



2015

2015 TECHNICAL SUMMARIES.

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Conferences & Courses
8-12 March 2015

Exhibition
10-11 March 2015

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SPIE would like to express its deepest appreciation to the symposium chairs, conference chairs, program committees, session chairs, and authors who have so generously given their time and advice to make this symposium possible.

The symposium, like our other conferences and activities, would not be possible without the dedicated contribution of our participants and members. This program is based on commitments received up to the time of publication and is subject to change without notice.

Conference 9429: Bioinspiration, Biomimetics, and Bioreplication V

Monday - Wednesday 9 -11 March 2015

Part of Proceedings of SPIE Vol. 9429 Bioinspiration, Biomimetics, and Bioreplication 2015

9429-500, Session Plen

Potential and Challenges for the Application of Smart Advanced Ceramic Materials

Alexander Michaelis, Fraunhofer-IKTS (Germany)

No Abstract Available

9429-501, Session Plen

Biomolecular Material Systems: Harnessing Nature's Smart Materials for Sensing, Actuation, and Energy Conversion

Donald J. Leo, The Univ. of Georgia (United States)

No Abstract Available

9429-1, Session 1

Paradigm for design of biomimetic adaptive structures (*Keynote Presentation*)

Carolyn Dry, Natural Process Design, Inc. (United States)

Nature builds by 1) using local, available materials 2) self-ordering or growing by attributes shared between material and environment; 3) repairing themselves, 4) sensing and adapting to changes in environment; 5) disintegrating, recycling back into the material sink; and 6) sometimes enhancing the shared environment.

Application of these rules in funded research projects include: 1) in-situ adaptive ports in ocean made from chemicals in seawater based on bio-mimicry of the human body, 2) self-repairing, self-sensing concrete and polymer composites. 3) bone-mimicry material self-formation to achieve a cement/polymer composite, 4) coating for concrete that strengthens the concrete by absorbing greenhouse gases, and 5) fly-ash building materials sequestering heavy metals.

9429-2, Session 1

Investigation of biological and biomimetic composites (*Invited Paper*)

David Kisailus, Univ. of California, Riverside (United States)

There is a growing need for the development of new light-weight structural materials with high strength and durability that are low-cost and recyclable. Nature has evolved efficient strategies, exemplified in the crystallized tissues of numerous species, to synthesize materials that often exhibit exceptional mechanical properties. These biological systems demonstrate the ability to control nano- and microstructural features that significantly improve the mechanical performance of otherwise brittle materials. In this work, we investigate a variety of organisms, specifically, the hyper-mineralized combative dactyl club of the stomatopods, a group of highly aggressive marine crustaceans, and the heavily crystallized radular teeth of the chitons, a group of elongated mollusks that graze on hard substrates for algae.

From the investigation of structure-property relationships in these unique organisms using modern chemical, morphological, and mechanical characterization techniques, we are now developing and fabricating cost-

effective and environmentally friendly engineering composites with impact resistance and biologically inspired nanomaterials for energy conversion and storage.

9429-3, Session 2

Exploring polarization features in light reflection from beetles with structural colors (*Invited Paper*)

Hans Arwin, Roger Magnusson, Lia Fernández del Río, Jan Landin, Linköping Univ. (Sweden); Arturo Mendoza-Galván, Ctr. de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional (Mexico); Kenneth Järrendahl, Linköping Univ. (Sweden)

Polarization of light reflected from a surface can be described with a Mueller matrix for arbitrary incident polarization. Here spectroscopic Mueller-matrix ellipsometry at variable angles of incidence is applied to beetle cuticles and polarization features in terms of ellipticity, polarization azimuth and degree of polarization of the reflected light are quantified. In addition a Mueller matrix can be used in electromagnetic modeling to determine structural parameters and can also be decomposed for classification of reflectors. In particular chiral phenomena in scarab beetles are addressed and origin of their structural colors and the observed high degree of circular polarization are discussed. Results from beetles in the Scarabaeidae subfamilies Cetoniinae and Rutelinae are presented including specimens with broad-band silver- or gold-like colors with metallic shine as well as specimens with narrow-band reflectors e.g. with green or red color. The variation of polarization with angle of incidence and occurrence of both left-handed and right-handed polarization from the same cuticle will be discussed.

9429-4, Session 2

InxAl1-xN chiral nanorods mimicking the polarization features of scarab beetles

Roger Magnusson, Jens Birch, Ching-Lien Hsiao, Per Sandström, Hans Arwin, Kenneth Järrendahl, Linköping Univ. (Sweden)

The scarab beetle *Cetonia aurata* is known to reflect light with brilliant colors and a high degree of circular polarization. Both color and polarization effects originate from the beetles exoskeleton and have been attributed to a Bragg reflection of the incident light due to a twisted lamellar structure. Our strategy for mimicking the optical properties of the *Cetonia aurata* was therefore to design and fabricate transparent, chiral films. A series of films with tailored transparent structures of helicoidal InxAl1-xN nanorods were grown on sapphire substrates using UHV magnetron sputtering. The x value is tailored to gradually decrease from one side to the other in each nanorod normal to its growth direction. This introduces an in-plane anisotropy with different refractive indices in the direction of the gradient and perpendicular to it. By rotating the sample during film growth the in-plane optical axis will be rotated from bottom to top and thereby creating a chiral film. Based on Mueller-matrix ellipsometry, optical modeling has been done suggesting that both the exoskeleton of *Cetonia aurata* and our artificial material can be modeled by an anisotropic film made up of a stack of thin layers, each one with its in-plane optical axis slightly rotated with respect to the previous layer. Simulations based on the optical modeling were used to investigate how pitch and thickness of the film together with the optical properties of the constitutive materials affects the width and spectral position of the Bragg reflection band.

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9429-5, Session 2

Toward authentic replication of structural and optical features of beetle bodies

Michael H. Bartl, The Univ. of Utah (United States); Akhlesh Lakhtakia, The Pennsylvania State Univ. (United States)

In this presentation, we will introduce and discuss various biotemplating techniques for the replication of structural features of biological species. These replication methods are based on solution chemistry and vapor deposition and are capable of fully preserving functionalities such as coloration of the exoskeleton, hydrophobicity of wings, and lensing effects of compound eyes. While this talk will focus on replication of exoskeleton scale structures, mainly used for coloration, we will also discuss how various biotemplating methods could be combined into an integrated process aimed toward the complete replication of the body and appearance of a beetle.

9429-6, Session 2

Light emission from compound-eye cornea with conformal fluorescent coating

Raúl J. Martín-Palma, Univ. Autónoma de Madrid (Spain) and The Pennsylvania State Univ. (United States); Amy E. Miller, Drew P. Pulsifer, Akhlesh Lakhtakia, The Pennsylvania State Univ. (United States)

The complex morphology of the apposition compound eyes of insects of many species provides them a wide angular field of view. This characteristic makes these eyes attractive for bioreplication as artificial sources of light. The cornea of a blowfly eye was conformally coated with a fluorescent thin film with the aim of achieving wide field-of-view emission. On illumination by shortwave-ultraviolet light, the conformally coated eye emitted visible light whose intensity showed a weaker angular dependence than a fluorescent thin film deposited on a flat surface.

9429-7, Session 2

Electromagnetic response of the protective pellicle of Euglenoids: influence of the surface profile

Marina E. Inchaussandague, Miriam L. Gigli, Diana C. Skigin, Analía Tolivia, Visitación Conforti, Univ. de Buenos Aires (Argentina)

Euglenoids are unicellular aquatic organisms. These microalgae show a typical surface structure that distinguishes them from the other protists. Most cells are naked and bounded by a plasma membrane surrounded by a pellicle formed by overlapping bands. In a recent paper we have investigated, from an electromagnetic point of view, the role played by the pellicle of Euglenoids in the protection of the cell against UV radiation. By modelling the pellicle as a diffraction grating, we have investigated the electromagnetic response of different species that exhibit different behaviors against the UV radiation. In this previous study, we have approximated the pellicle profile by a sinusoidal grating. However, it has been observed in the transversal cut images that the profiles are not exactly sinusoidal, and also vary from sample to sample. Since the electromagnetic response depends on the geometry of the grating, reflectance calculations that take into account a more accurate representation of the actual profile could provide more insight into this problem.

In this paper we investigate the electromagnetic response of the pellicle of Euglenoids for different grating profiles. The diffraction problem is solved by using the Chandezon method, which has demonstrated a successful performance for deep gratings of arbitrary profiles. We analyze the influence

of the shape, depth and period of the grating on the reflectance in the UV region. We show that the pellicle characteristics are critical parameters to increase the reflectance, thus reducing the penetration of the UV radiation within the cell and therefore, minimizing the damage and increasing the survival of these organisms.

9429-8, Session 3

Mechanisms of gecko adhesion and their application in gecko-like synthetic adhesives (GSAs) (*Invited Paper*)

Kellar Autumn, Lewis & Clark (United States)

Geckos use millions of hierarchical adhesive nanostructures on their toes to climb at speeds of over 1 m/s. No conventional adhesive could meet the challenges of climbing like a gecko. Conventional pressure sensitive adhesive are soft viscoelastic polymers that degrade, foul, self-adhere, and attach accidentally to inappropriate surfaces. In contrast, gecko toes bear angled arrays of branched, hair-like setae formed from stiff, hydrophobic keratin that act as a bed of angled springs with similar effective stiffness to that of PSAs. Gecko setae adhere by intermolecular van der Waals forces. Setae are sticky when pulled in one direction, yet slippery when pushed in the opposite direction. Adhesion is initiated and controlled by shear force, enabling either tough bonds or spontaneous detachment. Setae are self-cleaning and maintain function for months in dirty conditions.

Smart materials properties of gecko-like synthetic adhesives (GSAs) may enable rigid, inert, recyclable materials to replace glues, screws, and other attachment devices in the future. We have discovered nine benchmark properties of the gecko adhesive over the past decade: 1) anisotropy, 2) strong attachment with minimal preload, 3) easy and rapid detachment, 4) van der Waals adhesion / material independence, 5) self-cleaning 6) anti-self-adhesion, and 7) nonadhesive default state. Most recently, we discovered 8) dynamic adhesion and 9) wear resistance. There has been rapid progress in understanding the principles underlying these properties, and in applying the principles of gecko adhesion in the fabrication of GSAs. Properties 1-9 have been achieved in GSAs (although not yet in a single material).

9429-9, Session 3

Switchable bioinspired adhesives (*Invited Paper*)

Elmar Kroner, Mareike Frensemeier, Julia Purto, Leibniz-Institut für Neue Materialien gGmbH (Germany)

Bioinspired fibrillar adhesives have been investigated during recent years because of the unique combination of properties: high adhesion, easy detachment, residue-free contact, and self-cleaning effects. Many aspects have been successfully mimicked and improved to even outperform the adhesion capabilities of geckos. However, designing artificial fibrillar adhesion systems with switchable adhesion remains a big challenge. The gecko's adhesion system is based on a complex hierarchical surface structure and advanced biomechanics, which are both difficult to mimic. Thus, the talk will focus on new concepts and strategies to obtain switchable adhesion based on bioinspired fibrillar adhesives, particularly with regard to limitations of these systems and their potential for application.

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9429-10, Session 4

Bio-inspired preparation of polymer based hydrophilic ultrafiltration membrane using graphene oxide as a hydrophilic anti-bio fouling layer

Tae-seon Hwang, Woosoon Yim, Kwang Jin Kim, Univ. of Nevada, Las Vegas (United States)

Inspired by nature, we have investigated the effect of hydrophilic layer of graphene oxide on polysulfone membranes. The purpose of this study was to improve the anti-bio fouling properties of the membrane for use in ultrafiltration. Polysulfone membranes were obtained through the phase inversion method. Polyvinylpyrrolidone was added as a pore generator to fabricate the membrane, and then a layer of graphene oxide was deposited on the prepared membranes to enhance hydrophilicity via a vacuum-assisted filtration method. The resulting polysulfone/graphene oxide membranes were proved by cross-section/surface morphology, water-contact angle, and ultrafiltration performance. It is noted that Graphene oxide enhances the surface hydrophilicity of polysulfone membrane due to its highly oxygenated structure similar to many nature-produced membranes. The anti-bio fouling abilities of the manufactured membranes were investigated by comparing the water-flux recovery ratio between the pure water flux before and after ultrafiltration of a protein solution.

9429-11, Session 4

Phase separated polymer microparticles as pollen biomimetics

Olaf Karthaus, Chitose Institute of Science and Technology (Japan)

Polymer blends are materials containing two or more polymers with physical properties that are different from each pure polymer. The most common polymer blend is between two immiscible polymers (less common types are compatible polymer blends and miscible polymer blends) that show a phase separated structure on a nano-to-micrometer scale, which leads to synergistic effects that may strongly affect material behavior. The phase separated structure can form via a nucleation-and-growth mechanism or by spinodal decomposition. Various morphologies (spheres of polymer A in a continuous phase of polymer B, alternating lamellae of A and B, or bicontinuous structures) can be formed. Blends can be made by mixing polymer melts or by solution evaporation. The latter method uses a common solvent that evaporates and thus leads to reproducible results, even in ultra-thin films or in polymer particles. The phase separation starts when a critical concentration of the polymer is reached, and progresses until the material solidifies. Here, the type of solvent and the evaporation speed critically contributes to blend morphology. The slower the evaporation, the closer the resulting blend to the thermodynamic equilibrium.

When films are prepared on supporting substrates the film morphology also depends on the interaction parameters of both polymers at the substrate/solution and solution/air interfaces. For phase separation from an emulsion, the interfacial energy of the polymer solution and the aqueous phase is crucial.

Here we present our work on phase separated polymer microparticles prepared in solution that show a rich morphology of surface structures that are similar to the structures found in plant pollen.

9429-12, Session 4

Fabrications of durable micro wrinkle structures by using self-organized honeycomb structures

Yuji Hirai, Chitose Institute of Science and Technology

(Japan); Takuya Ohzono, Kosuke Suzuki, National Institute of Advanced Industrial Science and Technology (Japan); Masatsugu Shimomura, Chitose Institute of Science and Technology (Japan)

In nature, there are many functional anisotropic line and space patterned surfaces, such as shark skin riblets. It is well known that self-organized wrinkle structures can be formed by in-plane compressive strain for elastic films supported by deformable substrates. However, the adhesion between elastic films and the substrate often cannot withstand the internal stress associated with the formation of wrinkles, leading to partial delamination known as buckling delamination. So it is difficult to measure tribological properties and also practical use. We propose new wrinkle materials for solving this problem by embedding porous materials as hard top layers into supported deformable substrates. In this report, we will show fabrication of durable micro wrinkle structures by using self-organized honeycomb-patterned porous polymer films as embedded hard top layers.

We prepared honeycomb-patterned porous polymer films with polystyrene by breath figure method. After UV-O₃ treatment, honeycomb-patterned films were fixed upside down to glass substrate with poly(vinyl alcohol) as adhesive. Bottom of the films were peeled off by an adhesive tape, and divided surface layer of films turned upside down in water. Poly(dimethylsiloxane) (PDMS) precursor was poured into the top layer put on a glass substrate and cross-linked by heat treatment. Then porous structure embedded PDMS substrates were obtained. At that surface, successfully micro wrinkle structures were formed, repeatedly. And also, by metallizing only top of embedded honeycomb-patterned films, controlling of wrinkle period will be discussed.

9429-502, Session Plen

Optical Fiber Based Structural Health and Process Monitoring of Advanced Composite Structures

Nobuo Takeda, The Univ. of Tokyo (Japan)

No Abstract Available

9429-14, Session 5

A predictive model for artificial mechanical cochlea

Riaz Ahmed, Univ. of South Carolina (United States); Afifa Adiba, The Ohio State Univ. (United States); Sourav Banerjee, Univ. of South Carolina (United States)

In many engineering applications band pass filters and a specific frequency sensing are essential. Mechanical filters if designed to pass sonic frequencies needs to be designed with sizes comparable to the respective wave lengths. However, in this article we show that using a bioinspired mechanism a sub wave length scale filter can be designed. We propose a mechanical broadband frequency sensor with the ability of sensing sonic frequencies by utilizing the principle of the human cochlea. Human cochlea senses only sonic (20 Hz to 20 kHz) frequencies by filtering all other frequencies in the environment. Basilar membrane is the principal component of the cochlea which is responsible for this functionality. Hair cells in the ear capture the vibrational response of the BM and allow the membrane to spatially sense the sonic frequencies. In this study we intend to model a band pass frequency sensor by mimicking the principal and design of a Basilar Membrane (BM) in human cochlea. The micro thin silicon membrane is used to replicate the fibers of BM, whereas polyvinylidene fluoride (PVDF) is considered to sense the response from the silicon membrane at different frequencies. A predictive model has been developed to allow any user defined pass band frequency selectivity with appropriate model parameters. Using the proposed model it is expected that ultrasonic and infrasonic frequency sensors can also be introduced in addition to the sonic frequency

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sensor. On top of sensing applications, the proposed concept can also be implemented for wave isolation, vibration control etc.

9429-54, Session 5

Acoustic characteristic of a bat inspired membrane wing with adaptive compliances

Zhenbo Lu, Yongdong Cui, Marco Debiasi, National Univ. of Singapore (Singapore)

Bat inspired membrane wings with adaptive compliances have a great potential to improve the maneuverability, aerodynamic lift and acoustic performance of micro air vehicles (MAVs). In the present paper, the acoustic characteristic of low aspect ratio membrane wings made of dielectric elastomer actuators (DEAs) were investigated under various voltage-controlled-compliances. The exploration for the acoustic characteristic of the bat inspired membrane wing were conducted in two ways: 1) A fixed membrane wing with adaptive compliances placed inside the wind-tunnel at different attack angles under various flow speeds; 2) Two membrane wings with adaptive compliances under various flapping motions. It was found that the acoustic performances could be adjusted due to the changes of the membrane wings' compliances for both cases, which indicated the present membrane wings could be potentially used in a high lift and low noise MAV. Furthermore, the physics mechanisms of these complex fluid-membrane interactions were discussed for improving the acoustic performance of the present MAVs.

9429-15, Session 6

A low-cost simulation platform for flapping wing MAVs

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

Insect inspired Micro Air Vehicles (MAVs) have been a growing area of research in recent years. Insects have demonstrated an aerial agility that is unmatched by conventional aircraft systems. Dragonflies in particular also exhibit excellent glide and hover performance which is characteristic of fixed and rotary winged air vehicles respectively, making them extremely versatile flyers. Such excellent performance can be attributed to the wing articulation of insects that modulate aerodynamic forces. Much research has been performed on the performance of individual wings using numerical, computational and experimental methods. More importantly however is the effect that each wing has on the dynamics of a multi-winged flapping MAV at the systems level. To determine the effects that a wing-actuation system has on systems level performance of an MAV, we have developed a low computational effort flapping wing flight simulator capable of incorporating flapping wing forces with real-world flight dynamics. This tool enables us to perform benchmarking against existing fixed and rotary wing systems, investigate different control methods, and provide insight into the system level parameters that produce ideal flight. A full system flight simulation allows more rapid progress in flight control research. It is also hoped that this tool will have additional uses such as improving the quality of animations of flying insects for entertainment and research purposes. The implementation and behaviour of the flight simulator will be presented.

9429-16, Session 6

A three dimensional unsteady iterative panel method with vortex particle wakes and boundary layer model for bio-inspired multi-body wings

Akash V. Dhruv, Christopher J. Blower, Adam M.

Wickenheiser, The George Washington Univ. (United States)

Unmanned Aerial Vehicles (UAVs) continue to show their potential use in domestic and international airspace. The ability of UAVs to operate in complex and hostile environments makes them useful in military and civil operations concerning surveillance and reconnaissance. However, limitations in size of UAVs and communication delays prohibit their operation close to the ground and in cluttered environments, which create risks associated with turbulence and wind gusts that cause trajectory deviations and potential loss of the vehicle. In the last decade, scientists and engineers have turned towards bio-inspiration to solve these burning issues by developing innovative flow control methods that offer better stability, controllability, and maneuverability. This paper presents an aerodynamic load solver for bio-inspired wings that consist of an array of feather-like flaps installed across the upper and lower surfaces in both the chord- and span-wise directions, mimicking the feathers of an avian wing. Each flap has the ability to rotate into both the wing body and the inbound airflow, generating complex flap configurations unobtainable by traditional wings that offer improved aerodynamic stability against gusting flows and turbulence. The solver discussed is an unsteady three-dimensional iterative doublet-source panel method with vortex particle wakes and an integrated boundary layer model. This panel method models the wake-body interactions between multiple flaps effectively without the need to define specific wake geometries, thereby eliminating the need to manually model the wake for each configuration. To incorporate viscous flow characteristics, an iterative boundary layer theory is employed, modeling laminar, transitional and turbulent regions over the wing's surfaces, in addition to flow separation and reattachment locations. This technique enables the boundary layer to influence the wake strength and geometry both within the wing and behind it. The results obtained from this solver are validated using experimental data from a low-speed suction wind tunnel operating at Reynolds Number 300,000. This method enables fast and accurate assessment of aerodynamic loads for initial design of complex wing configurations compared to other methods available.

9429-17, Session 6

Aerodynamic analysis of bioinspired corrugated aerofoils using a parametric shape perturbation approach

Matteo Giacobello, Defence Science and Technology Organisation (Australia); Manas S. Khurana, RMIT Univ. (Australia); Javaan S. Chahl, Univ. of South Australia (Australia)

The feasibility of employing a bioinspired corrugated aerofoil for a Micro Air Vehicle (MAV) in gliding flight is assessed and compared to the performance of a flat plate aerofoil of the same thickness. A computational design-of-experiments (DoE) approach is used to model the aerodynamic forces for a two-dimensional corrugated wing in a glide at an angle-of-attack of 4.0° and Reynolds numbers (Re) of 20,000 and 34,000.

Using the corrugated aerofoil shape experimentally studied by Murphy and Hu [1] as the baseline the profile is systematically varied by independently displacing the y/c coordinate (where c is aerofoil chord length) of each of the twelve corrugation peaks and valleys (the control points in black in Figure 1) one factor at a time in increments, up to a maximum of 7% of aerofoil chord for both upper and lower surfaces relative to the baseline setting.

To cover the design space efficiently, computational algorithms for design automation were implemented in MATLAB for simulations by parallel processing on a high performance computing cluster. This consisted of automatic aerofoil shape parameterisation, followed by mesh generation in ANSYS ICEM and flow field analysis using FLUENT. Each module of the design structure was independently defined, developed and tested for integration into the planned DoE program. Due to the complexity of the aerofoil shape, a structured multi-block grid was used. The methodology permits acceptable grid orthogonality with control over cell aspect ratio

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and skew angles, particularly in the near-wall regions. A mesh morphing algorithm was further developed to maintain high grid quality measures during the shape perturbation process. The proposed scheme, together with the setup of the flow solver settings in FLUENT were validated against published experimental data. Acceptable agreement between CFD and wind tunnel data of within 5% for both lift and drag was recorded.

Following the design development and validation of the computational method, the aerodynamic performance of the aerofoils was established and is summarised in the paper. The results show that aerofoil corrugations result in improved aerodynamic performances relative to a flat plate for the chosen Re and angle-of-attack. The optimal corrugated aerofoil was identified as the shape that yields the highest lift-to-drag relative to the database of aerofoils that were generated and evaluated in CFD as part of the DoE test program. At Re = 20,000, it is the perturbation of the leading edge deflection that results in the increase of aerodynamic efficiency relative to a flat plate. At Re = 34,000, it is the perturbation of the trailing edge deflection that results in the maximisation of the lift-to-drag ratio. A detailed study of the flow structure and mechanisms that lead to this local optimum in Cl/Cd will be presented in this paper.

