peaks of response to a lower frequency. In order to validate the finite element model by experiment, vibration testing method based on non-contact impulse excitation using laser ablation was conducted. High-power YAG pulse laser was used to produce an ideal impulse force on the structural surface. The high frequency response was then measured on the structure. The loose condition was achieved by reducing the value of torque used to tighten the bolted joint. Several tightening torques lower than the standard torque were applied to the bolted joint. The experiment result had good agreement with the finite element analysis. Finally, an approach of loose bolt detection was demonstrated by applying statistical evaluation of Recognition-Taguchi (RT) method to a six bolt cantilever which had loose bolt.

8695-110, Session 21

Damage-patterns based method to locate discontinuities in beams

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The paper present a method to locate discontinuities in form of open cracks in beams, based on vibration measurements. Patterns characterizing frequency changes of the first ten weak-axis bending vibration modes are determined for all possible locations on the structure, using a relation contrived by the authors. It base on the correlation between the strain energy stored in a segment of the beam, which is proportional with the square of the mode shape curvature of the considered vibration mode at that location, and the frequency change for this mode by the occurrence of a discontinuity on that segment. The patters are formed by a series of ten values representing the normalized relative frequency shifts for the first ten vibration modes. For a structure similarly supported, by continuous or periodical measurements, potential frequency changes can be detected. By processing these data the so-called damage location index for that crack is found out, also as a series of ten values representing the relative frequency shifts of the ten vibration modes. To precise locate the crack a pattern matching method involving the database with all possible patterns and the damage location index is used. Knowing the location, it is easy to determine by analytic calculus the crack depth. The method is easy to be used, provide accurate results, demands modest computational effort and has the advantage that the measurements may be carried out in situ with rather simple equipment. The method was validated by experiments.

8695-111, Session 21

Dynamic characteristics and vibration-based damage inspection of structures with actual fatigue cracks

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Experimental verification of structural damage inspection methods is often performed on structures with artificial open cracks cut by saws or milling machines because it is difficult to create actual fatigue cracks in structures. Unfortunately, such open cracks cannot show the nonlinear breathing dynamics of actual cracks. To further validate our newly developed dynamics-based methodology for accurate damage inspection of thin-walled structures by combining a boundary-effect evaluation method (BEEM) for space-wavenumber analysis of measured operational deflection shapes (ODSs) and a conjugate-pair decomposition (CPD) method for time-frequency analysis of time traces of measured points, we prepare two 6061-T6511 aluminum beams with cracks created by fatigue bending.

Dynamic characteristics of cantilevered beams with a breathing crack are obtained for comparison by using finite elements. The proposed BEEM is for locating and estimating small structural damage by processing operational deflection shapes (ODSs) measured by a scanning laser vibrometer. BEEM is a nondestructive spatial-domain method based on sliding-window processing of ODSs and it works without using any structural model or historical data for comparison. CPD uses adaptive windowed regular harmonics and function orthogonality to perform time-frequency analysis of time traces by extracting time-localized regular and/or distorted harmonics. Numerical simulations and experimental results show that the combination of BEEM and CPD for space-wavenumber and time-frequency analysis provides an accurate tool for damage inspection of thin-walled structures with actual cracks.

8695-112, Session 21

Monitoring the fracture healing of an internally fixated pelvis using vibration analysis

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Patients who suffer from unstable pelvic fractures are usually implanted with internal fixations which provide structural rigidity as well as allow sufficient contact between fracture edges for healing to occur. A 12 week post-operative period of immobility is typically enforced on the patient to ensure this healing process is not hindered. This extended period of restricted movement could cause muscle wastage which results in additional rehabilitation time. It is therefore highly beneficial to develop a non-invasive method which can be used in-situ to monitor the healing of the pelvis in hopes of allowing patients to undertake earlier weight bearing activities and reduce muscle degradation. This paper studies the dynamic behaviour of a fixated synthetic pelvis by monitoring its response over varying stages of stiffness recovery. The synthetic pelvis was cut at the sacrum araldite was applied over the cut site and allowed to cure over a one hour period. Excitation signals were introduced to the synthetic structure by means of an impact hammer and a shaker using the fixation screws as wave guides. Transfer functions obtained from an array of sensors bonded to the pelvis and the fixation demonstrate significant changes occurring over the stiffness recovery period due to glue curing. If these changes can be quantified, future research could lead to the development of smart fixations which can monitor the state of healing in the pelvis.