Reference

[1] Hu, H. and Murphy, J. (2010) An experimental study of a bio-inspired corrugated airfoil for micro air vehicle applications, Exp. Fluids, Vol. 49, pp 531-546.

9429-58, Session 6

Dynamic response of a piezoelectric flapping wing

Alok Kumar, Gaurang Khandwekar, S. Venkatesh, D. Roy Mahapatra, Indian Institute of Science (India); Soma Dutta, National Aerospace Labs. (India)

Piezo-composite membranes have advantages over motorized flapping where frequencies are high and certain coupling between bending and twisting is useful to generate lift and forward flight. We draw examples of fruit fly and bumblebee. Wings with piezoceramic PZT coating are realized. These wings are ultimately aimed to be lithographically patterned with PZT and to be actuated by taking advantage of dynamic flexibility. First, the passive mechanical response of the wing is characterized experimentally and validated using finite element simulation. Piezoelectric actuation with uniform electrode coating is characterized and optimal frequency bands for flapping are identified experimentally and computationally. The experimental data are then used in an empirical model and the advanced ratio for a flapping insect like condition for various angular flapping orientations is estimated. The wing-beat frequency calculated lies on the rising part of the frequency response curve where the peak indicates the natural frequency of the flapping wing. Depending on the flapping velocity and the forward speed, we have tried to imitate the hover conditions observed in small insects like bumblebee, dragonfly etc. For zero advanced ratio, an equivalent payload mass is calculated which supports the hovering. The results show that this flapping wing offer better aerodynamic characteristic and performance with the calculated payload structural integrity. Various design optimization aspects are discussed.

9429-19, Session 7

Fin propulsion on a human-powered submarine

Iain A. Anderson, Ben Pocock, Antoni Harbuz, Ryan Chao, Daniel Vochezer, Cam Algie, The Univ. of Auckland (New Zealand); Benjamin Lu, Biomimetics Lab, Univ of Auckland (New Zealand)

Almost 100% of surface and underwater vessels are driven by screw propulsion; ideal for coupling to rotary engines and well understood after

over a century of development. But most aquatic creatures use fins for swimming. Although there are sound evolutionary reasons why fish have fins and not propellers, they are nevertheless agile, fast and efficient. Although fish-like robots such as the MIT Robotuna are providing good insight into fin-based swimming there are advantages for using humans in the experimental device. Like an airplane test pilot they can write crash reports.

We present preliminary results for the human powered finned submarine: Taniwha. The sub participated in the 2nd European International Submarine races in Gosport UK where it received a trophy for "Best Performing Non-Propeller" drive. Two sets of Hobie kayak, Mirage fin drives fixed to the upper and lower rear surfaces of the sub are linked by cable so that two pedals power both drives. The pilot has two levers at the front, one to pitch a pair of dive planes and one for yawing a large rudder.

Good speed, we estimate to be >3knots is possible with these fins although we haven't explored their full potential. Straying too near the surface or bottom can lead to an instability, synonymous to a stall, such that it is hard to return to mid-water. The mechanism for this will be discussed and solutions offered. Fish are 400 million years in front of us but one day we'll catch them.

9429-20, Session 7

Biologically-inspired robots elicit a robust fear response in zebrafish

Fabrizio Ladu, Tiziana Bartolini, New York Univ. (United States); Sarah G. Panitz, New York Univ. (United States) and Brooklyn Technical High School (United States); Sachit Butail, Indraprastha Institute of Information Technology (India); Simone Macri, New York Univ. (United States) and Istituto Superiore di Sanità (Italy); Maurizio Porfiri, New York Univ. (United States)

Anxiety-related disorders are a serious health issue impacting a significant portion of the population in western countries. Animal models represent a key instrument for gaining a better understanding of the biological drivers underlying anxiety and for screening novel therapeutic approaches in premedical tests. Zebrafish are becoming a valid alternative to mice and rats for laboratory studies, because of their genetic similarities with humans, their high stock density, and their fast development. Here, we study the response of zebrafish to three fear-evoking stimuli. In a binary choice test, we expose individual zebrafish subjects to three alternative stimuli: i) their live allopatric predator Red Tiger Oscar (*Astronotus ocellatus*); ii) a robotic replica, whose morphology and tail-beating are inspired by the Red Tiger Oscar; and iii) a computer-animated image also inspired by the motion and appearance of the live predator. The behavioral response of zebrafish is automatically scored using an in-house developed three-dimensional target tracking algorithm. Our results indicate that, unlike computer-animated images, both the live predator and its robotic replica induce a significant avoidance response in zebrafish. Importantly, the presence of the robotic replica causes a robust increase in thrashing behavior, which is a well-established anxiety indicator. We also find that the inter-individual response to the replica is more consistent compared to the response to the other two stimuli. Biologically-inspired robotic stimuli are expected to significantly contribute to new methodologies in animal testing, by enhancing the degree of control of experimental stimuli, reducing the number of subjects, and increasing the data throughput.

9429-21, Session 7

Artificial heart for humanoid robot using coiled SMA actuators

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

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Previously, we have presented the design and characterization of artificial heart using cylindrical shape memory alloy (SMA) actuators for humanoids [1]. The robotic heart was designed to pump a nonconductive blood-like fluid to parts of the robot such as the face to simulate blushing or anger by the use of elastomeric substrates for the transport of fluids. In this paper, we present an improved design by using high strain coiled SMAs and a novel pumping mechanism that uses sequential actuation to create peristalsis-like motions, and hence pump the fluid. Various placements of actuators will be investigated with respect to the silicone elastomeric body. This new approach will provide a better performance in terms of the fluid volume pumped.

[1] Potnuru, A., Wu, L., & Tadesse, Y. T. (2014, March). Artificial heart for humanoid robot. In SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring (pp. 90562F-90562F). International Society for Optics and Photonics.

9429-22, Session 7

Modeling of the energy savings of variable recruitment McKibben muscle bundles

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

McKibben artificial muscles are often utilized in mobile robotic applications that require compliant and light weight actuation capable of producing large forces. In order to increase the endurance of these mobile robotic platforms, actuation efficiency must be addressed. Since pneumatic systems are rarely more than 30% efficient due to the compressibility of the working fluid, the McKibben muscles are hydraulically powered. Additionally, these McKibben artificial muscles utilize an inelastic bladder to reduce the energy losses associated with elastic energy storage in the usual rubber tube bladders. The largest energy losses in traditional valve-controlled hydraulic systems are found in the valving implementation to match the required loads. This is performed by throttling, which results in large pressure drops over the control valves and significant fluid power being wasted as heat. This paper discusses how these throttling losses are reduced by grouping multiple artificial muscles to form a muscle bundle where, like in skeletal muscle, more elements that make up the muscle bundle are recruited to match the load. This greatly lessens the pressure drops by effectively changing the actuator area, leading to much higher efficiencies over a broader operation envelope. Simulations of several different dynamic loading scenarios are discussed that reveal the benefits of such an actuation scheme.

9429-23, Session 7

Design and fabrication of a three-finger prosthetic hand using SMA muscle wires

Filomena Simone, Zentrum für Mikrosystemtechnik Berlin (Germany) and Saarland Univ. (Germany); Alexander York, Zentrum für Mikrosystemtechnik Berlin (Germany) and Univ. des Saarlandes (Germany); Stefan S. Seelecke, Univ. des Saarlandes (Germany) and Zentrum für Mikrosystemtechnik Berlin (Germany)

Bio-inspired hand-like gripper systems based on shape memory alloy (SMA) wire actuation have the potential to enable a number of useful applications in, e.g., the biomedical field or industrial assembly systems. The inherent high energy density makes SMA solutions a natural choice for systems with lightweight, low noise and high force requirements, such as hand prostheses or robotic systems in a human/machine environment. The focus of this research is the development, design and realization of a SMA-actuated prosthetic hand prototype with three fingers. The use of thin wires (100 μm diameter) allows for high cooling rates and therefore fast movement of each finger. Grouping several small wires mechanically in parallel allows for high force actuation. To save space and to allow for a direct transmission of the motion to each finger, the SMA wires are attached directly within each

finger, across each phalanx. In this way, the contraction of the wires will allow the movement of the fingers without the use of any additional gears. Within each finger, two different bundles of wires are mounted: protagonist ones that create bending movement and the antagonist ones that enable stretching of each phalanx. The resistance change in the SMA wires is measured during actuation, which allows for monitoring of the wire stroke and potentially the gripping force without the use of additional sensors. The hand is built with modern 3D-printing technologies and its performance while grasping objects of different size and shape is experimentally investigated illustrating the usefulness of the actuator concept.

9429-24, Session 8

An insect-inspired flapping wing micro air vehicle with double wing clap-fling effects and capability of sustained hovering

Quoc-Viet Nguyen, Woei Leong Chan, Marco Debiasi, National Univ. of Singapore (Singapore)

We describe the technical design and fabrication, and performance tests in terms of force measurement and free flight test of a flying insect-inspired flapping wing micro air vehicle (FW-MAV). This FW-MAV has a wing span of 10 cm from wing root-to-wing tip (22 cm from wing tip-to-wing tip), weighs less than 20 grams with an onboard control system and battery, and mimics some apparent features of flying insects such as four wings, large wing flapping angle and rotation angle, and wing clap-and-fling mechanism for lift/thrust enhancement. With the natural inspirations from flying insects, we have invented a gear box which synchronously drives four wings by only one motor placed at the center of the gearbox. The gearbox combines two modules, each module consists of a crank-slider and linkage (two couplers and two output links), and a pair of wings arranged around the fuselage and flapped in opposite phase. This arrangement cancels out the pitching oscillations of the body axis usually associated with a two-wing flapping wing platform, resulting in more stable flying platform. The flapping angle of each wing is designed to be 90 degrees, corresponding to a flapping angle of 360 degrees for the flapping wing, to create double wing clap-and-fling effects at the end of downstroke and upstroke. In order to simplify the design, passive wing rotation is incorporated into the FW-MAV by means of hinges placed at the wing root and an initial slack angle implemented on the wing to create an initial wing camber for passive wing deformation. For stable hovering flight, the stabilizing surfaces inspired by demonstrations on FW robots are used and placed on the top and bottom of the FW-MAV. Attitude control flight of roll, pitch, and yaw is performed by control surfaces actuated by three servos. Effect of wing initial slack angle on lift/thrust production and flapping frequency is experimentally investigated. The experimental results indicated that the FW-MAV can produce a cycle-averaged vertical thrust larger than its own weight to take off at flapping frequency of 10 Hz, and wing initial slack angle of 5 degrees is the best wing configuration for maximum lift/thrust production. In addition, power consumption in air and vacuum have been conducted to characterize the performance of the FW-MAV. Finally, powered by an onboard single cell lithium polymer battery (3.7V, 70mAh), the proposed FW-MAV can demonstrate vertical take-off and hovering like insect, and sustained manually controlled flight of about three minutes.

9429-25, Session 8

Soap film flow visualization investigations of oscillating wing energy harvesters

Benjamin Kirschmeier, Matthew J. Bryant, North Carolina State Univ. (United States)

With increasing population and proliferation of wireless electronics, significant research attention has turned to harvesting energy from ambient sources such as wind, and water flows at scales ranging from micro-watt to mega-watt levels. One technique that has recently attracted attention is the application of bio-inspired flapping wings for energy harvesting. This

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type of system uses a heaving and pitching airfoil to extract flow energy and generate electricity. Such a device can be realized using passive devices excited by aeroelastic flutter phenomena, kinematic mechanisms driven by mechanical linkages, or semi-active devices that are actively controlled in one degree of freedom and passively driven in another. For these types of systems, numerical simulations have showed strong dependence on efficiency and vortex interaction.

To characterize these vortex interactions, a vertically falling, gravity driven soap film flow apparatus has been developed to produce flow visualization imagery. The soap film flow reaches a chord Reynolds number on the order of 103. An actuation and control system has been implemented to drive an airfoil in prescribed pitching and heaving motions, allowing for various kinematic parameters to be investigated. Previous numerical studies have shown energy harvesting efficiency dependence on many kinematic parameters. The parameters chosen include heave and pitch amplitude, reduced frequency, and sinusoidal versus non-sinusoidal motion. These parameters are varied independently and then in conjunction to demonstrate the difference in vortex interactions. The flow patterns are then compared with flow patterns from numerical studies and used to identify flapping kinematics appropriate for efficient energy harvesting devices.

9429-26, Session 8

The environment blending dynamics of biomimetic low observable platforms

Theodore B. Terry, Patrice M. Smith, Walden Univ. (United States)

An intelligent agent's ability to blend in with its environmental surroundings has the advantages of hiding in plain sight. In this paper, we highlight our technological definition of the chameleon effect, which mimics the camouflage/background blending capabilities commonly found in insects and reptiles through the introduction and examination of polymers and crystal sub layering structures. This flexible yet durable layered exoskeleton has several benefits. It is lightweight with similarities to the epidermis and dermis layers of the skin; and, is translucent with low reflective solar absorption properties allowing possible use of energy collection and energy regeneration. It is through the proprioceptive and exteroceptive sensory inputs, and optical reflective and refractive properties, managed by the chameleon module, which gives the perception of color pattern and surface texture matching within the dermis that allows the Biomimetic Low Observable Platform (BLOP), to blend in with its surroundings. Integration and interpretation of light refractive indices through multisensory processing influences the camouflage changes in the exoskeleton. Our analysis, based on the principles of refraction and extrapolation incorporated in this research makes the BLOP suitable for social street level studies and environmental monitoring.

9429-40, Session PTues

Preparation of hybrid materials from spider silk and conducting polymers

Kazuki Miyaura, Chitose Institute of Science and Technology (Japan)

Spider silk is a very promising material, because of its outstanding mechanical properties. Here we expand the applicability of the material by blending it with a conducting polymer. The bio-templated materials show conductivity and may be used in sensors.

9429-41, Session PTues

Precipitative self-healing of creep damage in steels: studies by mechanokinetic coupled modeling method

Eduard Karpov, Mansoor Ariyan, Univ. of Illinois at Chicago (United States)

A non-deterministic multiple scale approach based on numerical solution of the Monte-Carlo master equation on atomic lattices solved together with a standard finite element formulation of solid mechanics is discussed. The approach is illustrated in application to long-term evolutionary processes of volume diffusion, precipitation and creep cavity self-healing in nanocrystalline austenite (Fe fcc) samples. A two-way mechanokinetic coupling is achieved through implementation of strain-dependent diffusion rates and dynamic update of the finite element model based on atomic structure evolution. Effect of macroscopic static loading and cavity geometry on the total healing time is investigated. The approach is widely applicable to the modeling and characterization of advanced functional materials with evolutionary internal structure, and emerging behavior in material systems.

9429-42, Session PTues

Cell-free photosynthetic system fabricated by layer-by-layer assembly

Hongseop Hwang, Inha Univ. (Korea, Republic of)

Photosynthesis is an energy conversion process that all the living organisms derive their chemical and biological energy either directly or indirectly from sunlight. Light conversion mechanism of photosynthesis has been researched for more than 70 years and it is now actively pursued to utilize in an artificial device by using such as thylakoid membranes. However, the naturally occurred thylakoids are not stable enough to sustain their functionality in an artificial system. In our study, polymer-thylakoid nanostructured films were fabricated by immobilizing the thylakoid membrane particles on the substrate by the layer-by-layer assembly technique. The resulting film showed stable photoelectrochemical activities for weeks. We further investigated the properties of the thylakoid composite film utilizing a scanning electron microscopy (SEM), a zeta potential, and a UV-Vis spectroscopy. In addition, the sustained photosynthesis ability of the film was assessed by directly measuring oxygen concentrations. The resulting thylakoid film will suggest a natural functional material options to be applied in the fields of organic bioelectronics, bioreactors, and biosensors.

9429-44, Session PTues

Motion generation of peristaltic mobile robot with particle swarm optimization algorithm

Takahiro Homma, Norihiro Kamamichi, Tokyo Denki Univ. (Japan)

The earthworm is a slender animal moving in soil. It has a segmented body, and each segment can be shortened and lengthened by muscular action. It can move forward by traveling expanding motions of each segment backward, which is called 'peristaltic motion.' In this study, to develop mobile robots moving on an irregular ground or a narrow space, we focus on the peristaltic motion.

To realize effective motion of the peristaltic mobile robot, characteristics of the motion are investigated by numerical analysis. We introduce a dynamical model with displacement inputs, instead of the commonly used force input model, for ease in the analysis of the motion patterns. The friction forces between the body and contact ground are important for the locomotion of

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the peristaltic crawling robot. Since each segment of the robot repeats the moving phase and stop phase, both of static and kinetic frictions should be considered. Therefore, we apply the LuGre model as a friction model. Then, we searched effective motion patterns by numerical optimizations. In this paper, the particle swarm optimization (PSO) algorithm, one of the meta-heuristic optimization methods, is applied. The optimized results are investigated by comparing to simple periodic patterns.

9429-45, Session PTues

Effects of contact cap dimension on dry adhesion of bioinspired mushroom-shaped surfaces

Yue Wang, Jinyou Shao, Xi'an Jiaotong Univ. (China);
Yucheng Ding, Xiangming Li, Hongmiao Tian, Hong Hu,
Xi'an Jiaotong University (China)

Dry adhesion observed in small creatures, such as spiders, insects, and geckos, has many great advantages including repeatability and strong adhesiveness. These unique adhesive properties have inspired numerous researchers to design and fabricate various artificial micro-structured surfaces that could mimic and emulate these special performances. Among the proposed man-made structures, mushroom-shaped (laterally bulged) tops have drawn many attentions by scientists and engineers, and many studies have basically proved their superiority in highly enhancing adhesion compared with other sphere or simple flat tops. These works mainly focus on comparing the adhesion strength between the mushroom-shaped tops and other tops without any caps, but the effect of the cap dimension itself on the adhesion are generally neglected. Here, in order to study the relationship between the cap dimension and adhesion strength, we present a convenient and low-cost method of fabricating mushroom-shaped micropillars with differing cap diameters based on the conventional photolithography and molding. Firstly, a photoresist is spin-coated on a silicon wafer and then completely exposed by a UV light passing through a mask arrayed by micro-holes. In addition, the UV light irradiates the substrate side and a thin layer photoresist is thoroughly exposed. After precise development and molding, a micropillars array made of PDMS can be finally achieved. With different development times and substrate side exposure dosages, different cap diameters can be gained. The normal adhesion of these adhesives with varying cap diameters is measured and the adhesion strength improves with the cap diameter increasing. Also, such adhesives with the laterally bulged flat top created by a convenient and cost-effectively method will have potential application ranging from climbing robots to biomimetic patches.

9429-46, Session PTues

Electrowetting of liquid polymer on petal-mimetic microbowl-array surfaces for formation of microlens array with varying focus on a single substrate

Xiangmeng Li, Jinyou Shao, Xiangming Li, Hongmiao Tian,
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In some applications, microlens array (MLA) with varying focus on the same substrate is desired. However, it is not easy to achieve for present approaches. Electrowetting on dielectric (EWOD) is a useful strategy in microfluidic or optofluidic devices, owing to its effectiveness to tune the contact angle (CA). Many have studied on the EWOD effect on smooth surfaces, but few paid attention to rough surfaces. It is known that the CA is quite reversible for smooth surfaces, whereas a rough surface can provide with a high CA hysteresis which hinder the reversibility. Based on this concern, in this study, a focus-tunable MLA is presented on petal-mimetic microbowl array (MBA) surfaces which reveal highly adhesive hydrophobicity. Firstly, a SU-8 micro-texture with MBA is fabricated by EBL and used as master to replicate a polydimethylsiloxane (PDMS) mold. Then,

by nanoimprinting on a UV curable NOA thin film with the PDMS mold, a duplicated MBA of NOA is produced on the ITO substrate, followed by UV irradiation. Next, microdrops of NOA are generated from a microsyringe onto the MBA textured NOA surface. Finally, a voltage is applied between a platinum electrode which is inserted in the NOA drop and the ITO electrode, with the MBA surface as dielectric layer. It is observed that the CA decreases irreversibly with increasing the applying voltage. After UV irradiation, a shape-retainable and tunable MLA can be formed. Moreover, the EWOD effect of water droplet on this petal-mimetic MBA surface is also investigated experimentally and numerically.

9429-47, Session PTues

A study on the durability of gecko-like PDMS micro-structures by metal coatings

GyuHe Kim, Hui Yun Hwang, Andong National Univ. (Korea, Republic of)

Gecko-like adhesive micro- or nano-structures made of PDMS are widely used for medical patches. Since Gecko's feet have micro- and nano-hierarchical structures, most researchers have focused on the fabrication method to replicate the similar hierarchical structures. However, the durability of PDMS based Gecko-like structures tend to be limited for ensuring tacky surface of the microstructures. In this work, the metal coating method was investigated experimentally for improving the durability of PDMS based Gecko-like structures. PDMS micro-structures were made by the micro-molding method, and then various metals such as gold, platinum, silver, and copper were coated using the plasma sputtering equipment with respect to the coating thickness. Static adhesion tests as well as durability tests of PDMS micro-structures with and without metal coatings on the smooth glass plate were performed. Adhesion strengths of metal coated PDMS micro-structures depended on the coating materials and thickness as well as the geometrical parameters of micro-structures. But we found that metal coated PDMS micro-structures had higher durability than uncoated one, and there were the optimal coating conditions for each coating materials.

9429-49, Session PTues

Multifunctional clay-cellulose nanocomposites by mimicking structures of nacre

Daseul Jang, Bong Sup Shim, Inha Univ. (Korea, Republic of)

Nacre, mother of pearl, exhibits excellent mechanical properties such as high fracture toughness and tensile strength although its constitutional materials are more than 95 % of just brittle aragonite (calcium carbonate) nanoplatelets and less than 5 % of biopolymer like chitin and silk fibroin proteins. The origin of this unique property conversion from molecular to macro levels comes from hierarchical brick-and-mortar structures. Furthermore, composite organization of mimicking nacre's brick-and-mortar structures has also been demonstrated as sources of mechanical performances of man-made nanocomposites. Here, we introduce nacre-inspired montmorillonite (MMT)-cellulose derivatives (CDs) composites by a simple casting process which may be suitable for industrial scale-up process. The composites showed not just unique mechanical and optical properties, but also hydrophobic water-proof surfaces and eco-friendly biodegradability. The material performances were systematically searched by varying functional groups of cellulose derivatives, clay contents, and composite casting conditions. We also provide strategic approaches how we can further overcome rule-of-mixture of the composites.

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9429-50, Session PTues

Bistability and thermal coupling in elastic metamaterials with negative compressibility

Eduard Karpov, Michelle Chen, Univ. of Illinois at Chicago (United States)

When elastic metamaterials are subjected to tension they may respond by undergoing contraction instead of expansion as an ordinary material would (and vice versa). This negative compressibility behavior can only occur if the system moves from one stable state to a different stable state as the force is applied, i.e., displays bistability. With a simple model potential, we demonstrate that this negative behavior leading to a pinched hysteresis on the stress cycle diagram is a solid-to-solid condensation-type phase transformation. In addition, we show that the negative compressibility may disappear in realistic dynamical systems, unless coupling with an external heat sink is strong enough to stabilize the newly formed phase. Such a material is an open thermodynamical system where the condensation process is accompanied by a fast return of the released heat into the ambient. Molecular dynamics with Verlet integration is used to study the dynamics of this behavior.

9429-53, Session PTues

Biomimetic nanofur for drag reduction and oil-water separation

Hendrik Hölscher, Maryna N. Kavalenka, Claudia Zeiger, Matthias Mail, Marc Schneider, Stefan Walheim, Thomas Schimmel, Matthias Worgull, Karlsruher Institut für Technologie (Germany)

Many plants and insects possess multi-functional surfaces covered by dense nanohair. Such a nanofur is of high interest for various biomimetic applications like self-healing, air retention, and oil-water separation. Here, we introduce a highly scalable and competitive molding technique for the fabrication of biomimetic nanofur [1]. With this method, we pull nanofur out of flat polycarbonate and tune its wettability from hydrophilic to superhydrophobic. By mechanically structuring these samples we create various devices suitable for microfluidics. Aside from that, the nanofur can be used for the fabrication of self-healing surfaces inspired by pitcher plants as well as for air-retaining surfaces mimicking the water fern *Salvinia minima*. Finally, we utilize the nanofur for oil/water separation and the cleaning up of oil spills.

An advantage of the introduced fabrication technique is the option to apply it to several kinds of polymers. Nanofur can even be produced from so-called "liquid wood", a recyclable and biodegradable biopolymer based on lignin. The as-prepared microhaired material absorbs crude oil out of the water and separates oil/water mixtures [2]. On top of that, its surface properties can be changed to hydrophilic and underwater superoleophobic by a short argon plasma treatment cycle, making the microhaired wood-based material capable of both "oil-removing" and "water-removing" oil/water separation methods.

[1] Michael Röhrig, Matthias Mail, Marc Schneider, Henri Louvin, Andreas Hopf, Thomas Schimmel, Matthias Worgull, Hendrik Hölscher. Hot Pulling of Nanofur for Biomimetic Applications. *Adv. Mat. Interfaces*, 1300083 (2014)

[2] M. N. Kavalenka, A. Hopf, M. Schneider, M. Worgull and H. Hölscher, Wood-based microhaired superhydrophobic and underwater superoleophobic surfaces for oil-water separation, *RCS Advances* 3, 31079 (2014)

9429-55, Session PTues

The effect of the abdomen deformation on the longitudinal stability of flying insects

Sang-Yeon Choi, Joong-Kwan Kim, Jong-Seob Han, Jae-Hung Han, KAIST (Korea, Republic of)

Insect body is composed of several exoskeletal components connected with flexible muscle and internal organs, which enables the structure to passively deform under external loadings. Although several previous studies showed the effect of flexible wings on the aerodynamics, less research has been done about relationship between a deformable body and flight stability.

Previous research revealed that the whole structure of a flying insect deforms during the flight and suggested that the deformation of the body, such as the abdomen, may play an important role in longitudinal flight dynamic stability of a flying insect by shifting the location of center of mass which in turn changes the moment of inertia around the body pitching axis.

In this paper, we derive simple longitudinal nonlinear equations of motion of two connected body components (thorax and abdomen) to investigate longitudinal position and attitude of the flying insects and relative attitude between the thorax and abdomen. The blade-element theory, which is based on experimentally obtained aerodynamic coefficients, is used for the periodic force and moment excitation to the system. Here, we focus on the role of the deformable abdomen on the pitch rotation to investigate whether or not the flexible body is a decisive factor to the longitudinal flight dynamic stability.

Three cases: 1) rigid connection between thorax and abdomen, 2) flexible connection, and 3) active connection with a feedback control, are compared to check the role of the abdomen deformation on the longitudinal flight dynamic stability, by examining eigenvalues of linearized system model of each case. Also, the derived equations of motion are verified using a multibody dynamics solver.

9429-56, Session PTues

Exploration of electric properties of bone compared to cement: streaming potential and piezoelectric properties

Carolyn Dry, Natural Process Design, Inc. (United States)

Bone is a material after which to model construction materials for many reasons, including its great strength, toughness, and adaptability. This paper focuses on bone's intrinsic ability to adapt to its environment, namely loading conditions. Research on bone's electrical properties reveals that two phenomena occur in bone to allow it to adapt to environmental changes; they are the inherent piezoelectric property of bone and the streaming potential of bone. Together they create charge differences that attract ions to specific regions of the bone, namely those under greatest stress, in order to build up the region to handle the applied load. We researched the utilization of these properties in cement in order to increase adaptability. We studied the inherent electric properties of the cement itself and considered the introduction of a different polymer or ceramic within the cement to impart piezoelectricity and streaming potential.

9429-57, Session PTues

Improving energy efficiency in robot limbs through hydraulic dangle

Julian Whitman, Michael A. Meller, Ephraim Garcia, Cornell Univ. (United States)

Animals often allow their limbs to swing passively under their own inertia. For example, about 40% of a human walking gait consists of the primarily passive swing phase. Current hydraulic robots use traditional actuation

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methods in which fluid power is used for all limb movements, even when passive dynamics can be utilized. "Dangle" is the ability to allow a hydraulic actuator to freely sway back and forth in response to external loads, in which both sides of the actuator are disconnected from pressure and connected to the tank. Dangle offers the opportunity for efficiency gains by enabling the use of momentum, gravity, and external loads to move a limb without consuming fluid power. To demonstrate these potential efficiency gains, this paper presents an experiment that compares the fluid power consumed to actuate a two degree of freedom hydraulic leg following a human walking gait cycle trajectory in both a traditional manner and utilizing dangle. It was shown that the use of dangle can decrease fluid power consumption by 20% by utilizing pendular dynamics during the swing phase. At speeds higher than the natural dangling rate, more energy must be used to maintain the desired trajectory due to damping inherent in the configuration. The use of dangle as an energy saving method when driving hydraulic limbs could increase operation time for untethered hydraulic walking robots.

9429-503, Session Plen

Guided Acoustic Wavefield Imaging for Damage Detection, Structural Characterization, and Transducer Design

Massimo Ruzzene, Georgia Institute of Technology (United States)

No Abstract Available

9429-27, Session 9

Characterization of natural photonic structures by means of optimization strategies

Demetrio Macías, Alexandre Vial, Univ. de Technologie Troyes (France); Ana E. Luna, Diana C. Skigin, Marina E. Inchaussandague, Univ. de Buenos Aires (Argentina)

Natural photonic structures exhibit remarkable color effects such as metallic appearance and iridescence. A rigorous study of the electromagnetic response of such complex structures requires to accurately determine some of their relevant optical parameters, e.g. the dielectric constants of the materials involved. In a recent work, we have shown that heuristic optimization strategies are suitable tools for the retrieval of the complex refractive index of the materials comprising natural multilayer systems such as the Coleoptera's cuticle. Moreover, the numerical results obtained illustrate the great potential of these kind of algorithms not only for the study of natural photonic structures, but also for the design of biomimetic photonic devices for lightning, sensing or anti counterfeiting applications. In a first stage, we assumed that the materials which comprise the layers are characterized by isotropic non-dispersive dielectric permittivities. However, it is well known that the cuticle of many Coleoptera exhibit anisotropy in their constituent materials, and also dispersion has been reported.

In this contribution we improve our previous approach in order to have a more realistic and useful computational tool for the retrieval of the relevant parameters of biological structures. For this, we include, within the optimization loop, a dispersion model to describe the frequency-dependent dielectric permittivity of the layers' materials. Also, in order to guarantee the uniqueness of the solution and the convergence to the global optimum, we simultaneously include in the fitness function the information of several angles of incidence, as well as that of the p- and s-polarization states.

9429-28, Session 9

Transparency by randomness: omnidirectional anti-reflection properties of the glasswing butterfly (*Greta oto*)

Hendrik Hölscher, Radwanul H. Siddique, Karlsruher Institut für Technologie (Germany)

As its name suggests the Glasswing butterfly (*Greta oto*) has transparent wings with remarkable low reflectance for large view angles. This omnidirectional anti-reflection behavior is caused by small nanopillars covering the transparent region of its wings. In difference to other anti-reflection coatings found in nature these pillars are not periodically arranged and feature a random height and width distribution.

Here, we analyze the specular and diffuse reflection of the surface and explain the concept of transparency by randomness. Angle-resolved spectroscopy reveal that the transparent parts of the Glasswing have a low reflection of 2% (two surfaces) in the visible regime for high radiation angles of 65° and almost 5% even at 85° of incidence angle. We simulate these omnidirectional anti-reflection properties by considering a Gaussian height distribution of the nanopillars as in the original Glasswing. By varying size and distribution of the structures we demonstrate that the random distribution is the origin of the famous broadband omnidirectional anti-reflective property of *Greta oto*.

9429-29, Session 10

Biomimetics, color, and the arts (*Invited Paper*)

Franziska Schenk, Birmingham City Univ. (United Kingdom)

Color as dramatic, dynamic and dazzling as the iridescent hues on the wings of certain butterflies has never been encountered in the art world. Unlike and unmatched by the chemical pigments of the artist's palette, this changeable color is created by transparent, colorless nanostructures that, as with prisms, diffract and reflect light to render spectral color visible. Until now, iridescent colors, by their very nature, have defied artists' best efforts to fully capture these rainbow hues. Now, for the first time, the artist and researcher Franziska Schenk employs latest nature-inspired color-shift technology to actually simulate the iridescence of butterflies and beetles on canvas. Crucially, studying the ingenious ways in which a range of such displays are created by insects has provided the artist with vital clues on how to adapt and adopt these challenging optical nano-materials for painting. And indeed, after years of meticulous and painstaking research both in the lab and studio, the desired effect is achieved. The resulting paintings, like an iridescent beetle, do in fact fluctuate in perceived color - depending on the light and viewing angle. In tracing the artist's respective biomimetic approach, the paper not only provides an insight into the new color technology's evolution and innovative artistic possibilities, but also suggests what artists can learn from nature.

9429-30, Session 10

Fabrication of broadband, antireflection surfaces inspired by the black butterfly (*Pachliopta aristolochiae*)

Radwanul H. Siddique, Guillaume Gomard, Norbert Schneider, Yidenekachew Donie, Uli Lemmer, Matthias Worgull, Hendrik Hölscher, Karlsruher Institut für Technologie (Germany)

Bio-nanostructures have been extensively studied for antireflection (AR) purposes, leading to theoretical and experimental investigations of

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nanopillars, nanonipples etc. integrated either on a simple substrate or within a complete opto-electronic device (typically solar cells and LEDs). Antireflective nanostructures, with quasi-ordered nano-holes arranged between the μm -spaced triangular ridges, are found in the black dorsal scales of butterfly species *Pachliopta aristolochiae* and a few other black butterflies. Here, we present a fabrication procedure of this morphology by combining two nanostructuring techniques - nanothermoforming to create the triangular ridges and polymer blend lithography to include disordered nanoholes. The flexibility of this large scale fabrication technique allows us to tune the properties accordingly. Our designed nanopatterned antireflection coating is efficient over an extended spectral range (from UV to NIR), benefiting from the combination of nanoholes and micro-ridges inspired by *Pachliopta aristolochiae*. The collection efficiency is improved for short wavelengths due to the transport of the light preferentially within the nano-holes. At large wavelengths, the triangular micro-ridges guide light to a gradient refractive index region and provide an additional impedance matching layer.

9429-31, Session 10

Large-scale replication of the blue Morpho's hierarchical photonic nanostructures utilizing shape memory polymers

Norbert Schneider, Senta Schauer, Alexander Kolew, Marc Schneider, Karlsruher Institut für Technologie (Germany); Juerg Leuthold, ETH Zürich (Switzerland); Hendrik Hölscher, Matthias Worgull, Karlsruher Institut für Technologie (Germany)

The replication of complex 3D photonic nanostructures on large scales still lies beyond state of the art fabrication techniques. We introduce a replication process combining hierarchical 3D subwavelength structures required for optical applications with the capability of large scale manufacturing. As inspiration we chose the Morpho rhetenor butterfly which shows a brilliant blue iridescence due its "Christmas tree" like surface structures. Although various technical applications were suggested for these structures [1], their large-scale replication remains challenging.

To overcome this problem, we introduce shape memory polymers (SMP) to a unique combination of nanoimprint and thermoforming to manufacture undercut nano and microscale features. Furthermore, the flexibility of our process allows the implementation of additional biomimetic and artificial features like superhydrophobicity and self-cleaning.

First we use hot embossing to create primary structures in the SMP. This is then temporarily flattened again and acts as a pre-programmed active mold insert. A spincoated polymer layer is imprinted with the secondary photonic structures and folded on a micro-scale by the SMPs ability to recover to its initial state.

We present a successful implementation of our process and demonstrate bioinspired structures several orders of magnitude below current large-scale replication techniques [2].

[1] Sambles, Nature Photonics, 6, 141-142 (2012)

[2] Schneider et al., Optical Materials Express, 4, 1895-1902 (2014)

9429-32, Session 10

Simple mass-production method of the flexible Morpho-colored thin film for wide applications

Akira Saito, Osaka Univ. (Japan) and RIKEN (Japan); Kosei Ishibashi, Junpei Ohga, Megumi Akai-Kasaya, Yuji Kuwahara, Osaka Univ. (Japan)

Brilliant blue of some Morpho butterfly species is a typical example of the structural color and attracts interest due to a metallic luster from the biological body. However, this blue is known by a physically mysterious feature. The blue has high reflectance that is explained by an interference from an ORDERED microstructure on their scale, whereas the color does not change depending on the angle that contradicts the interference. This mystery is attributed to a specific nanostructure having nano-DISORDER to prevent the rainbow color. After successful prove of this principle by emulating the 3D nanostructures, wide potential applications of this specific structural color have been found. However, true applications require a variety of developments such as mass-production, control of optical properties, optical simulation on the nano-disorder, etc., which have recently been overcome step by step. The remaining key issue is the mass-production under the "substrate-free" condition, because all our processes have long been accompanied with the thick substrate designed with a specific nano-disorder, which has limited fatally the variety of applications. Following the successful and quite simple fabrication of the substrate-free Morpho-Powders in the last year, we succeeded in mass-production of the flexible thin film by maintaining the specific properties. These processes will extend effectively the applications of the specific color, giving the free-shape either in the flexible film or micro-powders. Not only for the color materials, our developed method will serve to mass-produce the flexible thin film in more general purpose of the functional film.

9429-33, Session 11

Development of a frequency-modulated ultrasonic sensor inspired by bat echolocation (Invited Paper)

Krzysztof Kepa, Nicole Abaid, Virginia Polytechnic Institute and State Univ. (United States)

Multi-agent systems are increasingly prevalent in engineering solutions due to their robustness and emergent behaviors, typically equipping agents with decoupled sensing and communication mechanisms. However, bat swarms are highly successful groups which use active sensing— sensing that relies on self-generated signals, i.e. sonar and radar— which cannot be captured by such models. These unique animals have been observed navigating in spite of negative interference from peers and beneficially using information from peers' signals. We develop a model of actively-sensing multi-agent systems aimed at capturing these benefits and validate it against wild bat swarms. Robotic applications of these results are discussed.

9429-34, Session 11

Biomimetic water transportation device learning from Wharf Roach *Ligia exotica* (Invited Paper)

Masatsugu Shimomura, Chitose Institute of Science and Technology (Japan)

Terrestrial animals have evolved diverse means to intake water using active mechanical and passive potential energies, including extraction of moisture from food, absorption through the skin, suckling through the proboscis, but mostly rely on the oral/anal intakes. Some animals only use the passive energies to transport water; the desert beetle collects by the patterned microstructures on elytra, the thorny devil transports to its mouth by the open capillary channels on grooved skins. However, little is known about the mechanism of water transport using passive potential energies. Here we show the mechanism of water transport by means of microstructures against the gravity force through the open-channels. Wharf roach, *Ligia exotica*, is a semi-terrestrial arthropod living by seashore, and should transport water properly to its gill to avoid drying. It possesses the open capillaries on its caudal legs consisting of two different types of micro protrusions; hair-like and paddle-like ones. We propose a novel water transportation device inspired by *Ligia exotica*.

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Four structural factors are pointed out for design of water transportation device.

- (1) micro-structured surface for easy regulation of wettability
- (2) capillary bundle structure for long distance and large volume transportation
- (3) fail safe by multiple pass by bundle of connected capillaries
- (4) multistep combination of "transport and store" provides long distance and large volume water transportation

We anticipate that this passive water transport mechanism may inspire novel biomimetic fluid manipulations with or without a gravitational field.

9429-35, Session 11

A synthetic leaf: the biomimetic potential of graphene oxide

Marilla Lamb, George W. Koch, Eric R. Morgan, Michael W. Shafer, Northern Arizona Univ. (United States)

Emerging materials such as graphene oxide (GO) have micro and nano features that are functionally similar to those observed in plant cell walls. Therefore, it may now be possible to design and build biomimetic trees to lift water via mechanisms similar to those employed by trees, allowing for potential applications such as passive water pumping, filtering, and evaporative cooling. The tallest trees can raise large volumes of water to over 100 meters using only energy that is available in the environment. This phenomenon occurs in all plants when capillary forces generated in the microscopic pores in the cell walls of leaves are collectively applied to large diameter xylem conduits. The design of a synthetic tree that mimics these mechanisms will allow water to be moved to heights greater than is currently possible by any human-engineered system that does not require the use of a mechanical pump. We have tested the suitability of membranous GO as the leaf of a synthetic tree and present results comparing the performance of those fabricated with porous ceramics to those using GO. The difference in performance between these two concepts is compared with analytic predictions, and design improvements are explored.

9429-36, Session 11

Efficiency testing of hydraulic artificial muscles with variable recruitment using a linear dynamometer

Jordan B. Chipka, Cornell Univ. (United States)

When a task calls for consistent, large amounts of power output, hydraulic actuation is a popular choice. However, for certain systems that require short bursts of high power, followed by a period of low power, the inefficiencies of hydraulics become apparent. One system that fits this description is a legged robot. McKibben muscles prove to be a wise choice for use on legged robots due to their light weight, high force capability, and inherent compliance. Variable recruitment, another novel concept for hydraulic actuation, offers the ability to further improve efficiency for hydraulic systems. This paper will discuss the efficiency characterization of variable recruitment McKibben muscles intended for use on a bipedal robot, but will focus on the novel test apparatus to do so. This device is a hydraulic linear dynamometer that will be controlled such that the muscles experience similar force-stroke levels to what will be required on our bipedal robot. The position of the drive cylinder will be controlled so that the muscles experience the proper position trajectory that will be needed on the robot. The pressure of the muscles will be controlled such that the force they experience will mimic the forces that occur on the robot while walking. Hence, these dynamic tests will ensure that the muscle bundles will meet the force-stroke requirements for our robot. Once these muscle bundles are integrated onto our walking robot, we will be able to demonstrate the power savings of variable recruitment McKibben muscle bundles compared to the traditional hydraulic system.

9429-37, Session 11

Variable deflection response of sensitive CNT-on-fiber artificial hair sensors from CNT synthesis in high aspect ratio microcavities

Keith Slinker, Air Force Research Lab. (United States) and Universal Technology Corp. (United States); Matthew R. Maschmann, Air Force Research Lab. (United States) and Universal Technology Corp. (United States) and Univ. of Missouri (United States); Corey Kondash, Air Force Research Lab. (United States) and Universal Technology Corp. (United States); Benjamin Severin, Federal Republic of Germany Liaison Office for Defense Material USA/Canada (United States) and Air Force Research Lab. (United States); David Phillips, Air Force Research Lab. (United States) and Universal Technology Corp. (United States); Benjamin T. Dickinson, Gregory W. Reich, Jeffery W. Baur, Air Force Research Lab. (United States)

Crickets, locusts, bats, and many other animals detect changes in their environment with distributed arrays of flow-sensitive hairs. Here we discuss the fabrication and characterization of a relatively new class of pore-based, artificial hair sensors that take advantage of the mechanical properties of structural microfibers and the electromechanical properties of self-aligned carbon nanotube arrays to rapidly transduce changes in low speed air flow. For air velocities less than 10 m/s we believe these display the highest sensitivity compared to published results. The pore is a glass microcapillary and the inner walls at the pore opening are sputter coated with a metal electrode. The hair is an S2 glass microfiber on which a radially-aligned carbon nanotube array is synthesized in situ with the S2 fiber inserted into the capillary and the CNTs fill the space between the fiber and the capillary wall. As the hair is deflected, the nanotubes are compressed against the metal electrode resulting in a typical change in resistance of 1 to 100 k Ω - or 5 to 50% of the nominal resistance. The quasi-static electromechanical response of the sensors to point loads applied in a laboratory scale setup are compared to the distributed load response to air flow. A plane wave tube is used to perturb the hair at acoustic frequencies in order to probe the dynamic response of the hair sensors. We envision many technological applications for artificial hair sensor arrays including the detection of spatio-temporal flow pattern over aircraft surfaces for more stable and agile flight.

9429-38, Session 12

Mechanical reinforcement of (bio)organic materials with inorganics through vapor phase processing

Mato Knez, Keith Gregorczyk, Ana Zuzuarregui, CIC nanoGUNE Consolider (Spain)

In spite of many advances in materials research and the resulting improvement of mechanical properties of (bio)polymeric materials in the recent decades, the technological developments in various branches more than ever require further improvement of the materials' mechanical properties in order to meet the current needs for lightweight and tough materials for more ecological and economical engineering.

A view to nature's strategies reveals that the presumably easiest way for obtaining materials with a high level of flexibility and toughness at the same time involves the inclusion of inorganics into (bio)polymeric matrices. For this reason, numerous approaches have been followed in order to merge inorganic materials with polymers in a beneficial way. Some of those approaches resulted in great improvement of the properties of the materials, sometimes obtained with very simple synthetic strategies.

Our strategy involves the adaptation of a thin film coating process, the

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so-called atomic layer deposition (ALD), enabling a special form of post treatment of polymers through diffusion into and interaction of metalorganic vapors with polymeric materials of different types. With such post processing, the mechanical properties of a variety of natural and synthetic polymers can be altered, including their toughness, extensibility, Young's Modulus or ultimate tensile strength. The presentation will show the impact of the processing on various spider silks, collagen and cellulose as natural polymers, and PTFE and polyaramids as synthetic polymers.

9429-39, Session 12

A bio-inspired spider web

Lingyue Zheng, Alex Hertman, Majid Behrooz, Faramarz Gordaninejad, Univ. of Nevada, Reno (United States)

The goal of this study is to develop an artificial adaptive spider web with similar behavior as a real spider web. By adjusting the pretension and stiffness in the spider web, energy absorbing ability of the web is controlled. The energy change characteristic in a spider web will be examined while the pretension and stiffness of the radial strings are varied. Various types of web materials and configurations, such as, damaged webs are investigated. It is demonstrated that the pretension and stiffness of the web's radial strings can significantly affect the total energy of the full and damaged webs.

9429-504, Session Plen

Smart Sensors and Actuators: From Concepts to Products

Shiv Joshi, NextGen Aeronautics, Inc. (United States)

No Abstract Available

Conference 9430: Electroactive Polymer Actuators and Devices (EAPAD) XVII

Monday - Thursday 9 -12 March 2015

Part of Proceedings of SPIE Vol. 9430 Electroactive Polymer Actuators and Devices (EAPAD) 2015

9430-1, Session 1

RoboSimian and the advancement of mobile manipulation in robotics (*Keynote Presentation*)

Brett A. Kennedy, Jet Propulsion Lab. (United States)

As robotic systems that get themselves from place to place become more common in the world, the frontier of mobile manipulation systems has opened. RoboSimian is the Jet Propulsion Laboratory's entry into the DARPA Robotics Challenge, a contest that explicitly demands robots that can both go and do in an abstracted disaster response environment. By incorporating four identical limbs on a human-scale body, RoboSimian represents a unique approach to the Challenge by deliberately combining the requirements mobility and manipulation, which provides an increased operational flexibility and range over other designs. This talk will describe the particular hurdles of designing a limbed robot inspired by simians (and other animals) within the constraints of current human technology. We will also discuss the practical issues of developing a robotic system that will be fieldable in the near term due to its amenability to manufacturing and maintenance. Finally, we will look at what system and component technology advances would most directly improve the execution of the vision of a highly mobile and dexterous robot system in the future.