8695-113, Session 22

Frequency response feature selection in a Bayesian framework

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Frequency response related quantities are widely used for damage detection and structural health monitoring (SHM), because of their easy-accessability and clear physical interpretations. In reality, there is uncertainty, could be noise or other operational variability, involved in any feature evaluation and any type of applciations, which makes it hard to select a robust and sensitive SHM feature. Two specific spectra are consisder in this paper, namely, frequency response function (FRF) and transmissibility, while FRF includes system resonances and transmissibility only has system zeros. A Bayesian model selection framework is adopted by comparing the Bayes factor of using either feature in structural health monitoring applications, and suggests a better feature extracting with respect to more plausibility. This framework is implemented with data acquired from a lab-scale frame structure, and to be more realistic, external artifical noise is contaminated to the data imitating a stringent test condition.

8695-114, Session 22

Abnormal behavior detection in the Jeremiah Morrow Bridge based on the long term measurement-data patterns

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Calibration of a finite element model based on measurement-data for complex structures is usually costly and sometimes not applicable. In this article, a methodology for detecting abnormal behavior including slow aging degradations of a structure solely based on historical patterns of the measurement data will be introduced. In the first step, Principal components of the measurement data - that is centered and scaled - are calculated. In the second step, unsupervised classification is applied to the measurement data that is regenerated based on the major principal components. The classification results of the collected static data from the Jeremiah Morrow Bridge are detailed and compared with other bridges. Finally, data clusters are fed to a neural network as a training input. The result of the final optimized neural network is used as a prediction model.

The specified algorithm applied separately to the measurement data of the truck load test on the same bridge. The clusters that are obtained from static data and dynamic data are compared and differences are noted.

The optimized model documents the “normal” or expected behavior of the structure to traffic and environment, respectively. Anomaly detector is then designed upon a threshold technique which minimizes the probabilities of false alarms and the missed detection of critical events based upon the capacity rating. Alarm scenarios are reviewed based upon the collected historical data from the monitors and compared with ARIMA models.

8695-115, Session 22

Advanced signal processing for imaging defects using scanning-laser-generated high order guided wave modes

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Small defects were imaged using a set of presented advanced signal processing techniques applied to scanning-laser-generated guided wave measurements. Guided waves are rapidly excited at a dense array of spatial imaging points using a scanning Q-switched laser system and sensed by a single fixed ultrasonic transducer. Through reciprocity, this produces a full-wave-field time history of a virtual wave being excited from the transducer. Using frequency-wavenumber processing, individual guided wave modes are estimated and isolated. This enables further processing of only those wave modes that scatter with significant energy when interacting with a targeted type of damage, substantially improving the signal-to-noise ratio. The isolated wave modes are then filtered by propagation direction in the frequency-wavenumber domain in order to capture only scattered energy and then imaged using a spatial matched filter. The approach was capable of resolving two millimeter by one millimeter deep blind holes in a 6 mm aluminum plate using an isolated first-order symmetric guided lamb wave mode when zero-order modes proved to be ineffective. Holes of varying radius and depth were further characterized through comparison of the frequency- and wave-mode-dependent scatter energy magnitude.

8695-116, Session 22

Multiscale pseudo-force model in 2D wavelet domain for damage detection of plate elements