9430-2, Session 1

Multifunctional electroactive polymers and nanocomposites: fascinating properties and novel applications (*Invited Paper*)

Qiming M. Zhang, The Pennsylvania State Univ. (United States)

The direct and efficient coupling between the electric signals and the elastic, thermal, optical and magnetic signals in ferroelectric based electroactive polymers makes them attractive for exploiting a broad range of cross-coupling phenomena and applications. This talk will present the recent advances in the Laboratory of Electroactive Materials and Systems at Penn State on electroactive polymers and nanocomposites and their related applications for micro-actuator and artificial muscles, and advanced solid state cooling. Specifically, making use of the proximity in energy between different phases which stability can be easily tuned by introducing "defects" in the polymers, we converted a normal ferroelectric P(VDF-TrFE) copolymer into a ferroelectric relaxor with a high dielectric constant and PVDF into a dielectric with reversible phase transformation between the polar- and non-polar phases, resulting in a high electroactive strain of larger than 7% with an elastic energy density higher than 1 J/cm³. The electroactive polymers with such a high electromechanical responses enable applications for a broad range of actuators and sensors in haptics and medical devices, as demonstrated recently by Novasentis, Inc. (formerly, StrategicPolymers Sciences, Inc. SPS). The direct coupling between the electric and thermal properties also lead to the electrocaloric (EC) effect, which could provide alternative to the century old vapor compression cycle refrigeration, if the effect is large. It was discovered recently that the multiphase coexistence near invariant critical point and relaxor nature of the materials lead to large electric field induced temperature and entropy change, more than one order of magnitude improvement over the state-of-the-art, promising for high efficiency and environmentally friendly solid state cooling devices. Recent works in the EC based devices will also be presented.

9430-3, Session 1

Reducing laser speckle with electroactive polymer actuators (*Invited Paper*)

Chauncey Graetzel, Marcel Suter, Manuel Aschwanden, Optotune AG (Switzerland)

Lasers provide numerous advantages over other light sources. For example, the low divergence allows precise control of very high optical power, thus making lasers very attractive for projection systems. Unfortunately, lasers do have the inherent problem of speckle. On rough optical surfaces, e.g. a wall or a cinema screen, local interferences occur which are observed as a grainy pattern of spots. This effect causes noise in projected images but also reduces the resolution of measurement systems.

Optotune's Laser Speckle Reducer (LSR) works in a similar way to a rotating diffuser to overcome the speckle issue. However, it is much more compact and economical. A diffuser is mounted on an elastic membrane and set into circular motion using four electroactive polymer actuators (EAP). With the correct electrode geometry and appropriate timing of the activation of the electrodes, a planar circular oscillation of the diffuser is generated. Using the resonance frequency of the mechanical system the diffuser deflects lateral between 300 to 500 μm at frequencies of about 300 Hz destroying the observed laser speckles.

With the development of the LSR, Optotune has succeeded in utilizing the advantages of EAP in a specialized optical component that has enabled a broad range of laser based systems including dental cameras and cinema projectors.

9430-4, Session 2

Dielectric elastomers for wave energy harvesting: current status and future expectations (*Invited Paper*)

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

Ocean-wave power is one of the most persistent, spatially-concentrated and predictable forms of intermittent renewable energies. Since the worldwide estimated resource amounts to nearly 3TW of yearly average power, wave-energy is expected to cover a significant portion of the intermittent renewable energy mix in the future.

Harvesting energy from waves is very challenging and the sector is still immature, with only a few pre-commercial systems being in operation around the world nowadays. Based on traditional technologies, current Wave Energy Converters (WECs) are showing: excessive complexity and costs for construction, installation and maintenance; scarce resistance to the marine environment; limited energy conversion efficiency.

In this context, Dielectric Elastomers Transducers (DETs) could provide the technological breakthrough that is required to make wave energy exploitable. DETs are highly deformable capacitors, made of elastomeric dielectric materials and compliant electrodes, which can be used to convert mechanical energy into electricity via the variable capacitance electrostatic generation principle.

Recently, the use of DETs for WECs has attracted significant interest from both the Academia and the Industry. Their potential advantages over conventional technologies are: large energy densities, direct-drive and cyclic operation, good and rate-independent efficiencies, good shock and corrosion resistance, silent operation and moderate/low cost.

In the context of the European Project PolyWEC (<http://www.polywec.org/>), we are investigating different concepts of DE-based WECs.

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This presentation reports on the latest advances we have achieved in the development and experimental testing of two DET-based WECs: the Poly-OWC and the Poly-Surge systems. Besides showing the very promising performances of the considered prototypes, the presentation also provides a discussion on the present limits and required advancements of DET technology for practical wave energy harvesting applications.

9430-5, Session 2

Analyses and comparison of an energy harvesting system for dielectric electro active polymer generators using a passive harvesting concept: the voltage-clamped multi-phase system

Rick C. L. van Kessel, SBM Offshore (Monaco) and Technische Univ. Delft (Netherlands); Ambroise Watzet, SBM Offshore (Monaco); Pavol Bauer, Technische Univ. Delft (Netherlands)

The monolithic structure and strong electromechanical coupling of Dielectric Electro Active Polymer generators yield simple, robust and cost-effective designs, which is an important prerequisite for commercial energy generation systems. The challenge lies in the combination with a Power Electronic system that has similar characteristics.

In previous work it was shown that in ambient energy harvesting applications with the majority of the cycles below 40% strain, the losses in the power electronic converter dedicated to each generator are dominant and the required converter power rating is disproportional without incorporating advanced topologies and harvesting cycles.

This work investigates and analyses a passive harvesting concept in which only non-controllable power electronic components are used at the generator level. The resulting diode voltage-clamped topology is drawn up for a plurality of DEAP generators and the operating principles are explained. Through a charge-voltage diagram the energy output is calculated analytically and the electric field intensity over the cycle is analysed and proves to be beneficial from a material life time perspective.

The optimal bus voltages are derived and through a comparison it is shown that the energy output for low-strain cycles is very similar to active harvesting concepts with dedicated converters for each generator. An outlook towards industrialization applied to SBM Offshore's S3 Wave Energy Converter points out the major advantages of the proposed passive harvesting system: simple, low-cost and robust operation using state-of-the-art and proven components.

9430-6, Session 2

Comparison of bidirectional power electronics with unidirectional topologies using active discharging circuits for feeding DEAP transducer

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

Transducers based on dielectric electroactive polymers (DEAP) use the electrostatic pressure to convert electrical energy into mechanical energy or vice versa. Besides an intelligent setup of the transducer depending on the application, high voltage power electronics are indispensable. Due to the capacitive behavior of the DEAP DC/DC converter with current feeding are used to drive the DEAP. The flyback-converter is a promising converter topology for output powers up to several 100 of Watts, what is sufficient for the most actuator applications.

Besides the capability to charge a DEAP transducer, the utilized power electronics also has to provide the capability to discharge the transducer

in order to enable a continuous voltage adjustment. Thus, on the one hand a unidirectional flyback-converter with active discharging circuit can be used. In this case the energy is dissipated during discharging. On the other hand a flyback-converter with bidirectional energy flow is appropriate to recover the energy stored in the DEAP back to the DC-link. Although the bidirectional flyback-converter provides a higher efficiency, especially the electrical components of the secondary side must resist very high voltage stresses. Therefore, within this contribution also unidirectional flyback-converter with novel active discharging circuits are introduced, corresponding control strategies are developed and analyzed to investigate whether these topologies can be realized with lower effort, e.g. concerning the specifications of the utilized components.

Finally, measurement results of realized prototypes of both topologies are compared and discussed.

9430-7, Session 2

Electronics drivers for high voltage dielectric electro active polymer (DEAP) applications

Zhe Zhang, Michael A. E. Andersen, Technical Univ. of Denmark (Denmark)

Dielectric Electro Active Polymer (DEAP) can be used in actuation, sensing and energy harvesting applications, but driving the DEAP based actuators and generators has three main challenges from a power electronics standpoint; i.e. high voltage (around 2.5 kV), nonlinearity, and capacitive behavior. In this paper, electronics drivers for heating valves, loud speakers, incremental motors, and energy harvesting are reviewed, studied and developed in accordance with their corresponding specifications. Following the introduction, diverse power converters are presented in Section II. Due to simplicity and low power capacity (below 10W), the reversible Fly-back converters with both magnetic and piezoelectric transformers are employed for the heating valve and incremental motor application, in which only ON/OFF regulation is adopted for energy saving. For the DEAP based energy harvesting, the non-isolated Buck/Boost converter is used, due to the system's high power capacity (above 100W), but voltage balancing across the series-connected high voltage IGBTs is a critical issue. Accordingly a novel gate driver circuitry is proposed and equipped. Due to the requirements of the audio products, such as low distortion and noise, the multi-level Buck converter based Class-D amplifier, which has high control linearity, is implemented for loud speaker application. A synthesis among these converter topologies and control techniques is given in Section III; therefore, for these DEAP based applications, their diversity and similarity of electronics drivers, as well as the key technologies employed are analyzed. Thus, an overview of how to choose the proper topologies can be revealed. Then, the design guidelines, in order to achieve high efficiency and reliability, are discussed in Section IV. Finally, the conclusion is presented in Section V.

The research work is supported by the Danish National Advanced Technology Foundation in the research platform "DEAP-Green Production".

9430-8, Session 3

Towards fast, reliable, and manufacturable DEAs (Invited Paper)

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

Dielectric elastomer transducers (DETs) are known for their large strains, low mass and compliance, making them attractive for a broad range of applications, from soft robotics to tuneable optics, or energy harvesting. However, 15 years after the first major paper in the field, commercial applications of the technology are scarce, owing to high driving voltages, short lifetimes, slow response speed, viscoelastic drift, and no optimal solution for the compliant electrodes.

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At the EPFL's Microsystems for Space Technologies laboratory, we have been working on the miniaturization and manufacturability of DEAs for the past 10 years. In the frame of this talk, we present our fabrication processes for high quality thin-film silicone membranes, and for patterning compliant electrodes on the sub mm-scale. We use either implantation of gold nano-clusters through a mask, or pad-printing of conductive rubber to precisely shape the electrodes on the dielectric membrane. Our electrodes are compliant, time stable and present strong adhesion to the membrane. The combination of low mechanical losses elastomers with robust and precisely-defined electrodes allows for the fabrication of very fast actuators that exhibit a long lifetime. We present different applications of our DEA fabrication process, such as a soft tuneable lens with a settling time smaller than 175 microseconds, a motor spinning at 1500 rpm, and a micro aerial vehicle equipped with DEA-based controlled surfaces.

9430-9, Session 3
Dielectric Materials, Design and Realization (Invited Paper)

Dorina M. Opris, EMPA (Switzerland); Jose Enrico Q. Quinsaat, Simon Dunki, Yee Song Ko, EMPA (Switzerland) and Ecole Polytechnique Fédérale de Lausanne (Switzerland); Mihaela Alexandru, EMPA (Switzerland) and Ecole Polytechnique Fédérale de Lausanne (Switzerland) and Petru Poni Institute of Macromolecular Chemistry (Romania); Carmen Racles, Petru Poni Institute of Macromolecular Chemistry (Romania); Frank A. Nüesch, EMPA (Switzerland) and Ecole Polytechnique Fédérale de Lausanne (Switzerland)

It has been the dream of many scientists to create polymeric materials with simultaneously high dielectric permittivity, low glass transition temperature, and excellent elastomeric properties. Such material would be a highly attractive dielectricum in electromechanical actuators. Within this topic we are focusing on silicones because of their excellent elastomeric properties over a wide temperature and frequency range combined with low glass transition temperatures. To increase their low permittivity, we followed different approaches which include: blending the matrix with highly polarizable conductive and polar nanofillers and chemical modification of the silicones with polar side groups. This presentation will show the advantages and disadvantages of the two strategies we have been following and will provide an assessment of their future potentials.

We thank Prof. F. Kremer, University of Leipzig, and his co-workers for competent help with dielectric spectroscopy. M.A. thanks the CRUS for a postdoc stipend within the SCIEX program. J.Q., S.D., and S.K. acknowledge financial support from the SNSF.

9430-10, Session 3
Electro-active polymer thin films and flexible electrodes for artificial muscle sphincters

Vanessa Y. F. Leung, Bekim Osmani, Tino Töpfer, Florian M. Weiss, Marco D. Dominietto, Bert Müller, Univ. Basel (Switzerland)

Sphincter implants for treating incontinence are currently based on mechanical systems with high failure rates, requiring revision after 3 to 5 years [1]. To overcome this drawback, we are developing an artificial muscle sphincter based on bio-mimetic electro-active polymer (EAP) actuators.

Medical implants require (a) polymer films that are nanometer-thin, allowing actuation below 24 V, and (b) electrodes that are stretchable, remaining conductive at strains of 10 %.

The first of these challenges lies in the realization of uniform thin films

on the nanometer scale. We report on our fabrication process based on vacuum deposition of EAP sandwich stacks [2], which has so far allowed us to produce 250 nm-thin PDMS and 5 nm-thin gold films. Ultimately, the molecular deposition system under construction will allow monitoring the deposition of multilayered EAP-nanostructures with in situ ellipsometry.

The second challenge for the fabrication of EAP actuators is the stiffness of conventional metallic electrode layers. We will present our results on pre-strained metal electrodes, with tunable anisotropic micro- and nano-structures that show a preferred actuation direction, mimicking the anisotropic functionality of natural muscles.

Finally we will report on EAP cantilevers [3], where the actuation of the cantilever is determined by a laser beam deflection method we developed to characterize the flexibility of EAPs.

[1] H. D. Becker, et al., *Urinary and Fecal Incontinence* (Springer-Verlag, Berlin, 2005).

[2] F. M. Weiss, et al., *Proc. SPIE 8340, 83400A* (2012).

[3] F. M. Weiss, et al., *Proc. SPIE 9056, 905607* (2014).

9430-11, Session 3
Performance prediction of circular dielectric electro-active polymers membrane actuators with various geometries

Steffen Hau, Alexander York, Stefan S. Seelecke, Univ. des Saarlandes (Germany)

Dielectric electro-active polymer (DEAP) technology holds promise in enabling lightweight, energy efficient and scalable sensors and actuators. The circular DEAP configuration (also known as cone or diaphragm actuator) in particular shows potential in applications such as pressure sensors, pumps, valves, micro-positioners and loudspeakers. DEAP's can also be uniquely tailored to perform optimally for any application. Properties such as electrode material and geometry highly influence the performance of DEAP devices. They dictate the stroke and work output performance of DEAP actuators and the sensitivity and resolution of DEAP sensors.

This work presents an experimental investigation of DEAP actuators and sensors made with various geometries and various electrode inks. For electrode inks, rectangular samples made from various material mixtures are printed on a silicone film. Then the conductivity is measured for different stretch levels. DEAP actuators and sensors of various geometries are then tested. They consist of a silicone based elastomer, the previously tested ink electrodes, and are held together with a stiff frame. They are tested for mechanical and electrical properties while loaded mechanically and electrically. The influence of various parameters, such as electrode material and different sizes of the inner and outer diameters, are then documented. Measurements such as force, displacement, capacitance, resistance and power allow us to predict the actuation and sensing performance and will be used for future modeling efforts as well as adapting these DEAP's to new applications.

9430-12, Session 3
Characterization of the dielectric breakdown field strength of PDMS thin films: thickness dependence and electrode geometry

Florentine Foerster, Tanja Grotepass, Helmut F. Schlaak, Technische Univ. Darmstadt (Germany)

The electrical voltage which can be applied to a dielectric elastomer generator during the energy harvesting cycle plays an important role for the amount of energy harvested. A higher voltage and therefore a higher

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electrical field strength leads to a higher energy gain. However, the applied electrical voltage and field strength is restricted due to the dielectric breakdown field strength of the dielectric elastomer in the generator. For appropriate operation of the generator the dielectric breakdown field strength of the elastomer has to be known. From literature it is known that the breakdown strength of polymers depends on several parameters like the thickness of the material. In addition, for a reliable characterization of the breakdown strength the electrodes used play an important role.

In this work the dielectric breakdown strength of a novel PDMS thin film material for the fabrication of dielectric elastomer transducers developed by Wacker Chemie AG is investigated. Several PDMS films with different thicknesses are compared to determine the influence of the film thickness on the breakdown strength. The results show decreasing breakdown strength with increasing film thickness however this effect seems to be much lower in comparison to other elastomers.

As well, analytical calculations and numerical simulations are used to find an optimal electrode shape for the characterization of the dielectric breakdown field strength of PDMS thin films. Different electrode geometries are investigated and compared in order to find an electrode shape which reduces the influence on the measured breakdown strength to a minimum.

9430-13, Session 4
Thermal behavior of ionic electroactive polymer actuators

Andres Punning, Indrek Must, Urmas Johanson, Alvo Aabloo, Univ. of Tartu (Estonia)

The high spatial, temporal, and thermal resolution of the thermal imaging system Optotherm EL InfraSight 320 is used for investigation of the thermal behavior of the ionic electroactive polymer (IEAP) actuators. The resolution of 10-20 pixels in the direction of their thickness is close to the theoretical limit restrained by the infrared light wavelength registered by the imaging system. The videos, recorded with the frame rate of 30 fps, demonstrate show the propagation of heat along the membrane. The analysis of the thermal images provides the foundation for precise modeling of the IEAP actuators, taking into account the thermally induced mechanical and electrochemical effects. Experiments conducted with the IEAP actuators of different types (ionic polymer-metal composite, carbon-polymer composite, conducting polymer actuators) allow comparing their efficiencies. The experiments show demonstrable, that the IEAPs, used improperly, overheat to the inadmissible temperatures within seconds only. This, in turn, evaporizes the volatile electrolyte, and shortens the life expectancy of the IEAP devices.

9430-14, Session 4
Modeling of the time-dependent strain response of electroactive NCC-PEO and PVDF composites

Patrick S. Bass, Lauchlin Blue, Lin Zhang, Auburn Univ. (United States) and Materials Research and Education Ctr. (United States); Mi Li, Auburn Univ. (United States) and Forest Products Lab. and Ctr. for Bioenergy and Bioproducts (United States); ZhongYang Cheng, Auburn Univ. (United States) and Materials Research and Education Ctr. (United States); Maobing Tu, Auburn Univ. (United States) and Forest Products Lab. and Ctr. for Bioenergy and Bioproducts (United States)

Ionic electroactive polymers have been widely studied, wherein the electrically induced ionic motion generates an overall actuation response. The electromechanical bending observed in these polymers is due to the size difference between two types of ions which results in an unequal

expansion and contraction between the two sides. Nanocrystalline cellulose (NCC) is a biodegradable, renewable, and inexpensive biomass derivative. Poly(ethylene oxide) (PEO) is also biodegradable and a well-known solid-state electrolyte capable of having both cations and anions diffuse through its matrix under an applied electric field. In this study, NCC is mixed with the PEO to make 0-3 composites with increased Young's modulus and improved actuation performance. Based on experimental results, it was found that the time-dependent strain response for these composites followed an Arrhenius behavior. Using the Stokes-Einstein model, under an applied electric field, the flux of the ions within in the polymer matrix were defined as charged, spherical particles moving through a viscous medium with low Reynold's number. This new approach makes it possible to calculate parameters that may otherwise have been difficult or impossible to obtain. In this work, calculations for these kinds of properties, such as: apparent ionic diffusion coefficient, ionic velocity, and the dynamic viscosity of the matrix material are analyzed and presented. For example, the parameters for PEO-NCC composites doped with 5.0 wt.% lithium were calculated to be $3.58e-10$ cm²/s, 102 nm/s, and 275 Poise, respectively. Electroactive polyvinylidene fluoride (PVDF) films were also synthesized for comparison and refinement of the introduced model.

9430-15, Session 4
A physics-based model for actuation and sensing of ionic polymer metal composites

Youngsu Cha, Maurizio Porfiri, New York Univ. (United States)

Ionic polymer metal composites (IPMCs) are a novel class of soft electroactive materials that are receiving considerable attention for their potential use as actuators, sensors, and energy harvesters. IPMCs are composed of a hydrated ionomeric membrane that is sandwiched between noble metal electrodes. A voltage difference across the IPMC electrodes induces a macroscopic, and, vice versa, an imposed mechanical deformation produces a voltage difference across the electrodes. Here, we propose a modeling framework to study quasi-static large deformations and electrochemistry of IPMCs. Our approach is based on a new chemo-electro-mechanical constitutive model of IPMCs, in the form of a novel Helmholtz free energy density. Such Helmholtz free energy explicitly accounts for mechanical stretching of the IPMC, electric polarization, and ion mixing. We focus on a plate-like IPMC, for which we take into consideration the presence of metal particle layers in vicinity of the electrodes. Such layers are formed during the process of metal electrode deposition and contribute to a complex interfacial region that is highly dissimilar from the neat ionomer. We compute the bending moment of the IPMC from the solution of a nonlinear one-dimensional modified Poisson-Nernst-Planck system, associated with stretching-controlled counterion motion through the thickness. For small static deformations, we present a semi-analytical solution based on the method of matched asymptotic expansions. Our findings suggest that the linearity of IPMC actuation in a broad voltage range should be attributed to the interplay of two competing nonlinear phenomena, associated with Maxwell stress and osmotic pressure.

9430-16, Session 4
Development and characterization of an IPMC hair-like transducer

Barbar J. Akle, Elio Challita, Nady Khairallah, Lebanese American Univ. (Lebanon)

Hair-like sensors are very common in natural and biological systems. Such sensors are used to measure acoustic pressures, fluid flows, and chemical concentrations among others. Hair-like actuators are also used to control fluid flows and perform temperature management. This study presents a manufacturing technique for a hair-like IPMC transducer. A thorough study is presented on the building process of the sensor optimized using Taguchi design of experiments. The method used to control the diameter

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and the electrodes thickness of the transducer is developed. The sensing and actuation behavior of the manufactured transducers are experimentally characterized. Relation between the transduction performance and the hair geometry is established.

9430-17, Session 4

Development of a micro-scale circuit for low-current tethering applications of cylindrical IPMC actuators

Jameson Lee, Woosoon Yim, Kwang Jin Kim, Univ. of Nevada, Las Vegas (United States)

IPMCs are ideal as micro-scale actuators due to their small size, low-voltage requirement, high-strain rate, and fast response. One disadvantage of using these materials as actuators is their high-current draw. This study aims to address high-current draw in IPMC applications by proposing a novel IPMC mount. The mount would contain an embedded circuit that would receive charge through low-current lines, and promote discharge to an IPMC at a high-current during actuation. The proposed circuit would store incoming charge using a supercapacitor. Transistor to transistor logic would be employed to both actuate and charge the IPMC.

9430-18, Session 5

Robust position control for a DEAP stack-actuator

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

Transducers based on dielectric electroactive polymers (DEAP) use the electrostatic pressure to convert electrical energy into mechanical energy or vice versa. Besides an intelligent setup of the transducer depending on the application, a power electronics that provides output voltages in the kilovolt range is required to achieve electric field strengths in the range of 50V/ μm for a sufficient actuation. For this purpose, here a bidirectional flyback-converter is considered to charge and discharge a DEAP transducer with high efficiency.

To use a DEAP actuator for positioning applications, multilayer technologies increase the absolute deformation or force of the actuator. Thus, here a DEAP stack-actuator is taken into account. Based on the characteristic behavior of the flyback-converter and the electromechanical coupling of the DEAP stack-actuator a dynamic model is required to determine the deformation of the actuator. Within this contribution, the model of the overall system is derived to design a closed loop position control.

Since the flyback-converter can charge or discharge a constant energy increment the design of a nonlinear switching controller is preferable. Furthermore, due to electromechanical coupling and the resulting dependence of the electrical parameters on the mechanical state either an adaptive or a robust controller should be chosen for a high control precision. Therefore, based on the derived model a nonlinear position controller with high robustness against parameter uncertainties and variations is designed.

Based on a prototype of the bidirectional flyback-converter and automated manufactured DEAP stack-actuators, the position controller is experimentally validated.

9430-19, Session 5

Electromechanical characterization of a new synthetic rubber membrane for dielectric elastomer transducers

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Sant'Anna (Italy)

Dielectric Elastomers (DE) are incompressible polymeric solids that experience finite elastic deformations and are electrically non-conductive. Stacking multiple DE films separated by compliant electrodes makes a deformable capacitor transducer, namely a DE Transducer (DET), which can expand in area while shrinking in thickness and vice versa. DETs can be used as solid-state actuators, sensors and generators.

The development of an effective DET requires the accurate knowledge of the constitutive behavior of the employed DE material. In this context, this paper reports the experimental results of the electromechanical characterization of a new synthetic dielectric elastomer membrane. With regard to electrical behavior, dielectric susceptibility, dielectric strength and electrical resistivity are considered together with their strain-induced dependencies. With regard to mechanical behavior, both elastic and inelastic responses are considered that include hyperelasticity, plasticity, viscosity and Mullins effect.

The performance of the considered membrane in a DE generator are also presented to demonstrate its potentialities as compared to other known elastic dielectrics such as silicone elastomers, acrylic elastomers and natural rubber.

9430-20, Session 5

Silicone films with high stiffness and increasing permittivity through dipole-grafting

Martin Blümke, Michael Wegener, Hartmut Krüger, Fraunhofer-Institut für Angewandte Polymerforschung (Germany)

Dielectric elastomer actuators (DEAs) enable a wide range of interesting applications since they are soft, lightweight, low-cost and have direct voltage control. However, one of the main obstacles to their wide-spread implementation is their high operating voltage, which tends to be several thousand volts. The operating voltage can be lowered by reducing the thickness, increasing the permittivity (ϵ_r) or lowering the stiffness of the elastomer. Recently, we offered a method to increase the permittivity of silicones from 3 to 6 simultaneously connected with significant stiffness reduction by dipole-grafting down to an elastic modulus E of 300 KPa. For some applications it might be beneficial to work with higher stiffness. By modifying the dipole grafting process it is possible to obtain a similar increase in permittivity, however, also an increase of the elastic modulus to about 1-2.2 MPa. Within the modified dipole grafting process, the organic dipole molecule N-allyl-N-methyl-4-nitroaniline was used for preparation of silicone films with dipole concentrations in the range of 5 to 25 wt%. To demonstrate the influence of the dipoles on the permittivity, we introduced N-allyl-N-methyl-aniline, which possess a high molecular similarity but a lower dipole moment. This allows the production of films with the same principle molecular structure, but with a lower permittivity ($\epsilon_r = 3.3$) and increased elastic stiffness ($E = 5$ MPa). The chemical, mechanical, electrical and electromechanical properties were thoroughly characterized and will be discussed.

9430-21, Session 5

Large-Strain, High-Stress Tubular Dielectric Elastomer Actuator with High Pre-stretch and Oil Encapsulation

Gih-Keong Lau, Desmond D. T. Tan, Thanh-Giang La, Nanyang Technological Univ. (Singapore)

Typically a rolled dielectric elastomer actuator (DEA) is prepared by rolling up a flat DEA which is made of pre-stretched membrane of dielectric elastomer. However, the rolled ones perform much poorer than the flat ones, in terms of axial strain and electrical breakdown strength. Typically,

the rolled ones produce not more than 37.3% axial strain; while the flat ones reported greater than 100% axial strain. Due to relaxation from hoop pre-stress, a rolled DEA is subjected to severe necking and non-homogenous deformation, and thus more prone to electrical breakdown. This study shows that oil encapsulation helps a single-wound roll realize its fullest actuation potential by suppressing pre-mature breakdown.

Oil encapsulation clearly raises the electrical breakdown voltage of the same prepared tubular DEA. Under isotonic test, oil-encapsulated tubular DEAs sustain up to up to 712.0 MV/m electric field, 50% higher than that of the dry DEAs. As a result, the oil-encapsulated can produce an axial strain of up to 50%. Meanwhile, it produces an isometric stress up to nearly 0.6 MPa, 114% higher than that of the dry one. On the other hand, the present dry tubular DEAs without oil encapsulation produce also a very large axial strain of up to 80.2% at high field of 476.0 MV/m, which is made possible by large hoop pre-stretch ratio of 6 and the use of fine graphite powder as compliant electrodes.

9430-22, Session 5

Thermodynamics and instability of dielectric elastomers

Liwu Liu, Yanju Liu, Jinsong Leng, Harbin Institute of Technology (China)

Dielectric elastomer is a kind of typical soft active material. It can deform obviously when subjected to an external voltage. Dielectric elastomers usually fail when electromechanical instability, snap-through instability or electrical breakdown occurs. If the failure can be avoided, there will be adiabatic temperature change and isothermal entropy change in dielectric elastomer. Here, we investigated the stability (electromechanical stability, snap-through stability), failure (electrical breakdown, loss of tension, rupture, instability), voltage induced deformation, entropy change and temperature change of dielectric elastomers. Considering the influence of temperature, we established the temperature, polarization and deformation coupling thermodynamical free energy model to calculate the electric field induced deformation, adiabatic temperature change and isothermal entropy change of dielectric elastomers. These simulation results are helpful for guidance of the design and fabrication of excellent transducer based on dielectric elastomers.

9430-88, Session PTues

Performance analysis of the polymeric structures applied for flexible solar cells

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The effects on the flexible EAP-HC substrates treated by different manners have been investigated as contact angle technique is a known method for assessing the cleanliness of the substrates. The ITO films are deposited at room temperature by DC magnetron sputtering from a ceramic target of a 90% In - 10% Sn alloy. It is found that optical properties of the ITO (resistivity and carrier concentration) are critically dependent on the flow ratio of Ar to O₂ during sputtering. Even though surface of the ITO film is treated by detergent treatment, we can obtain the ITO film with a resistivity of 5.6 \times 10⁻⁴ Ω -cm and average optical transmittance of 84.1% in the visible-region. The cleanliness can also be monitored by complementary XPS. Detergent can significantly enhance the degree of crystalline of organic solar cells. In addition, the ITO film shows morphological structure and a very smooth surface area. In conclusion, we have investigated the relationship between the methods used to clean ITO surface and the work function using photoelectron spectrometer. ITO surface cleaned by detergent for 5 minutes and by UV ozone for 20 minutes results in significant increase of the WF value (5.22 eV). The optimal surface treatment (detergent for 5 min and UV ozone for 20mins) increases conversion efficiency for Al/ P3HT:PCBM/ PEDOT:PSS/ ITO/ EAP-HC organic solar cell with conversion efficiency of 2.12% being the best treatment. These results show that polymer-based materials and manufacturing techniques

are suitable for flexible solar-cell applications in energy harvesting. Using best treatment, 36.6% enhancement in J_{sc} and 92.7% enhancement in conversion efficiency over the untreated organic solar cell have been demonstrated.

9430-89, Session PTues

Electromechanical and electrostrictive behavior of polyurethane: effects of urethane type

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The electromechanical behavior of thermoplastic elastomer polyurethane (TPE-PU) was investigated under the effects of urethane type (ester and ether-types) and soft-hard segments at various electric field strengths and temperatures. The highest dielectric constant, electrical breakdown strength, and specific conductivity belonged to the ester-type polyurethane (LPR matrix), while the lowest values were obtained from the ether-type polyurethane composing predominantly with the soft-segment (E 80A matrix). Under the electric field strength in the range between 0 and 2 kV/mm, the LPR matrix attained the storage modulus sensitivity ($\Delta G'/G'0$) up to 2 at 2 kV/mm. For the temporal response, the polyurethanes behaved with good reproductively (number of cycles >105 times) and with very good recoverability. The steady state behavior can be attained at the first actuation and at the electric field strength of 1 kV/mm. Furthermore, the storage modulus (G') showed linearly negative responses with increasing temperature. In the deflection experiments, the deflection distance and the dielectrophoresis force increased monotonically with increasing electric field strength. All of the TPE PU possessed very fast response times for activation (<10 s.) and deactivation (<5 s.). TPE-PU material was systematically shown here to be a potentially good actuator material with high efficiency based on the electrostrictive performance data obtained.

9430-90, Session PTues

Electroactive ionomeric fibers for cilia-based underwater robotic systems

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

In this study, we report on the development of electroactive ionomeric fibers that can be utilized to create cilia-based robotic systems for aquatic applications. Recently, locomotion of biological cells and microorganisms through unique motion of cilium (flagellum) has received great interest. It is envisioned that artificial cilia can be effective strategy for maneuvering and sensing in small-scale bio-inspired robotic systems. Herein, we report biomimetic cilia fibers that actuate in aqueous medium when subjected to an external electric field of about 5 V/mm. The fibers are fabricated from Nafion precursor resin through melt-drawing process and have a circular cross-section with a diameter of 30-70 μ m. When properly activated (hydrolyzed) and subjected to an electric field with switching polarity, the ionomeric fibers exhibit cyclic actuation with adequate response time (0.05-5 Hz). The preliminary experimental results are presented and discussed to demonstrate the performance and feasibility of biomimetic cilia-based microactuators.

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9430-91, Session PTues

Comprehensive modeling of ionic polymer-metal composite actuators based upon variable surface resistance and underlying physics of the polymer

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In this study, we theoretically predict and experimentally investigate the electro-mechanical response of the IPMC actuator. A physical model of IPMC actuator is proposed. The model combines the effect of surface resistance change during the deformation and the physics of the polymer membrane. IPMC samples were prepared. Experiments were performed to test the samples. The results show that the theoretical model can accurately predict the actuating performance of IPMC. Current study may be beneficial for the comprehensive understanding of the surface electrode effect on the IPMC actuator.

9430-92, Session PTues

Comparison of custom manufacturing methods of Nafion to commercially available Nafion for the purpose of ionic polymer-metal composite (IPMC) applications

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Since the selection of commercially available Nafion geometries is limited, flexibility to create any thickness or shape through custom manufacturing techniques is highly desired in ionic polymer-metal composite (IPMC) applications. The objective of this study is to manufacture both cylindrical and strip IPMCs by custom manufacturing methods and to compare their material characteristics and mechanoelectric performance properties to IPMCs manufactured using preformed commercially available Nafion. The custom manufacturing methods used in this study are polymer extrusion, injection molding, and hot press method to form Nafion polymer beads into the desired shape (ie. strip and tube). The Nafion shapes are then made into IPMCs through electroless plating. The custom made IPMCs are then put through a series of mechanoelectrical performance tests. The results from the material characterization and performance tests of the custom-made IPMCs are compared to characterization and performance results of the IPMCs made from commercially available Nafion geometries.

9430-93, Session PTues

Actuation behavior of flexible sulfonated polyaniline-polyimide films

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In order to improve the processability and mechanical strength of polyaniline (PANI), suitable amounts of in-house organo-soluble polyimide (PI) were blended with sulfonated PANI (PANI-S). The homogeneous mixture was cast on a glass substrate and cured at 80 degree C to obtain a series of flexible and free-standing films with various ratios of PANI-S and PI. The conductivity of those low-temperature processed PANI-S/PI films after HCl-doping is in the range of 10^{-6} to 10^{-2} S/cm. In addition to the excellent doping and de-doping properties, tunable electrical conductivity and high pH-sensitivity, the resultant PANI-S/PI films exhibit ultrafast

bending motion with the stimulus of water or acetone vapors at either side of the film. The bending direction and degree are both affected by the types of vapor and the concentration of sulfonic groups in the film. Upon the removal of the stimulus, the film instantaneously returns to its original state. The presence of PANI-S in PI matrix creates unique microstructure and enhances the rigidity of films. The preliminary results indicate that those features lead to the movement of polymer chains and consequently the reversible actuation behavior.

9430-94, Session PTues

Prediction of rate dependent deformation of dielectric elastomer using artificial neural network

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Dielectric elastomer has been recognized as a potential actuator material applicable in many disciplines including mechatronics, robotics, automation, medicine, biomimetics, biotechnology, fluidics, optics and acoustics due to its high dielectric strength, low elastic modulus to induce large actuation strain and high specific energy density. But realization of this material in actuator technology is still challenging due to its significant deterioration of mechanical and electrical properties over time and unfavorable environmental conditions. Previous studies show that the prediction of viscoelastic or rate-dependent deformation poses to be one the most vital challenges for successful application of this potential dielectric elastomer actuator technology. In this work, uniaxial tensile tests are performed on dielectric elastomer at various strain rate conditions. An artificial neural network (ANN) is developed to predict the rate dependent large deformation. The inputs of the ANN model are strain rate and engineering strain, while the output of the model is engineering stress. The model is successfully trained at different deformation domains by Levenberg-Marquardt training algorithm. ANN model can learn from the experimental data without knowing the complex nonlinear relation among the variables, reproduces it to prescribed accuracy, and even predicts beyond the range of training. Hence, ANN model can be a better alternative to theoretical constitutive models for nonlinear viscoelasticity of elastomeric materials. The performance of the trained neural network has been validated with new experimental results at intermediate strain rates. The predictions of ANN model are found to be in good agreement with the experimental results.

9430-95, Session PTues

A novel approach of fabricating dielectric elastomer actuator with interpenetrating double network

Ji Hyeon Lee, Bismark Mensah, Gi-Bbeum Lee, Yujin So, Changwoon Nah, Chonbuk National Univ. (Korea, Republic of)

For an efficient application of dielectric elastomer actuator (DEA) for haptic function, a lower driving voltage and high reaction speed are essential. Although many works have been done on driving voltage of silicon (SR) and acrylic (AR) rubbers but further research is needed to reduce the initiation voltage.

In this study, the SR-based DEA was modified by fluorine rubber (FKM) having higher dielectric constant of -12 to lower the actuating voltage via an interpenetrating network (IPN) formation by swelling method. Two different procedures of the IPN formation were used:

Method 1: A SR sheet vulcanizate was first swollen in FKM solution. After drying, fluorine elastomer network was crosslinked and the sheet was stretched bi-axially from 50 to 500%. Then carbon grease was painted on both side of the sheet.

Method 2: A SR sheet vulcanizate was stretched bi-axially from 50 to 300% and it was swollen in FKM solution. After drying, fluorine elastomer network was crosslinked and then carbon grease was painted on both side of the sheet.

The dielectric constant was measured as a function of frequency. The actuation performance was also measured. The morphology and structure of the two networks was characterized using scanning electron microscopy (SEM). The dielectric constant was decreased with increased bi-axial stretching. In the case of Method 2, the dielectric constant was initially decreased and then increased with further increasing of the bi-axial stretching. The driving voltage of DEA based on Method 2 was found to be much lower than that of Method 1.

9430-96, Session PTues

Large-area manufacturing method of dielectric elastomer stack transducers (DESTs) made from pre-fabricated dielectric films

Tanja Grotepaß, Florentine Förster, Holger Moessinger, Helmut F. Schlaak, Technische Univ. Darmstadt (Germany)

Multilayer dielectric elastomer stack transducers (DESTs) are a promising new transducer technology with many applications in different industry sectors, like medical devices, human-machine-interaction, etc. Stacked dielectric elastomer transducers show larger thickness contraction driven by lower voltages than transducers made from a single dielectric layer. Traditionally multilayered DESTs are produced by repeatedly cross-linking a liquid elastomeric pre-polymer into the required shape. Our recent research focusses on a novel fabrication method for large-area stack transducers with an area over 200 x 300 mm by processing pre-fabricated elastomeric thin films of less than 50 µm thicknesses. The thin films are provided as two- or three-layer composites, where the elastomer is sandwiched between one or two sacrificial liners. Separating the elastomeric film from the residual layers and assembling them into dielectric elastomer stack transducers poses many challenges concerning adhesion, since the dielectric film merely separates from the liner if the adhesive forces between them are overcome. Conversely, during the assembly of a dielectric elastomer stack transducer, adhesive forces have to be established between two elastomeric layers or between the dielectric and the electrode layer. The very low Young's modulus of at least one adhesion partner requires suitable means of increasing the adhesive forces between the different adhesive layers of a dielectric elastomer stack transducer to prevent a delamination of the transducer during its lifetime. This work evaluates different adhesion methods, like corona discharge, primers and liquid adhesives and their applicability in the production of large scale DESTs made from pre-fabricated elastomeric films.

9430-97, Session PTues

Energy harvesting based on dielectric elastomers: maximum converted energy, dissipation, and wave power generator

Xiongfei Lv, Liwu Liu, Yanju Liu, Jinsong Leng, Harbin Institute of Technology (China)

Dielectric elastomer is a kind of smart soft material. It is able to produce large deformation under mechanical force and electric field, so that it can achieve mutual conversion between mechanical energy and electrical energy. Based on this property, dielectric elastomer is widely used in energy harvesting field. In this paper, we firstly analysed the influence of constitutive relations under different superelastic models (Gent and Neo-Hookean) based on both theoretical and experimental study. Secondly, we depicted the allowable areas in force-displacement and voltage-charge plane based on different failure modes, then calculated the theoretical

maximum converted energy and the achievable maximum converted energy. Thirdly, we analysed the energy dissipation in energy harvesting process, taking into account two conditions: viscoelastic and leakage current, in which the viscoelastic can lose the input mechanical energy and the leakage current can lose the output electrical energy. Finally, we designed and assembled an ocean wave power generator, it can light several diodes through a designed energy harvesting circuit, then we measured and calculated the output electrical energy and compared it with the theoretical value.

9430-98, Session PTues

Facile hydrophobicity/hydrophilicity modification of SMP surface based on metal constrained cracking

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This study demonstrates an easy way to change surface characteristics, the water contact angle on polystyrene based shape memory polymer (SMP) surface alters before and after cracking formation and recovery. The contact angle of water on the original SMP surface is about 93.4 degree, after coating with aluminum and then kneading from side face at glass transition temperature T_g , cracking appeared both on Al film and SMP; cooling down and removing the Al film, cracks remain on SMP surface while the contact angle reduced to about 37.6 degree. When reheated above T_g , the cracks disappeared, and the contact angle go back to about 93 degree. The thin Al film bonded on SMP surface was coated by spurting, that constrains the deformation of SMP. Heating above T_g , there are complex interactions between soft SMP and hard metal film under kneading. The thin metal film cracked first with the considerable deformation of soft polymer, whereafter, the polymer was ripped by the metal cracks thus polymer cracked as well. Cracks on SMP can be fixed cooling down T_g , while reheating, cracks shrinking and the SMP recovers to its original smooth surface. The water contact angle changes with the cracking formation and vanishing during the above process, while equivalent samples without crack formation (no kneading) showed no change in contact angle. Furthermore, the experimental cycle is repeatable. This study demonstrates an easy way to change surface characteristics of SMP and put forward a potential application of SMP for recyclable cell/molecule capture and release.

9430-99, Session PTues

Development of a soft robot using self-sensing IPMC integrated with Gallium-Indium alloy

Sarah Trabia, Viljar Palmre, Kwang Jin Kim, Woosoon Yim, Univ. of Nevada, Las Vegas (United States)

IPMCs have the ability to produce many types of deformations. This allows for the actuator to be used in applications where complex movement is needed. To improve the precision of IPMC actuation, a feedback circuit based on gallium-indium (GalIn) alloy is integrated into the actuator, creating a self-sensing IPMC. The alloy is used as a strain gage within the IPMC, giving the actuator information about its own movements to accurately reach the desired motion. Typical resistive strain gages tend to break after a long period of use or from fatigue, causing the accuracy of the data being read to decrease over time. GalIn is flexible as a solid and can work well with the IPMC as it deflects to different positions. A PID controller will use the information from the alloy for a feedback loop and correct the motion of the IPMC.

9430-100, Session PTues

Ionic polymer-metal composite based on anionic functionalized polysulfone membrane

Viljar Palmre, Univ. of Nevada, Las Vegas (United States); Angela D. Mohanty, Chulsung Bae, Rensselaer Polytechnic Institute (United States); Kwang Jin Kim, Univ. of Nevada, Las Vegas (United States)

This paper describes an ionic polymer-metal composite (IPMC) fabricated with aromatic polysulfone-based anion-exchange membrane. While extensive research on IPMCs has been conducted with various cation-exchange polymers, particularly with perfluorinated sulfonic acid ionomers, very few studies have been done with different anion-exchange polymers. Herein, we investigate the transduction properties of the IPMC prepared with anionic trimethylbenzylammonium-functionalized polysulfone membrane. This functionalized polysulfone is thermally and chemically stable, and easy to modify and fabricate. Electroless plating method for plating the membrane with platinum electrodes is developed. Experimental results describing the actuation and mechano-electrical sensing response of the prepared anionic membrane-based IPMC are reported and discussed.

9430-101, Session PTues

Design and fabrication of compliant proximity-tactile sensor using carbon micro coils

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This paper presents novel stretchable and flexible proximity-tactile sensor (PTS) using Carbon Micro Coils (CMC) based on silicone (HR-G700). The PTS consists of the pair of multiple positive electrodes and one ground electrode, which are composed of the single cell of 4 by 4 arrayed sensor. The proximity and tactile sensing capability are obtained through CMC layer composing a dielectric material, and conductive silicone. And, the PTS has two layers. First layer is constituted of 16-active and 1-ground electrodes using conductive silicone on the silicone rubber substrate. The other layer is the 4 by 4 arrayed dielectric layer using the mixture of 5% CMC and silicone (HR-G700). The sensing area is 40?40 mm², and its thickness is 2.3 mm. The two layers were fabricated by molding and casting methods. To evaluate tactile sensing and proximity sensing, experiments was conducted. As shown in the figure, the prototype was fabricated and we could measure the normal force from 0 to 0.5 N as well as a distance up to 200 mm.

9430-102, Session PTues

Poleable nanoparticles as fillers towards non-linear optically active actuators

Yee Song Ko, Frank A. Nüesch, Dorina M. Opris, EMPA (Switzerland)

Research on dielectric elastomer actuators (DEAs) focuses mainly on the enhancement of the permittivity (?) as it linearly increases actuation displacement. Most recent developments include the grafting of polar molecules onto the elastomer backbone to increase the intrinsic matrix permittivity. In the field of non-linear optics, the poling of polymers containing polar molecules is a well-established method to create non-linear optical (NLO) materials. The alignment of the dipole in an amorphous polymer is done in a high electric field at temperatures above its glass transition temperature (T_g) followed by freezing of the oriented material by

cooling below T_g while the electric field is maintained. Poleable elastomers can be realized by blending high T_g polymeric nanoparticles into an elastomer matrix.

Synthesis and characterization of the nanoparticles, as well as preliminary results of a poleable DEA are being presented. It will be shown, that a material with a novel mixture of mechanical and optical properties can be obtained using this route.

9430-103, Session PTues

Natural melanin composites by layer-by-layer Assembly

Tae Sik Eom, Inha Univ. (Korea, Republic of)

Electroceuticals are recently demonstrated concept that broadly include all of the bioelectronic medicine except chemical and mechanical treatment. For that, development of electrically conductive and biocompatible materials are essential. To overcome this issue, naturally occurring conducting material such as melanin, ?-carotene, indigo, tyrian purple, and beyond are now receiving attention because their conjugate backbone structures provide conducting pathways. Among them, we used natural melanin from Sepia officinalis ink and fabricated the biocompatible conducting composites of melanin by layer by layer assembly (LbL) methods and electrochemical deposition method with other polymers such as poly(vinyl alcohol) (PVA), poly(diallyldimethylammonium) (PDAA), poly(3,4-ethylenedioxythiophene) (PEDOT) and synthetic melanin. We further demonstrate the nanostructures, electrical properties, and biocompatibility of resulting composites by scanning electron microscope (SEM), electrochemical impedance measurement, and in vitro cell test of PC12, respectively.