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Wavelet transform (WT)-based nondestructive damage identification has been investigated in a variety of applications. In most studies, WT is used as an effective signal analysis tool to filter out noise and bring damage-incurred singularities into prominence. In spite of its proven effectiveness, this type of processing is often dropped into the scope of single analysis while lacking theoretical backup sustained by solid mechanics. This characteristic makes damage feature inscrutable in physical sense. To circumvent this limitation, the authors have proposed a multi-scale pseudo-force model of beam elements over one-dimensional wavelet domain. This model gives rise to a new mechanism for use of WT to damage characterization of beam elements with explicit physical implication. As an following-up investigation, a model of plate elements over two-dimensional (2D) wavelet domain are explored in present study. The multi-scale pseudo-force model are created by using appropriate 2D wavelet to process the governing equation of motion of a plate element with a crack. During the course of model creation, 2D WT is used as a multi-scale smoothing and differential operator that brings significant benefits to reveal and intensify feature of damage under noisy measurement conditions. The underlying hypostasis of the model has clear physical meaning that provides a sophisticated solution to the problem of damage characterization in a plate element. As proof-of-concept validation, a fine crack in a plate element of a complicated structural system is detected using the model through numerical simulation and experiment. The results demonstrate the effectiveness of the model in characterizing tiny damage with clarified physical interpretation and enhanced tolerance of noise.

8695-117, Session 22

The PRICONA algorithm for biological spectra normalization

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There is an increasing use of spectroscopic techniques, such as high-resolution NMR spectroscopy, to examine variations in cell metabolism and/or structure in response to numerous physical, chemical, and biological agents. In these types of studies, in order to obtain relative

quantitative information, a comparison between signal intensities of control samples and treated or exposed ones is often conducted. The methods thus far developed for this purpose are not directly related to the overall intrinsic properties of the samples, but rather to the addition of external substances of known concentrations or to indirect measurement of internal substances. Another possibility is to estimate, by a suitable algorithm, a normalization constant which takes into consideration all cell metabolites present in the sample.

Recently, different algorithms for NMR spectra were proposed, both in the frequency and in the time domain. All those algorithms are specific for NMR spectroscopy and are based on NMR spectroscopy signal properties; furthermore they are developed for single comparison of a single control sample with a single exposed sample spectrum.

In this paper a new normalization algorithm, based on Principal Component Analysis (PCA), is presented. PCA is a well-known statistical technique for analysis of large, multivariate datasets, which extracts the basic features of the data. The PRICONA (PRIncipal COmponent Normalization Algorithm) algorithm uses PCA in a new totally different manner: in fact, PCA is used to normalize spectra in order to obtain quantitative information about the treatment effects. PRICONA is advantageous in normalizing great datasets of spectra simultaneously, such as in a typical chemical-shift imaging experiment or a kinetic experiment with perfused cells, in individuating signals that could have been affected by the agent, and allowing to measure their quantitative variation. The algorithm was tested by Monte Carlo simulations as well as experimentally by comparing four samples of known contents with the new method and with an older one which uses a standard.

At the end, PRICONA algorithm shows that in order to extract basic features in a multivariate dataset of biological samples, the interpretation of the first Principal Component (PC) is critical. In fact, as shown, the first PC could identify normalization signals and not signals affected by a treatment, so caution has to be used when looking for markers by PCA in biological samples.

8695-118, Session 22

Structural damage detection based on Teager energy operator

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Vibration-based nondestructive damage detection relying on curvature mode shapes has been investigated in various applications. Regarding curvature mode shape, an intrinsic deficiency is its proneness to noise inevitably present in a measured mode shape. The adverse effect of noise probably masks actual damage feature, resulting in false results of damage detection. To circumvent this deficiency, a nonlinear Teagar energy operator, different from modal curvature operation, is adopted to treat mode shape for creating a new algorithm of damage detection. First, a second-order derivative Gaussian wavelet transform is applied to preprocess the mode shape, in order to separate effective component of mode shape from noisy interference and remain features of damage. Then, a nonlinear Teager energy operator is employed as a singularity detector of signal energy, acting on the separated effective component of mode shape, to reveal and characterize feature of damage. The capabilities of both one-dimensional and two-dimensional Teager energy operators in damage identification of beams and plates are demonstrated in numerically simulated damage cases with different crack severities and noise levels. The effectiveness of the algorithm is experimentally validated by using advanced scanning laser vibrometer to acquire mode shapes of damaged beams and plates with fine resolution and accuracy. The numerical and experimental results show that Teager energy operator, aided by wavelet transform-based preprocessing, behaves in a manner of stronger sensitivity to slight damage and greater robustness to noise than traditional curvature mode shape and wavelet transform-based damage detection methods.