9430-104, Session PTues

Property modification of Nafion via polymer blending

Jungsoo Nam, Dong-Chan Lee, Viljar Palmre, Kwang Jin Kim, Univ. of Nevada, Las Vegas (United States)

Nafion has been predominantly used as synthetic ionomer for IPMCs, however further property improvements have been limited due to its resistance to chemical modification and lack of processability. In this work, we investigated the feasibility of property modification of Nafion by blending it with other functional polymers. We chose a ground-up approach to fabricate blend films from homogeneous solutions of Nafion and polymers such as poly(acrylic acid), poly(vinyl alcohol), and poly(amic acid) via a solvent casting. Poly(amic acid)/Nafion blend film was further converted to polyimide/Nafion using a thermal treatment. The electromechanical and mechano-electrical responses of the newly blended materials in their form of IPMC were presented.

9430-105, Session PTues

Fabrication and characterization of aligned electroactive conducting polymer nanotubes and nanofibers for neural application

Mohammad Reza Abidian, Ning Ye, The Pennsylvania State Univ. (United States)

Electroactive conducting polymers (EACP) such as poly(pyrrole) and poly(3,4-ethylenedioxythiophene) (PEDOT) have been widely employed in biomedical applications including bioelectronics, drug delivery systems, and bioactuators. Recently EACP have been considered for neural interfaces and neural prosthetic devices in particular neural recording and axonal

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regeneration. Axons are guided along specific pathways using physical and chemical guidance cues in their extracellular matrix. The aim of this study is to fabricate and characterize aligned EACP nanofibers and nanotubes for axonal regeneration.

Here we report a templating method for fabrication of aligned PEDOT nanofibers and nanotubes on a gold substrate. The fabrication process includes electrospinning of poly (L,lactide) (PLLA) and poly(lactide-co-glycolide) (PLGA) nanofibers followed by electrochemical deposition of PEDOT around electrospun nanofibers using applied current density 0.5 mA/cm². We have characterized the surface topography, alignment, and size of PEDOT nanofibers and nanotubes using scanning electron microscopy (SEM). SEM images revealed that while the inner diameter of nanofibers and nanotubes is a function of electrospinning parameters (i.e. flow rate, voltage, distance between syringe tip and substrate), the surface topography is a function of electrochemical polymerization parameters (i.e. applied current density and time) We have measured electrical properties of PEDOT nanofibers and nanotubes using impedance spectroscopy and cyclic voltammetry. The impedance of substrates decreased and capacity of charge transfer of substrates increased after formation of PEDOT nanofibers and nanotubes. We will investigate the effect of alignment and electrical stimulation of PEDOT nanostructures on the rate of axonal regeneration in vitro.

9430-106, Session PTues

Cylindrical conducting polymer-based trilayer actuator for catheter application

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Minimally invasive surgery and catheterization have wide range of application in biomedical treatment of patients due to their unique advantages including short recovery and hospitalization times, and low pain and cost. Issues with the current methods, such as poor controllability of the guide wire, was the motivation behind this research to replace the combination of the guide wire and passive catheter with an "active catheter". In this paper, we report on the design and fabrication of a high aspect ratio cylindrical actuator composed of a combination of double-network and conducting polymers. Double network polymer is used as the catheter body and ion reservoir. A conducting polymer layer is deposited onto this cylindrical substrate to form a bending actuator similar to a conventional trilayer, but with a circular cross-section. In performing lithography on such a high aspect ratio (long, thin) cylindrical shape it is very challenging to pattern uniformly and cleanly. The conducting polymer layer is instead patterned by laser and electrical discharge micromachining (EDM) processes. No lithography, chemical etching or photoresist is used. Laser micromachining is shown to be preferable to EDM due to its faster machining and ability to remove conductive, but does not have the built-in ability to remove only the conductive materials, and thus requires careful monitoring. The 20 μm width of the laser beam with good controllability in the depth of material removal and patterning makes it a suitable fabrication process. The result is an active catheter of outer of 0.7 mm with the desired ability to bend with a radius of curvature of less than 15 mm.

9430-107, Session PTues

Variable stiffness structure using nylon actuators arranged in a pennate muscle configuration

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Emerging compliant variable impedance actuators provide versatile solutions to complex and sophisticated mechanical actuator/sensor systems. A new biomimetic structure of nylon actuator is presented that imitates the human pennate muscle using 16 silver coated nylon coiled fibres arranged attached to a tendon at an angle of 20°. In the actuator response, as the current passes through each nylon coils, it provides 5MPa stress and near 20% strain. Each fibre is independently switched ON and Off with a transistor so that each element can be recruited in time and also the amount of input power controlled with pulse width modulation (PWM) techniques. Unlike classic stiff actuators including electrical motors, the intrinsic spring behaviour of nylon coil actuator both in active and passive state enables to store energy and decouple inertia. It is observed that the spring constant of material varies from in passive state, 842 N.m⁻¹ at resonate frequency of 2.3Hz to 1480 N.m⁻¹ with resonate frequency of 3.06 Hz in active state where all the fibres are switched ON.

9430-108, Session PTues

A multi-segment soft actuator for biomedical applications based on IPMCs

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With rapid progress of biomedical devices towards miniaturization, flexibility, multifunction and low cost, the restrictions of traditional mechanical structures become particularly apparent, while smart materials become research focus in broad fields. As one of the most attractive smart materials, Ionic Polymer-Metal Composite (IPMC) is widely used as artificial muscles and actuators, with the advantages of low driving-voltage, high efficiency of electromechanical transduction and functional stabilization. In this paper, a new structure of multi-segment tube actuator with column-shaped IPMCs embedded, was proposed, designed and tested. Firstly, a 3D Finite Element model was employed to optimize the tube structure with embedded IPMCs. Secondly, the column-shaped IPMCs were fabricated by the solution casting method, reducing plating method and cut into shapes successively. The multi-segment tube was shaped by casting and curing silicon in a plastic mold fabricated by 3D printing. Then, a new controlling method was introduced to realize the intuitive mapping relationship between the tube actuator and the joystick manipulator. The controlling circuit was designed and tested. Finally, the multi-degree-of-freedom tube actuator with 2 segments column-shaped IPMCs was implemented and all-direction bending movements were achieved, which could be a promising actuator for biomedical applications, such as endoscope, catheterism, laparoscopy and the surgical resection of tumors.

9430-109, Session PTues

Novel composite piezoelectric material for energy harvesting applications

Giedrius Janusas, Asta Guobiene, Arvydas Palevicius, Igoris Prosycevas, Sigita Ponelyte, Valentinas Baltrusaitis, Rokas Sakalys, Kaunas Univ. of Technology (Lithuania)

Past few decades were concentrated on researches related to effective energy harvesting applied in modern technologies, MEMS or MOEMS systems. There are many methods for harvesting energy as, for example, usage of electromagnetic devices, but most dramatic changes were noticed in the usage of piezoelectric materials in small scale devices. Major limitation faced was too small generated power by piezoelectric materials or high resonant frequencies of such small-scale harvesters. In this research, novel composite piezoelectric material was created by mixing PZT powder with 20% solution of polyvinyl butyral in benzyl alcohol. Obtained paste was screen printed on copper foil using 325 mesh stainless steel screen and dried for 30 min at 100°C. Polyvinyl butyral ensures good adhesion and flexibility of a new material at the conditions that requires strong binding. Five types

of a composite piezoelectric material with different concentrations of PZT (40%, 50%, 60%, 70% and 80 %) were produced. As the results showed, these harvesters were able to transform mechanical strain energy into electric potential and, v.v. In experimental setup, electromagnetic shaker was used to excite energy harvester that is fixed in the custom-built clamp, while generated electric potential were registered with USB oscilloscope PICO 3424. The designed devices generate up to 80 V at 50 Hz excitation. This property can be applied to power microsystem devices or to use them in portable electronics and wireless sensors. However, the main advantage of the created composite piezoelectric material is possibility to apply it on any uniform or nonuniform vibrating surface and to transform low frequency vibrations into electricity.

9430-110, Session PTues

Electrical properties of nanoscale metallic thin film coatings on dielectric elastomer

Md. Shahnewaz Sabit Faisal, Zhihang Ye, Zheng Chen, Ramazan Asmatulu, Wichita State Univ. (United States)

No Abstract Available

9430-111, Session PTues

Electrospun nanofibers for improved electrical and thermal conductivities of fiber-reinforced composites

Ibrahim M. Alarifi, Abdulaziz Alharbi, S. Khan, Ramazan Asmatulu, Wichita State Univ. (United States)

No Abstract Available

9430-112, Session PTues

Inkjet-printed MWCNT electrodes for dielectric elastomer actuators

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Dielectric elastomer actuators (DEA's) offer promising applications as soft and light-weight electromechanical transducers. It is known that beside the dielectric material, the electrode properties are of particular importance regarding the DEA performance. Therefore, in recent years various studies have focused on the optimization of the electrode in terms of conductivity, stretchability and reliability. However, less attention was given to efficient electrode processing and deposition methods. In this study digital inkjet printing was used to deposit highly conductive and stretchable electrodes on silicone. Inkjet printing is a versatile and cost effective deposition method, which allows depositing complex-shaped electrode patterns with high precision. The electrodes were printed using a formulated ink based on industrial low-cost MWCNT. Experiments have shown that the strain-conductivity properties of the printed electrode are strongly depended on the deposition parameters like drop spacing and substrate temperature. After the optimization of the printing parameters, thin film electrodes could be deposited exhibiting conductivities of up to 25 S/cm without the need of any post-treatment. In addition, electromechanical tests with fabricated DEA's have revealed that the inkjet printed MWCNT electrodes are capable to self-clear in case of a dielectric breakdown.

9430-23, Session 6A

High speed electromechanical response of ionic microactuators (*Invited Paper*)

Cédric Plesse, Univ. de Cergy-Pontoise (France); Ali Maziz, Univ. de Cergy-Pontoise (France) and IEMN CNRS UMR-8520 (France); Caroline Soyer, Eric Cattan, Univ. de Valenciennes et du Hainaut-Cambrésis (France); Frédéric Vidal, Univ. de Cergy-Pontoise (France)

Ionic EAP micromuscles converting electrical energy into micromechanical response in open-air are presented. Translation of small ion motions into large deformations in bending microactuator and its amplification by fundamental resonant frequency are used as tools to demonstrate that small ion vibrations can still occur at frequency as high as 1000 Hz in electrochemical devices. These results have been achieved through the microfabrication of ultrathin conducting polymer microactuators. First the synthesis of robust interpenetrating polymer networks (IPNs) has been combined with a spin-coating technique in order to tune and drastically reduce the thickness of conducting IPN microactuators using a pseudo "trilayer" configuration. Patterning of electroactive materials as thin as 6 μm is demonstrated with existing technologies, such as standard photolithography and dry etching. Electrochemomechanical characterizations of the micrometer sized beams are presented and compared to existing model. Moreover, thanks to downscaling large displacements under low voltage stimulation (+/- 4V) are reported at a frequency as high as 930 Hz corresponding to the fundamental eigenfrequency of the microbeam. Conducting IPN microactuators are then presenting unprecedented combination of softness, low driving voltage, large displacement and fast response speed which are the keys for further development of new MEMS. Finally, in order to avoid any manual handling a novel and tunable method will be presented. Considerations on contact positioning and direct integration will be discussed.

9430-24, Session 6A

Measuring blocking force to interpret ionic mechanisms within bucky-gel actuators

Karl Kruusamäe, Takushi Sugino, Kinji Asaka, National Institute of Advanced Industrial Science and Technology (Japan)

Bucky-gel laminates are straightforward tri-layer structures where polymeric electrolyte film is sandwiched between two compliant electrode layers of carbon nanotubes and ionic liquid. This kind of ionic and capacitive structures can be regarded as a type of electromechanically active polymers (EAP) that have the perspective of becoming soft bending actuators in the fields such as biomimetic robotics or lab-on-chip technology. A typical electromechanical step response of bucky-gel actuators in a cantilever configuration exhibits fast bending displacement followed by some reverse motion referred to as the back-relaxation. It has been proposed that the bending but also the back-relaxation of bucky-gel laminates occur due to the relocation of cations and anions within the tri-layer structure. A great number of modeling of ionic EAP materials aims to predict the amplitude of free bending or the blocking force of the actuator. However, as the bucky-gel laminates are viscoelastic, the relation from generated force to bending amplitude is not always straightforward - it can take the form of an integro-differential equation with speed (i.e. the amplitude and type of the input signal) and temperature (i.e. the electronic conductivity of the material and driving current) as just some of the parameters. In this study we measure blocking force and current of bucky-gel actuators to elaborate how both the cations and anions contribute to produce the time domain electromechanical responses registered under step voltage input.

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9430-25, Session 6A

A power-autonomous self-rolling wheel using ionic and capacitive actuators

Indrek Must, Toomas Kaasik, Inna Baranova, Urmas Johanson, Andres Punning, Alvo Aabloo, Univ. of Tartu (Estonia)

The mobile robotic appliances are often considered as a perspective field of use for the ionic electroactive polymer (IEAP) actuators; however, only a few real proof-of-concept-stage robots have been built previously, a majority of which are dependent on an off-board power supply. In this work, a spherical, power-autonomous robot, propelled by four IEAP actuators having carbonaceous electrodes, is constructed. The robot consists of a light outer section in the form of a hollow cylinder, and a heavy inner section, referred to as a rim and a hub, respectively. The hub is connected to the rim using IEAP actuators, which form "spokes" of variable length. The effective length of the spokes is changed via charging and discharging of the capacitive IEAP actuators and a change in the effective lengths of the spokes eventuate in a rolling motion of the robot. The constructed IEAP robot takes advantage of the distinctive properties of the IEAP actuators. The IEAP actuators transform the geometry of the whole robot, while being fully soft and compliant. The low-voltage IEAP actuators in the robot are powered directly from a single-cell lithium-ion battery, with no voltage amplification required. The charging of the actuators is commuted correspondingly to the robot's transitory position using an on-board control electronics. All control electronics and the power supply is contained in the hub section of the robot. The constructed robot is able to roll for an extended period on a smooth surface. The locomotion of the IEAP robot is analyzed using video recognition.

9430-26, Session 6A

Long-term response of ionic electroactive polymer actuators in variable ambient conditions

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

Ionic electroactive polymers or IEAPs are considered as an attractive actuators and sensors in various applications. Many of these polymer composites are designed to be used in an ambient environment. However, the ambient conditions may significantly vary depending on the seasonal or the geographical irregularities generated by the power of nature.

Taking the advantage of the fluctuating weather conditions of Estonia, different IEAP materials were continuously monitored for about 6 weeks. During this time the temperature and relative humidity of the ambient environment varied between 30-58 % and 23-29 °C respectively. The experiment was conducted in a non-air-conditioned lab facility where the parameters such as temperature, humidity, atmospheric pressure were registered. Concurrently the electromechanical impedance of 12 actuators of different types was registered. This setup brings out the degradation as well as the impact of the environment to the IEAP actuators. The analysis reveals that the performance of the actuators under research is highly correlated with the ambient relative humidity level which can increase or decrease their performance more than 2 times. Naturally, this issue needs to be addressed in characterization, modeling and control areas. In contrast, the changes of pressure and temperature appeared to have no significant influence on the performance of the actuators investigated.

9430-27, Session 6A

Long-term degradation of the ionic electroactive polymer actuators

Andres Punning, Indrek Must, Inga Põldsalu, Veiko Vunder,

Friedrich Kaasik, Alvo Aabloo, Univ. of Tartu (Estonia)

The research is focused on lifetime and degradation of ionic electroactive polymer actuators (IEAP). The lifetime measurements were carried out using identical methodology upon the different iEAP types. The experiment conducted with large number of samples shows that two types of degradation have serious effect to the IEAPs: degradation during operation and spontaneous self-degradation. Additionally, two ways of occasional damage decrease their overall reliability. In the scope of the current paper we describe degradation of two different types of IEAP actuators: with carbonaceous electrodes and with conducting polymer electrodes. Nevertheless, the common evolutionary trends, rather than the comparative data analysis or formal statistics of all particular samples, are given.

Analyzing the electromechanical and electrical impedances of the samples during their whole lifetime, we have found that observing the electric current gives adequate information about the degradation level of any IEAP actuator. Moreover, tracking this electrically measurable parameter enables detecting the occasional damage of an actuator.

This experiment of large scale gave several unexpected results. In the scope of the current paper we present just a few of them.

9430-28, Session 6A

High energy density interpenetrating networks from ionic networks and silicone

Liyun Yu, Søren Hvilsted, Technical Univ. of Denmark (Denmark); Anne L. Skov, Technical Univ. of Denmark (Dominica)

The energy density of dielectric elastomers (DEs) is sought increased for better exploitation of the DE technology since an increased energy density means that the driving voltage for a certain strain can be lowered in actuation mode or alternatively that more energy can be harvested in generator mode. One way to increase the energy density is to increase dielectric permittivity of the elastomer. A novel silicone elastomer system with high dielectric permittivity was prepared through the development of interpenetrating networks from ionically assembled silicone polymers and covalently crosslinked silicones. The system has many degrees of freedom since the ionic network is formed from two polymers (amine and carboxylic acid functional, respectively) of which the chain lengths can be varied, as well as the covalent silicone elastomer with many degrees of freedom arising from amongst many the varying content of silica particles. A parameter study is performed to elucidate which compositions are most favourable for the use as dielectric elastomers.

References:

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[2] L.González, L.Yu, S.Hvilsted and A.L.Skov. Dielectric properties of supramolecular ionic structures obtained from multifunctional carboxylic acids and amines. *RSC Adv.*, 2014, DOI: 10.1039/c4ra06195k.

9430-29, Session 6B

Nanoscale engineering of functional materials for high performance electrochemical actuator (Invited Paper)

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Ionic electroactive polymers (i-EAPs) have attracted great attention for a variety of biomimetic applications due to their impressive large-strain under low-voltage stimulation and air-working capability. However, subjected to the ions diffusion process, response for large strain is usually slow. It still remains great challenge to develop practically viable i-EAPs with

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both fast response and large deformation. Based on our previous work on carbon nanotube and graphene electrochemical actuators, here we show a novel i-EAP actuator using hierarchically architected nanocomposite electrodes in which vertically aligned nanosheets are grown on the surface of graphene-carbon nanotube conductive network. Large specific surface area and fast ion transmission channel of this porous electrodes enable us to achieve large deformation in quick switching response (18.4 mm per 0.05 s) to low voltage, and high durability upon 500,000 times continuous operations in air. The interesting results represent an important step towards artificial muscle technology where nanoscale interface coupling plays an important role in promoting the electromechanical conversion.

9430-30, Session 6B
Cross-linked carbon nanotubes buckygel actuators: an in-depth study

David Gendron, Istituto Italiano di Tecnologia (Italy); Grzegorz Bubak, Istituto Italiano di Tecnologia, Robotics, Brain and Cognitive Sciences Department (Italy); Alberto Ansaldo, Istituto Italiano di Tecnologia (Italy); Luca Ceseracciu, Istituto Italiano di Tecnologia, Smart Materials (Italy); Davide Ricci, Istituto Italiano di Tecnologia (Italy)

Recently, materials that can convert electrical energy into mechanical work have drawn great attention. Applications in robotics, tactile or optical displays and microelectrochemical systems are currently investigated. Likewise, interest in actuators devices is increasing toward applications where low voltage and low weight properties are required. One way to achieve such prerequisites is to combine the mechanical and electronic properties of carbon nanotubes (CNTs) with the stability and conductivity of ionic liquids. Indeed, the CNTs can be dispersed in ionic liquids to form hybrid composites also named bucky gels, thanks to the non-covalent (π - π stacking and cation- π) interactions. In our previous studies, we demonstrated an improvement in actuator performance whilst using cross-linked CNTs. Indeed, our preliminary results showed an increase in the capacitance together with a faster response of the actuator. At the time, these results were explained by an actuation mechanism model.

Herein, we designed new experiments in order to allow us to get a deeper insight in the effect the crosslinking process on the carbon nanotubes properties. Thus, we present a set of electromechanical and electrochemical data that shed light on the chemical modification of the CNTs, the different cross-linking strategies and also on the uses of cross-linked CNTs polymer blends. Finally, corresponding bucky gels actuators performances will also be discussed.

9430-31, Session 6B
Parylene coated carbon nanotube actuators for tactile stimulation

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Ionic liquid/carbon nanotube based actuators have been constantly improved in recent years owing to their suitability for applications related to human-machine interaction and robotics thanks to their light-weight and low voltage operation. However, while great attention has been paid to the development of better electrodes and electrolytes no adequate efforts were made to develop actuators to be used in direct contact with the human skin. Herein, we present our approach, based on the use of parylene-C coating. Indeed, owing to its physicochemical properties such as high dielectric strength, solvents resistance, biological and chemical inactivity/inertness, parylene fulfils the requirements for use in biocompatible actuator fabrication. In this paper, we study the influence of the parylene coating on the actuator performance. To do so, we analysed its mechanical and electrochemical properties. We looked into the role of

parylene as a protection layer that can prevent alteration of the actuator performance likely caused by external conditions. In order to complete our study, we designed a haptic device and investigated the generated force, displacement and energy usage.

9430-32, Session 6B
Development of 3D knitted CNT fabric as smart textiles

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An efficient procedure for the fabrication of highly stretchable (over 600% from the original size) knitted carbon nanotube (CNT) /spandex textiles has been developed. The fabrication has been carried out continuously by incorporating carbon nanotube sheet directly from a CNT forest into the polyurethane fibres during the knitting process. Resulting conductive highly stretchable 3D CNT knitted fabric has been produced. The mechanical and electrical properties of the knitted CNT/spandex fabric are very stable for over 1000 cycles of strain and/or bending. In addition the electrical resistivity of the knitted CNT/spandex structure is changed uniformly when it is exposed to strain and has an ability to be utilized as smart textiles. As-prepared structures have been used as strain gauges and the results indicated a great potential for applications including sensors, electronic textiles and wearable electrodes.

9430-33, Session 6B
Electrical actuation properties of epoxy shape memory polymers/flexible carbon nanotubes paper composite

Wenxin Wang, Yanju Liu, Harbin Institute of Technology (China); Yongyi Zhang, Suzhou Institute of Nano-tech and Nano-bionics (China); Jinsong Leng, Harbin Institute of Technology (China)

Shape memory polymers composites can be developed into multifunctional materials actuated by various methods, such as electricity, heat, light and solution. This paper aims to construct novel electro-induced epoxy based SMP composites. The shape recovery process of composite was carried out by electrical resistive heating generated by flexible carbon nanotubes paper. The flexible carbon nanotubes paper possesses super-flexible and excellent heat conductive properties which can serve as a conductive layer to transmit heat through the polymer. Recovery tests, then, were carried out at different applied voltage that varied from 1 volt to 9 volt. Investigation on shape recovery behavior reveals that increasing the applied voltage results in an increase in shape recovery speed and the recoverability of the composite approximated to 100% only taking 10 seconds under 9 volt. The temperature distribution and recovery behavior of samples were recorded with infrared video in a recovery test. After that, the structure of flexible carbon nanotubes paper was characterized by scanning electronic microscopy and the electrical volume resistivity of it was measured by four-point probe method. Epoxy shape memory polymers/ flexible carbon nanotubes paper composite is an example of a promising potential in a range of applications as actively moving polymers, which can undergo significant macroscopic deformation in a predefined manner between/among shapes in the presence of appropriate stimulus. The composite greatly enhance the performance of the SMPs and widen their potential applications.

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9430-34, Session 6B

CNT: polymer composite membrane as active device

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The Polymer CNT composites can be developed systematically dispersing CNT in different quantity and can be aligned across the thickness of the film. The CNT act as easy channel for the hydrogen molecules. The CNT are suspended in the polymer and organic solvent after sonication for 6 hours, the solution is allowed to evaporate in presence of electric or magnetic field. The CNT are found to align. In this paper we are presenting effect of CNT doping in polymer films, can be used as good separating media. The MWNT in 0.1-0.3wt% of PC and PMMA is doped and solution casted films 30-40 μ m. The gas permeability of these membranes is due to sorption diffusion process. These composites can be used as good gas sensors by depositing thin films on multi penetrating electrodes in longitudinal or transverse geometry.

9430-35, Session 7A

Interfacing dielectric elastomer actuators with liquids

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We investigate compatibility of liquids and dielectric elastomer actuators (DEAs). Some promising applications of DEAs require the device to be in direct contact with liquids. In some cases the devices are designed to act on liquids and generate a flow (ex. micro-pump) or move an encapsulated volume (ex. tunable lenses). In other cases liquids are only present due to external constraints. For example, biomedical applications typically require immersion in a culture media that provide essential nutrients to the biological sample.

Prior work in our laboratory indicated that immersion in aqueous electrolyte solution could degrade DEAs actuation performance and lead to premature failure of the system. We report here on the actuation strain stability and lifetime of DEAs immersed in different media. A DEA-based deformable cell culture system developed in our laboratory is used for the experiments. Similar devices are tested in air and aqueous solutions of different electrolyte concentrations. Direct contact with liquids can affect the actuation strain through various mechanisms such as modification of the Young's modulus and dielectric permittivity or swelling of the elastomer. The different possible contributions and their relative importance are discussed.

We also report on silicone elastomers permeability to liquids, a critical parameter for fluid encapsulation. Permeability of thin silicone elastomer membranes (0.05-0.1 mm) is tested for a set of nonaqueous liquids including oils, silicone fluids and ionic liquids. We find that permeability of thin membranes can diverge from observations made on bulk material. All our findings are summarized to provide guidelines in DEA-liquid compatibility.

9430-36, Session 7A

Silicone elastomers with high dielectric permittivity and high dielectric breakdown strength based on tunable functionalized copolymers

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High driving voltages currently limit the commercial potential of dielectric

elastomers (DEs). One method used to lower driving voltage is to increase dielectric permittivity of the elastomer. A novel silicone elastomer system with high dielectric permittivity was prepared through the synthesis of siloxane copolymers, thereby allowing for the attachment of high dielectric permittivity molecules through copper-catalysed azide-alkyne 1,3-dipolar cycloaddition (CuAAC). The synthesised copolymers allow for a high degree of chemical freedom, as several parameters can be varied during the preparation phase. Thus, the space between the functional groups can be varied, by using different dimethylsiloxane spacer units between the high dielectric permittivity molecules. Furthermore, the degree of functionalisation of the copolymers can be varied accurately by changing the feed of high dielectric permittivity molecules. As a result, a completely tuneable elastomer system, with respect to functionalisation, is achieved. It is investigated how the different functionalisation variables affect essential DE properties, including dielectric permittivity, dielectric loss, elastic modulus and dielectric breakdown strength, and the optimal degree of chemical functionalisation, where important properties are not significantly compromised, is also determined.

9430-37, Session 7A

Elastomer modulus and dielectric strength scaling with sample thickness

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Material characteristics such as adhesion and dielectric strength have well recognized dependencies on material thickness. There is disagreement, however, on the scale: the long held dictum that dielectric strength is inversely proportional to the square root of sample thickness has been shown to not always hold true for all materials, nor for all possible thickness regions. In D-EAP applications some studies have postulated a "critical thickness" below which properties show significantly less thickness dependency.

While a great deal of data is available for dielectric strength, other properties are not nearly as well documented as samples get thinner. In particular, elastic modulus has been found to increase and elongation to decrease as sample thickness is lowered. This trend can be observed experimentally, but has been rarely reported and certainly does not appear in typical suppliers product data sheets.

Both published and newly generated data were used to study properties such as elastic modulus and dielectric strength vs sample thickness in silicone elastomers. Several theories are examined to explain such behavior, such as the impact of defect size and of common (but not well reported) concentration gradients that occur during elastomer curing that create micron-sized layers at the upper and lower interfaces with divergent properties to the bulk material.

As Dielectric Electro-Active Polymer applications strive to lower and lower material thickness, changing mechanical properties must be recognized and taken into consideration for accurate electro-mechanical predictions of performance.

9430-38, Session 7A

Dielectric elastomer actuators as self-sensing devices: a new method of superimposing actuating and sensing signals

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Dielectric elastomer actuators (DEAs) have a lot of advantages such as high energy efficiency, unrivaled power-to-weight ratio and soft structure. Furthermore this new kind of actuator is capable of sensing its deformation and status without extra sensing devices. Therefore, DEAs are also acknowledged as self-sensing actuators. In this contribution a new self-sensing technique for DEAs is presented, in which the capacitance of DEAs under deformation is measured using high voltage signals. For this purpose, simple signal processing algorithms and a novel method of superimposing actuating and sensing signals are implemented. By connecting the ground potential electrode of the DEA to a sinusoidal sensing signal, the DEA is used as a passive first order low pass filter. The other electrode of the DEA is connected to the actuation voltage, which is superimposed with the sinusoidal signal. The amplitude of this signal is basically dependent on the capacitance of the actuator. Therefore, the change of the capacitance induced by contraction of the actuator alters the amplitude of the sinusoidal signal. The amplitude change can then be interpreted as capacity change and can be used to estimate the mechanical deformation of the DEA. In comparison to existing methods, this approach is promising for a miniaturized circuit and therefore for later use in mobile systems. In this paper, the new concept of superimposing actuating and sensing signals for self-sensing DEAs is validated with an experimental setup and several known capacities. The first results are presented and discussed in detail.

9430-39, Session 7A

Leakage current and stability of acrylic elastomer subjected to high DC voltage

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Dielectric elastomers such as 3M VHB4910 acrylic film, have been widely used for electromechanical energy conversion such as actuators, sensors and generators, due to their lightweight, high efficiency, low cost and high energy density. Mechanical and electric properties of such materials have been deeply investigated according to various parameters (temperature, frequency, pre-stress, nature of the compliant electrodes...). Models integrating analytic laws deduced from experiments increase their accuracy. Nevertheless, leakage current and electrical breakdowns reduce the efficiency and the lifetime of devices made with these polymers. These two major phenomena are not deeply investigated. Thus, this paper describes the current-voltage characteristics of acrylic 3M VHB4910 and investigates the stability of this current under high electric field (kV) for various temperatures (from 20°C to 80°C) and over a long period (12h). Experimental results show that, with gold electrodes at ambient temperature, charging current decreases with time to a stable value corresponding to the conduction current. This decrease occurs during 6 hours, whereas in the literature values of current at short time (less than 1 hour) are generally reported. This decrease can be explained by relaxations mechanisms in the polymer. Schottky emission and Poole-Frenkel emission are both evaluated to explain the leakage current. It emerges from this study that the Schottky effect constitutes the mechanism of electric current in the 3M VHB4910. For high temperatures, the steady state is reached quickly. To end, first results on the leakage current changes for pre-stretch VHB4910 complete this study.

9430-40, Session 7B

Soft linear electroactive polymer actuators based on polypyrrole

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There is a growing demand for human-friendly robots that can interact and work closely with humans. Such robots need to be compliant, lightweight and equipped with silent and soft actuators. Electroactive polymers such as conducting polymers (CPs) are "smart" materials that deform in response to electrical stimulation and are often addressed as artificial muscles due to their functional similarity with natural muscles. They offer unique possibilities and are perfect candidates for such actuators since they are lightweight, silent, and driven at low voltages.

The majority of CP actuators are fabricated using electrochemical oxidative synthesis, for which some form of metal coating is usually required as a seed layer. We developed new CP based fibres employing a metal-free combined chemical-electrochemical synthesis routes. We will present the fabrication and characterisation of these soft fibres as well as their performance as linear actuators.

9430-41, Session 7B

Biotemplated conducting polymer membrane supercapacitor

Vishnu Baba Sundaresan, Robert Northcutt, The Ohio State Univ. (United States)

A nanostructured conducting polymer membrane is fabricated using phospholipid vesicles as soft-templates and is referred to as a biotemplated conducting polymer membrane. The biotemplated conducting polymer membrane is fabricated into a supercapacitor and has been shown that the nanostructured membrane undergoes 33% reduced mechanical strain when compared with a planar membrane. It has also been shown that the specific capacitance of the biotemplated membrane (~500 F/g) is significantly higher than contemporary planar membranes (~200 F/g). It has been shown swelling characterization via simultaneous topography imaging and electrochemical imaging that the redox active sites are distributed in a three-dimensional space forming a nanostructured array. The redox currents have been shown to be proportional to the areal density of active redox sites and percent availability. The biotemplated membranes have been shown to have the highest availability of nanostructured conducting polymer membranes (78%) and have further room for improvement by modifying the nanostructured arrays. This article will discuss the characterization of a supercapacitor fabricated using biotemplated membranes. The morphology of the biotemplated membranes (shell thickness, vesicle diameter, overall membrane thickness and ion concentration) will be varied to develop structure-capacity relation and design rules for the fabrication of a supercapacitor will be discussed.

9430-42, Session 7B

Sequential growth for lifetime extension in biomimetic polypyrrole actuator systems

John C. Sarrazin, Stephen A. Mascaró, The Univ. of Utah (United States)

Electroactive polymers (EAPs) present prospective use in actuation and manipulation devices due to their low electrical activation requirements, biocompatibility, and mechanical performance. One of the main drawbacks with EAP actuators is a decrease in performance over extended periods of operation caused by over-oxidation of the polymer and general polymer

degradation. Synthesis of the EAP material, polypyrrole with an embedded metal helix allows for sequential growth of the polymer during operation. The helical metal electrode acts as a scaffolding to support the polymer, and direct the 3-dimensional change in volume of the polymer along the axis of the helix during oxidative and reductive cycling. The metal helix also provides a working metal electrode through the entire length of the polymer actuator to distribute charge for actuation, as well as for sequential growth steps during the lifetime of operation of the polymer. This work demonstrates the method of sequential growth can be utilized after extended periods of use to partially restore electrical and mechanical performance of polypyrrole actuators. Since the actuation must be temporarily stopped to allow for a sequential growth cycle to be performed and reverse some of the polymer degradation, these actuator systems more closely mimic natural muscle in their analogous maintenance and repair.

9430-43, Session 7B

Fabrication of ion-conducting carbon polymer composite electrodes by spin coating

Inga Põldsalu, Sven-Erik Mändmaa, Anna-Liisa Peikolainen, Arko Kesküla, Alvo Aabloo, Univ. of Tartu (Estonia)

We report a fabricating method for ion-conducting carbon electrodes on top of industrially produced PVDF membrane by spin coating. Spin coating is desirable due to its potential application in large scale actuator manufacturing and its possibility to produce very thin electrodes. The industrial grade membrane was chosen in order to investigate more accurately the results of spin coating without considering the deviations present in a hand-made membrane.

Spin coating and surface resistance measurement via four-point probe were described in further detail.

The production process of electrode suspension and suspension dispensing were developed and fine-tuned. The spin coater was programmed to obtain electrodes with uniform electrical properties. The arrangement of the spin coater was slightly altered to remove swelling and bubble formation effects concurrent with usage of the porous membrane.

Electrodes produced with the developed method were measured and analyzed. Thickness of the film was measured with micrometer screw gauge and four-point probe was used to measure sheet resistance, in addition film was studied under scanning electron microscope (SEM). In best cases the coefficient of variation for sheet conductivity was 6.2 %. For all electrode sheet conductivities the median coefficient of variation was 7 %. The thickness of the electrodes varied from 6 to 23 μm .

As a proof of concept for the developed method a working actuator with spin coated electrodes was produced.

9430-44, Session 7B

Stacking trilayers to increase force generation

Meisam Farajollahi, Saeede Ebrahimi Takallo, The Univ. of British Columbia (Canada); Adelyne Fannir, Univ. de Cergy-Pontoise (France); Maan Almarghalani, Edmond Cretu, The Univ. of British Columbia (Canada); Giao T. M. Nguyen, Cédric Plesse, Frédéric Vidal, Univ. de Cergy-Pontoise (France); Farrokh Sassani, John D. W. Madden, The Univ. of British Columbia (Canada)

Trilayer actuators enable large mechanical amplification, but at the expense of force. Thicker trilayers can generate more force, but displacement drops. In this work we explore the stacking of trilayers driven by conducting polymers in order to combine large deflection and reasonable force. Trilayer actuators operating in air have been fabricated using a solid double network polymer interpenetrated on the top and bottom with a layer of PEDOT. The

forces and displacements of individual and stacked layers are measured, and compared to beam bending model predictions of force at zero displacement and maximum displacement at zero load. The models do not account for the effects of sliding interactions between stacked trimorphs or for differences in response between individual trilayers (due to the fact that the trilayers are not perfectly identical), but is nevertheless useful in providing an upper bound in the performance. The increased forces, displacements and the use of parallel as well as series electrical configuration are reported upon.

9430-45, Session 8A

Bistable, giant, and high-speed actuation with dielectric elastomers (Invited Paper)

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

Dielectric elastomer actuators capture many desirable properties of muscles, with impressive actuation strain and speed, low density, compliance and silent operation. They have the potential to be used in the development of smart soft machines with capabilities formerly reserved to nature.

Inspired by mechanical instabilities harnessed for rapid movements in bio-mechanical systems such as the Venus flytrap or grasshoppers, we asked ourselves how to achieve bistable, giant and high speed actuation with dielectric elastomers. Remembering our childhood games with balloons, we identified balloon actuators, with their mechanical snap-through instability as ideal model system for such studies. In this presentation I will review several approaches to achieve giant, voltage triggered deformation in balloon actuators. Large volume changes of 1500 % at a high speed volume expansion rate of 2300 % are easily achieved. Remote operation is possible with coupled balloon membrane systems. Potential applications not only range from implementations to soft robots, but also to Braille and haptic displays.

9430-46, Session 8A

Solvent and electrolyte effects in PPyDBS free standing films

Rudolf Kiefer, Univ. of Tartu (Estonia); Jose G. Martinez-Gil, Toribio Fernández Otero, Univ. Politécnic de Cartagena (Spain); Arko Kesküla, University of Tartu (Estonia); Friedrich Kaasik, Matis Harjo, Univ. of Tartu (Estonia); Robert Valner, Vishwaja Vaddepally, Anna-Liisa Peikolainen, University of Tartu (Estonia); Alvo Aabloo, Univ. of Tartu (Estonia)

The construction of conducting polymer actuators requires a conductive surface on a film to obtain, by electrochemical polymerization, a uniform conducting polymer film. Bending actuators, as trilayer, are usually supported by a non-conductive and flexible non-conductive membrane (such as PVdF) with arrangement on one side or on both sides of conductive coatings required to support the electropolymerization of the conducting polymer layer. The oxidation/reduction, or charging/discharging, of those CP layers in electrolytes requires the incorporation of ions and solvent for charge and osmotic balance. The concomitant volume variations triggered by the reaction gives the bending motion of the trilayer actuator. Our aim in this study was to investigate the actuation properties of conducting polymers (polypyrrole doped with dodecylbenzoatesulfate) deposited electrochemically on PPy(chem.)-PVdF-PPy(chem.) to obtain PPyDBS-trilayer devices. Subsequent studies of the PPyDBS-trilayers in different solvents (aqueous, acetonitrile, propylene carbonate and ethyleneoxide) but in same electrolyte (0.5 M LiClO₄) been made under steady state condition (charging/discharging in balance) to evaluate solvent and electrolyte exchange effects. The expected cation driven actuation for PPyDBS actuators found in polar solvents while in organic solvents, the anion driven actuation dominates. SEM, FTIR and electrochemical studies are implemented to investigate how the actuation cycles influence the actuator control in different solvents.

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9430-47, Session 8A

Super soft silicone elastomers with high dielectric permittivity

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For improved actuation of dielectric elastomers at a given voltage the ratio of dielectric permittivity over Young's modulus (ϵ/γ) needs to be increased. Addition of high permittivity fillers such as metal oxides increases the dielectric permittivity of the resulting elastomers but the Young's modulus is usually increased by the same order of magnitude, such that improved actuation is not obtained. In the present study we show that super soft silicone elastomers with high permittivity can be developed from functional copolymers in a modular way or alternatively as a one-pot solution where functional copolymers are added as an additive to commercial silicone elastomer systems. The copolymer consists of a silicone backbone, which make it compatible with the commercial silicones and with a functionality grafted on to it that serves both as a dielectric permittivity enhancer as well as a covalently grafted plasticiser. We show improvements in the ratio of ϵ/γ of the order of 50 times of that of a current benchmark silicone elastomer.

9430-48, Session 8A

Simple casting based fabrication of PEDOT:PSS-PVDF-ionic liquid soft actuators

Aiva Simaite, LAAS-CNRS (France) and INSA-Toulouse (France); Bertrand Tondou, INSA-Toulouse (France) and LAAS-CNRS (France); Emeline Descamps, Philippe Soueres, Christian Bergaud, LAAS-CNRS (France)

Despite a growing interest in conducting polymer based actuators, a robust fabrication technique is still not available. The interface between the membrane and the polymer plays a crucial role in the performance of an actuator and is often a drawback, limiting the cycle-life of the devices. Although polyvinylidene fluoride membranes (PVDF) have excellent mechanical and chemical properties, their hydrophobicity lead to a very weak interface between the membrane and the conducting polymer. On the other hand, due to diffusion through, hydrophilic membranes are not a suitable option either. We suggest modifying commercially available PVDF membranes by Ar induced plasma grafting. The surface of the membrane is functionalized, creating up to 40 μm hydrophilic polyethylene glycol-graft-PVDF, which allows diffusion of PEDOT:PSS in the pores of the membrane. Thus creating a thick interfacial layer and ensures strong adhesion. Furthermore, membranes are only partly modified; leaving at least 40 μm of hydrophobic PVDF that prevents short circuits.

Once membranes are ready, conducting polymer based actuators can be made by simply drop casting the wanted amount and composition of commercially available PEDOT:PSS and drying. Ready actuators can be incubated in ionic liquids and actuated in air with no sign of delamination for hundreds of cycles (PEDOT:PSS layer would peel off from non-functionalised PVDF as soon as it is put in the ionic liquid). The actuation depends on the structure of the actuator but 0.3% strain and 0.01 %/s strain rates can be easily achieved.

9430-49, Session 8A

Three Dimensional Responsive Structure of Tough Hydrogels

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Yongbin Jin, Zhejiang Univ. (China); Ziqi Zhu, Zhejiang University (China); Junjie Liu, Tiefeng Li, Zhejiang Univ. (China)

Three dimensional responsive structures have high value for the application of responsive hydrogels in various fields such as micro fluid control, tissue engineering and micro robot. Whereas various hydrogels with stimuli-responsive behaviors have been developed, enhancing the mechanical toughness, designing and fabricating of the three dimensional responsive structures remain challenging. We develop a temperature responsive double network hydrogel with excellent mechanical toughness, and using novel fabrication methods to assemble the complex three dimensional responsive structures. The shape changing behavior of the structures can be significantly increased by building blocks with various responsiveness. Mechanical instability is built into the structure with the proper design and enhance the performance of the structure. The responsive structure can change shape slowly initially, yet at a critical point can undergo sudden large shape change. Finite element simulation are conducted to guide the design and investigate the responsive behavior of the hydrogel structures.

9430-50, Session 8A

Improved actuation strain of PDMS-based DEA materials chemically modified with softening agents

Martin Blümke, Miriam Biedermann, Michael Wegener, Hartmut Krüger, Fraunhofer-Institut für Angewandte Polymerforschung (Germany)

Polydimethylsiloxanes offer unique mechanical, chemical, and optical properties. At the same time they are easily and cost-effectively accessible. Particularly in recent years the use of PDMS materials for the development of dielectric elastomer actuators (DEAs) has gained much in interest. DEAs enable a multitude of interesting capabilities since they are soft, lightweight and have direct voltage control. Thus, different applications were suggested in a wide range of fields, for example as elements in arm wrestling robots, miniaturized pumps, pneumatic valves or optical devices.

A significant limitation to the application of such DEAs is their high operation voltage in the range of several thousand volts. Thus, an active field of research is the decrease of the required operation voltage to make these materials even more attractive for versatile use. Promising approaches to overcome this restriction are the reduction of the film thickness, the increase of the permittivity or the lowering of the mechanical stiffness.

One object of our work is to improve the actuation properties by the covalent incorporation of mono-vinyl-terminated low-molecular PDMS chains into the PDMS network. These low-molecular units act as a kind of softener within the PDMS network. The loose chain ends interfere with the network formation. In first studies the resulting PDMS films with up to almost 30 percent by weight of low-molecular PDMS additives indicate an enhancement of the actuation strain up to a factor of 10 at 35 V/micrometer. The chemical, mechanical, electrical, and electromechanical properties of these novel materials are investigated in more detail.

9430-51, Session 8B

Molecular to continuum analysis of the coupling between mechanics and electrostatics in polymer chain networks

Gal deBotton, Noy Cohen, Ben-Gurion Univ. of the Negev (Israel)

Electroactive polymers (EAPs) are materials capable of undergoing large deformations when stimulated by an electric field. At the present, there are models describing the polymers uncoupled electrostatic response under the influence of an electric field at both the macroscopic and the microscopic

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levels. Similarly, there are models describing the polymers reaction to purely mechanical loadings, macroscopically as well as through their molecular microstructure. The connection between the micro and the macro analyses shed light on the overall response of polymers and provide tools for optimizing their performances. In recent years, the electro-mechanical coupling in EAPs has been characterized and modeled at the macroscopic-continuum level. To the best of our knowledge, the corresponding analysis at the molecular microscopic level is not available yet.

Our work [Cohen and deBotton. Mech. Solids, 2014; Cohen and G. deBotton. Eur. J. Mech. A-Solids, 2014] is aimed toward understanding and analyzing the relation between the structure of EAPs and the forces and stresses that develop due to electrostatic excitations. To this end we introduce a multi-scale model that assumes known geometries of the chains before and after the deformation. In addition, a variational approach is used leading to the development of an expression for the internally stored electrical enthalpy in the polymer and the corresponding stresses that develop. In a way of an example a polymer with specific chain structure under constant electric excitation and axial deformation is examined. The results are compared with a common phenomenological model as well as with experimental findings.

9430-52, Session 8B

Modeling and simulation of transport phenomena in ionic gels

Peter Leichsenring, Thomas Wallmersperger, Technische Univ. Dresden (Germany)

The ongoing research and development in biomedical sciences and engineering requires for new sensor technologies. Hydrogel based microsensors - developed at the Solid-State Electronics Laboratory in Dresden - are a step forward in developing versatile chemical sensor systems for in situ measurements.

Ionic hydrogels belong to the class of polyelectrolyte gels or ionic gels. Their ability to swell or shrink under different environmental conditions such as the change of pH or temperature make them promising materials for applications in microsensors and microactuators. The hydrogel swelling exhibits nonlinear effects due to different transport phenomena. This makes the determination of the environmental state, obtained from the sensor output, a challenging task.

Numerical simulations are an essential part in the ongoing sensor development. In order to determine transport effects due to diffusion, migration and convection a multiphase mesoscale model based on porous media is applied. The governing field equations are solved in the transient regime by applying the Finite Element Method.

Numerical results of a free swelling hydrogel are compared with experimental data from literature. By means of the derived numerical framework a detailed investigation of the different transport phenomena is carried out. Therefore numerical experiments with respect to chemical and mechanical loads are performed.

Finally, based on the results, the dominating transfer phenomena are characterized for chemical, mechanical and combined chemo-mechanical stimulation. The investigations lead to a precise knowledge of the behavior of the sensor. Consequently, guidelines for the sensor design can be derived to enhance the response time, uncertainty and sensitivity of the novel sensor.

9430-53, Session 8B

Maximizing strain in miniaturized dielectric elastomer actuators

Samuel Rosset, Oluwaseun A. Araromi, Herbert R. Shea, Ecole Polytechnique Fédérale de Lausanne (Switzerland)

We present a theoretical model and its experimental validation to optimize the unidirectional motion of a rigid object bonded to a miniaturized

dielectric elastomer actuator (DEA), a configuration found for example in AMI's haptic feedback devices, or in our tuneable RF phase shifter (Proc. SPIE 90562M). Recent work has shown that unidirectional motion is maximized when the membrane is both anisotropically prestretched and subjected to a dead load in the direction of actuation (Soft Matter, 2012, 8, 6167). The use of dead weights for miniaturized devices is clearly highly impractical. Consequently smaller devices use the membrane itself to generate the opposing force. Since the membrane covers the entire frame, one has the same prestretch condition in the active (actuated) and passive zones. Because the passive zone contracts when the active zone expands, it does not provide a constant restoring force, reducing the maximum achievable actuation strain. We have determined the optimal ratio between the size of the electrode (active zone) and the passive zone, as well as the optimal prestretch in both in-plane directions, in order to maximize the absolute displacement of the rigid object placed at the active/passive border. Our model and experiments show that the ideal ratio is 2/3, with a displacement 18% smaller than what can be obtained with a dead load. We expand our fabrication process to also show how DEAs can be laser-post-processed to remove carefully chosen regions of the passive elastomer membrane, thereby increasing the actuation strain of the device.

9430-54, Session 8B

Micro-mechanics of ionic electroactive polymer actuators

Andres Punning, Inga Põldsalu, Friedrich Kaasik, Veiko Vunder, Alvo Aabloo, Univ. of Tartu (Estonia)

Commonly, modeling of the bending behavior of the ionic electroactive polymer (IEAP) actuators is based on the classical mechanics of cantilever beam. It is acknowledged, that the actuation of the ionic electroactive polymer (IEAP) actuators is symmetric about the centroid - the convex side of the actuator is expanding and the concave side is contracting for exactly the same amount. Actuating IEAP actuators under scanning electron microscope (SEM), in situ, reveals that for some types of them this approach is incorrect. Comparison of the SEM micrographs using the Digital Image Correction (DIC) method results with the precise strain distribution of the IEAP actuators in two directions: in the axial direction, and in the direction of thickness. This information, in turn, points to the physical processes taking place within the electrodes as well as membrane of the trilayer laminate of sub-millimeter thickness. The exact strain distribution enables detecting the position of the neutral layer of bending - an important requisite of the second area moment and bending moment of the beam.

The proposed methodology is demonstrated by comparing IEAP actuators of different types. The results show that similar bending strain (strain difference) of an arched actuator can be obtained with totally different combinations of the electrode strains. Therefore the widely used methodics of the strain measurement via tip displacement may give inadequate information.

9430-55, Session 8B

Optimized design of a multilayer DEAP stack-actuator based on a finite element model

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

Dielectric elastomers (DE) are thin polymer films belonging to the class of electroactive polymers (EAP), which are coated with compliant and conductive electrodes on each side. Due to the influence of an electrical field, dielectric elastomers perform a relatively high amount of deformation with considerable force generation. Because single layer polymer films have to be very thin in order to realize high electric fields with a limited voltage level, novel multilayer actuators are utilized to increase the absolute displacement and force. In case of a multilayer stack-actuator, many

actuator films are mechanically stacked in series and electrically connected in parallel, which compress in case of a charging EAP capacitance.

This contribution deals with the optimization of a multilayer DEAP stack-actuator design whereby the behavior and the actuation of the stack-actuator can be improved. At first the mechanical and electrical properties of a single actuator film as well as a multilayer stack-actuator are simulated as a holistic electromechanical model. To enable a linear movement and a force transmission to the application when embedding the stack-actuator into a certain system, end caps and mechanical connections are required on the top and/ or bottom of the actuator. Due to the influences of the end caps and the mechanical connections as well as of the encapsulation optimized actuator design rules can be derived by the developed multi-physics simulation model. Finally, the numerical FEM-model will be validated by comparing them to automated produced stack-actuators.

9430-56, Session 8B

Numerical study on 3D composite morphing actuators

Kazuma Oishi, Nabtesco Corp. (Japan) and Univ. of Washington (United States); Makoto Saito, Nabtesco Corp. (Japan); Minoru Taya, Univ. of Washington (United States); Kevin Kadooka, Nishita Anandan, University of Washington (United States)

There are a number of actuators using the deformation of electroactive polymer (EAP), where fewer papers seem to have focused on the performance of 3D morphing actuators based on the analytical approach, due mainly to their complexity. The present paper will introduce a numerical analysis approach on the large scale deformation and motion of a 3D approximately half dome shape actuator composed of thin soft membrane (passive material) and EAP strip actuators (EAP active coupon with electrodes on both surfaces), where the locations of the active EAP strips is a key parameter. Simulia/Abaqus Static and Implicit analysis code, whose main feature is the high precision contact analysis capability among structures, were used focusing on the whole process of the membrane to touch and wrap around the object. The unidirectional properties of the EAP coupon actuator were used as the material properties for the simulation and the verification of our numerical model, and compared to the existing 2D solution. The numerical results can demonstrate the whole deformation process of the membrane to wrap around not only smooth shaped objects like a sphere or an egg, but also irregularly shaped objects. A parametric study reveals the proper placement of the EAP coupon actuators, with the modification of the dome shape to induce the relevant large scale deformation. The numerical simulation for the 3D soft actuators shown in this paper could be applied to a wider range of soft 3D morphing actuators.

9430-57, Session 8B

Thermo-electro-mechanical deformation of dielectric elastomer: experiment and theoretical model

Bo Li, Lei Liu, Hualing Chen, Dichen LI, Xi'an Jiaotong Univ. (China)

An Electroactive polymer (EAP) is capable of converting electrical energy into mechanical energy. In this paper the thermoelastic effect in field-based EAP, dielectric elastomer (DE), is studied. A thermodynamic model is developed to analyze the nonlinearity of dielectric constant induced by the stretch and temperature change. The ferroelectricity when the temperature falls below the Curie point is studied during the polarization. Experimental characterization is conducted to evaluate how the ambient temperature and pre-stretch affect the actuation performance, which exhibits an exceptionally large influence of temperature on the deformation of DEs. For DEs with pre-stretch of 2, the increase of temperature from -10? to 80? enhances the actuation strain up to more than 1700%. Furthermore,

low pre-stretched DE is more susceptible to temperature variation. High pre-stretched DE is relatively insensitive to temperature, for its energy conversion is dominated by mechanical stretching rather than thermal conduction.

9430-58, Session 9A

Applications of piezoelectric polymers in electrical power generation using ocean waves (*Invited Paper*)

Ji Su, NASA Langley Research Ctr. (United States); Hiroshi Asanuma, Chiba Univ. (Japan)

One of well recognized and attractive applications of piezoelectric materials is to generate electrical power using ocean waves. In recent years, various devices and systems have been developed, using piezoelectricity in direct or indirect mechanisms. Among these technologies, several of them are based on piezoelectric polymers. The piezoelectric polymers, such as poly (vinylidene-fluoride), or PVDF and its copolymers, have demonstrated some advantages including flexibility, durability and low cost, as well as excellent processing properties. However, they still face some disadvantages or challenges such as low conversion efficiency (only 0.5- 4%) and instability due to their low glass transition temperatures and Currie transition temperatures. The presentation will provide a review of the promising candidate piezoelectric polymers and advances in the applications of them in the development of devices and systems for electrical power generation using ocean waves, especially how the power generation systems can be adopted in an ocean shore natural disaster protection system. Meanwhile, possible mechanisms to improve the performance of the piezoelectric polymers by intrinsic mechanisms or by device/system design will also be presented and discussed.

9430-59, Session 9A

Fiber-constrained dielectric elastomer for soft robotic actuators

Samuel Shian, Harvard Univ. (United States); Shijie Zhu, Harvard Univ. (United States) and Fukuoka Institute of Technology (Japan); Jiangshui Huang, David R. Clarke, Harvard Univ. (United States)

Unimorphic actuators fabricated from dielectric elastomers are susceptible to twisting and curling as the actuation voltage is increased. In this work we show that these distortions can be suppressed by introducing fiber constrains to the elastomer by embedding a low volume fraction of aligned fibers. The unimorph was fabricated by stacking layers of non-prestretched acrylic elastomer membranes with nylon fibers and carbon nanotubes as stiffener and electrodes, respectively. The performance of unimorph, such as curvature and blocking force, were characterized and analyzed as function of actuation voltage and fiber spacing. The stiffened elastomer actuators exhibit a larger stable flexural deformation than that of the un-stiffened elastomer. To gain insight on the deformation, the unimorph were numerically simulated using finite element method. In addition to showing local stress and strain, the simulation revealed important parameters including morphology and elastic modulus of the stiffener that affect the bending performance of the unimorph. Finally, the utility of fiber-constrained actuators were demonstrated for soft robotic applications.

9430-60, Session 9A

A Passive Autofocus System by Using Standard Deviation Of the Image on a Liquid lens

Pejman Rasti, Univ. of Tartu (Estonia); Arko Kesküla, Univ of Tartu (Estonia); Gholamreza Anbarjafari, Univ. of Tartu (Estonia); Henry Haus, Helmut F. Schlaak, Technische Univ. Darmstadt (Germany); Alvo Aabloo, Rudolf Kiefer, Univ. of Tartu (Estonia)

Autofocus fluid lens principle is based on meniscus changes of the interface between oil/water by applying an electric field over supported electrodes. The new design of the liquid lens are working based on an actuator membrane with round hole in the middle (diameter: 4 mm) placed between the two liquids. Due to the surface tension a meniscus will be formed between the 2 liquids over the hole of the actuator membrane that can operate as lens. Electroactive polymers (EAPs) in liquid lens cells are suitable for ionic EAPs, recently investigated based on conducting polymer actuator membranes. The goal of this research was to apply electronic and ionic EAPs in liquids (oil/water) and their control to achieve high focal lenses. In case of applying DEA (electronic EAPs) operating in liquids a suitable encapsulation of the DEA is necessary to avoid short circuits. Encapsulated DEA membranes were produced in stacked formation with middle hole. Ionic EAPs based on conducting polymers did show lens changes properties with applied voltage in the range of $\pm 0.3 - 0.7$ V. When the actuator membrane is activated over low voltage (ionic EAP) or high voltage (electronic EAP), the hole dimension changes by contraction of the actuator membrane and therefore the curvature of the meniscus formed between oil and water changed. The effect of this lens on digital zooming (super resolution) by using discrete wavelet transform based resolution enhancement will be studied.

9430-61, Session 9A

Soft, flexible micromanipulators comprising polypyrrole trilayer microactuators

Alexandre Khaldi, Linköping Univ. (Sweden); Gursel Alici, Geoffrey M. Spinks, Univ. of Wollongong (Australia); Edwin W. H. Jager, Linköping Univ. (Sweden)

Within the areas of cell biology, biomedicine and minimal invasive surgery, there is a need for soft, flexible and dextrous biocompatible manipulators for handling biological objects, such as single cells and tissues. Present day technologies are based on simple suction using micropipettes for grasping objects. The micropipettes lack the possibility of accurate force control, nor are they soft and compliant and may thus cause damage to the cells or tissue. Other micromanipulators use conventional electric motors however the further miniaturization of electrical motors and their associated gear boxes and/or push/pull wires has reached its limits. Therefore there is an urgent need for new technologies for micromanipulation of soft biological matter.

We are developing soft, flexible micromanipulators such as micro- tweezers for the handling and manipulation of biological species including cells and surgical tools for minimal invasive surgery. Our aim is to produce tools with minimal dimensions of 100 μ m to 1 mm in size, which is 1-2 orders of magnitude smaller than existing technology. We present newly developed patterning and microfabrication methods for polymer microactuators as well as the latest results to integrate these microactuators into easy to use manipulation tools. The outcomes of this study contribute to the realisation of low-foot print devices articulated with electroactive polymer actuators for which the physical interface with the power source has been a significant challenge limiting their application. This is a significant step towards widening the application areas of the soft microactuators.

9430-62, Session 9A

DEA for soft robotics: 1-gram actuator picks up a 60-gram egg

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We present a 2-finger soft gripper capable of picking-up various objects. The gripper consists of a few cm long bending actuators weighed around 1 g each, realizing simple open-close movement. The compliance of the gripper leads to conformation of the structure against the object surface, which is proved by successful handling of objects with different geometries such as a pencil, a flat paper, and a ping pong ball. Also, by the fact that the conformed structure increases the contact area, the holding force in shear direction is improved while avoiding damaging the object, which is highlighted by the ability to pick-up and hold a raw egg mass of around 60 g. In the gripper, each actuator is composed of a 50 μ m thick pre-stretched dielectric elastomer actuator (DEA) attached onto a sub-mm thick silicone substrate, resulting in bending actuation when a voltage is applied. The use of DEA provides not only the actuation but also the electroadhesion caused by the charges on the electrodes, which assists the holding of the object by adding a normal force. The configuration of the actuator is similar to dielectric elastomer minimum energy structures, but has several features: the entire structure is soft, and bidirectional actuation can be achieved in addition to unidirectional actuation by adding another DEA onto the other side of the substrate. During the presentation, the actuation principle, characterization results on both the actuator and the gripper, and the demonstration of the device's ability to pick-up various objects are shown.

9430-63, Session 9A

Electroactive polymer scaffolds for cardiac tissue engineering

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By-pass surgery and heart transplantation are traditionally used to restore the heart's functionality after a myocardial infarction (MI or heart attack) that results in scar tissue formation and impaired cardiac function. However, both procedures are associated with serious post-surgical complications. Therefore, new strategies to help re-establish heart functionality are necessary.

Tissue engineering and stem cell therapy are the promising approaches that are being explored for the treatment of MI. The stem cell niche is extremely important for the proliferation and differentiation of stem cells and tissue regeneration. For the introduction of stem cells into the host tissue an artificial carrier such as a scaffold is preferred as direct injection of stem cells has resulted in fast stem cell death. Such scaffold will provide the proper microenvironment that can be altered electronically to provide temporal stimulation to the cells.

We have developed an electroactive polymer (EAP) scaffold for cardiac tissue engineering. The EAP scaffold mimics the extracellular matrix and provides a 3D microenvironment that can be easily tuned during fabrication, such as controllable fibre dimensions, alignment, and coating. In addition, the scaffold provides electrical and electromechanical stimulation to the stem cells which are important external stimuli to stem cell differentiation. This stimulation will increase the differentiation ratio of stem cells into cardiomyocytes, increasing the formation of cardiac tissue. Excellent biocompatibility was achieved using primary cardiovascular progenitor cells. We present the fabrication, electrochemical and electromechanical characterisation as well as the response of the stem cells to the scaffolds and to the stimulation.

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9430-64, Session 9B

A beam-power splitter membrane based on shape memory micropattern

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A dynamic thermally activated beam-power splitter based on a shape memory polystyrene membrane with a programmable micropattern is demonstrated. The splitters are produced using the excellent shape-memory effect of a shape memory polymer membrane with precise replication of surface micropattern features using typical spin-coat wafer processing. The micropattern of the shape memory polymer membrane disappears and the membrane becomes transparent when the membrane is hot pressed at a temperature 20°C higher than the glass transition temperature (T_g). After the membrane is cooled and fixed, a thermal beam-energy splitter membrane is obtained, that demonstrates the optical property response of the dynamic surface micropattern features. Through reheating of the membrane to a temperature above T_g , the original programmable micropattern and the optical properties can be recovered. During this recovery process, the transmission light switches from a mono-beam to multi-beam because of the optical diffraction effect of the micropattern, and the divided directions and beam-power distribution depend upon the design of the micropattern. The diffraction efficiency of the shape-memory polymer membrane with different micropatterns is qualitatively and quantitatively analyzed during the whole thermal recovery process. Experimental and theoretical results clearly indicate that the dynamic changes in the micropattern of the membrane can effectively regulate the direction and power of the transmission light beam.

9430-65, Session 9B

Low-voltage driven ionic polymer actuators composed of nanostructured block copolymers and ionic liquids

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Electroactive actuators based on ionic liquids (ILs)-containing polymers have attracted great attention toward a range of biomimetic applications such as artificial muscles, soft robotics and microsensors. Key factors in achieving practically viable actuators are the development of fast response time, large displacement in bending motion, low operating voltage and durable operation in air. Here we are motivated to solve these issues by employing nanostructured block copolymers and imidazolium ILs as a polymer layer in the actuator. Interestingly, the bending strain and durability were found to be tunable in a straightforward manner by controlling the block architecture and molecular weight of the block copolymer. It has also been revealed that the type of cations and anions in ILs makes impact on the actuation performance. Remarkably, we showed the effectiveness of utilizing nanostructured ionic block copolymers containing ILs in EAP actuators by demonstrating large bending strains (up to 4%) under voltages of 1-3V. In particular, large strain values of 0.5-1.0% were recorded at ± 1 V in the frequency range of 0.05-1 Hz in the case of our actuator, which then became a new record for ionic polymer actuators. To underpin the molecular-level understanding of actuation mechanisms underlying the improved performance, we carried out in situ spectroscopy and in situ scattering experiments under actuation. The key to success stemmed from the evolution of the well-defined ionic channels of nanostructured block copolymers with dimensional gradients beneath the cathode during actuation, which facilitated fast ion migration with a reduced tendency to form ion clusters.

9430-66, Session 9C

Fiber-reinforced Dielectric Elastomer Laminates with Integrated Function of Actuating and Sensing

(Invited Paper)

Tiefeng Li, Yuhan Xie, Chi Li, Guoyong Mao, Shaoxing Qu, Zhejiang Univ. (China)

Inchworm, cockroaches and cuttlefish are agile and adaptive to extreme environments. These creatures have inspired the development of soft machines that can achieve large actuation, can move in complex environments and with multiple functions. With the attributes of fast response, large actuation and light weight, dielectric elastomer can largely expand application fields and enhance the performances of soft machines. Here we show mechanics and bionics play very important role in guiding the structural design and operation of dielectric elastomer soft machines. With structural design from FEM simulation, electromechanical instabilities can be either suppressed or harnessed to enhance the performance of the soft machines. Mechanical analysis guided material engineering can fabricate better dielectric elastomer material with suitable electromechanical properties. Bio-inspired structural design enables the dielectric elastomer soft machines have the comparable behaviors of natural insects.

9430-67, Session 9C

Fast torsional actuators

Seyed Mohammad Mirvakili, Massachusetts Institute of Technology (United States); Soheil Kianzad, The Univ. of British Columbia (Canada); Ian W. Hunter, Massachusetts Institute of Technology (United States); John D. W. Madden, The Univ. of British Columbia (Canada)

Almost all torsional actuators (i.e. electric motors, pneumatic motors) are made from more than one body component and making a structure that can rotate within one body (i.e. artificial muscle type) enables miniaturization for application in biomedical devices and many others. Most of thermal actuators such as shape memory alloys, meet this requirement of actuation within one body.

Shape memory alloys have been studied extensively due to their great linear actuation properties. Different techniques are used to make torsional actuators and torque tubes but none of them have fast actuation response with high number of rotations. In this work, we have demonstrated a way to address this issue. By twisting fine strands of shape memory alloy wires, SMA yarns with length of up to 100 mm and diameter of up to 75 μ m were made. Torsional peak speed of more than 6,000 RPM is achieved with torsion amplitude of more than 40 °/mm of yarn's length.

9430-68, Session 9C

Nylon actuator operating temperature range

Soheil Kianzad, Milind Pandit, Ali Rafiee, John D. W. Madden, The Univ. of British Columbia (Canada)

Automotive and aerospace applications, among others, require a wide temperature range of operation. Newly discovered nylon actuators provide potentially affordable and viable solutions for driving mechanical devices, but little is known about their operation at low temperatures in particular. We study the mechanical behaviour of nylon coil actuators by testing Young's modulus and by investigating actuation tensile stroke as a function of temperature. The temperatures investigated range from -40 °C up to 200 °C. Young's modulus ranges from 670 MPa to B 320 MPa over the temperature range studied, acting to reduce stroke under increasing loads.

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Keeping the input power constant, the actuation stroke increased from 7 % at -40°C to 16 % when starting from room temperature. The modulus increases with frequency at all temperatures by as much as 17 % between 0.1 Hz and 40 Hz.

9430-69, Session 9C

McKibben with a twist: high torque to mass pneumatic torsional and linear artificial muscle

Seyed Mohammad Mirvakili, Massachusetts Institute of Technology (United States); Douglas Sim, The Univ. of British Columbia (Canada); Ian W. Hunter, Massachusetts Institute of Technology (United States); John D. W. Madden, The Univ. of British Columbia (Canada)

Torsional actuators with carbon nanotubes and niobium nanowire yarns have demonstrated producing reasonable torque suitable for small scale devices (e.g. miniature mixers); however, for application in robotics, their scalability and cost are the two limiting factors. In this work, we are introducing a new approach for making torsional actuation using the same actuation principles as proposed for CNT and Nb nanowire yarns. A soft pipe closed at one end is wrapped with stiff wires and then pressurized with air. Similar to McKibben pneumatic artificial muscle, but in this case the positive pressure inside the pipe leads to rotation and contraction depending on the wrapping structure. Torque to mass ratio of 1.9 N.m/kg is achieved at 345 kPa (50 psi) with ~ 4% linear actuation which is around the same number for CNTs and Nb NW yarns.

9430-70, Session 10A

Modeling of a corrugated dielectric elastomer actuator for artificial muscle applications

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Dielectric elastomer actuators have many advantages, including light weight, simplicity, high energy density, and silent operation. These features make them suitable to replace conventional actuators and transducers, especially in artificial muscle applications where large contractile strains are necessary for lifelike motions. This paper will introduce the concept of a corrugated dielectric elastomer actuator, which consists of dielectric elastomer (DE) laminated to a thin elastic layer to induce bending motion at each of the corrugations, resulting in large axial deformation. The location of the DE and elastic layers can be configured to provide tensile, compressive, or bidirectional axial strain. Such corrugated DE actuators are also highly scalable: linking multiple actuators in series results in greater deformation, whereas multiple actuators in parallel results in larger force output. Analytical closed-form solutions based on linear elasticity for the displacement and force output of cantilever-beam and corrugated DE actuators, both consisting of an arbitrary number of lamina, are derived to predict the nonlinear behavior of the actuator. The performance of multilayered DE cantilever unimorph actuators (VHB F9469PC) are suitably predicted by the former formulation. Modeling results of the corrugated DE actuator predicts axial strains several times greater than a simple DE plate actuator, due to the highly anisotropic stiffness of the corrugated structure. Also investigated are a long stroke, high force actuator composed of a bundle of the aforementioned corrugated DE actuators for potential use in a robotic hand application, as well as the actuator's time-dependent behavior by a viscoelastic analysis.

9430-71, Session 10A

Novel dielectric elastomer structure of soft robot

Chi Li, Yuhan Xie, Xiaoqiang Huang, Junjie Liu, Zhejiang Univ. (China); Yongbin Jin, Zhejiang University (China); Tiefeng Li, Zhejiang Univ. (China)

Inspired from the natural invertebrates like worms and starfish, we propose a novel elastomeric smart structure. The smart structure can function as a soft robot, and wearable human assisting equipment. The soft robot is made from a flexible elastomer as the body and driven by dielectric elastomer as the muscle, which makes the robot run fast and resilient to extreme mechanical condition. Finite element simulations based on nonlinear field theory are conducted to investigate the working condition of the structure, and guide the design of the smart structure. The effects of the prestretch, structural stiffness and voltage on the performance of the smart structure are investigated. This work can guide the designs of soft robot and wearable equipment.

9430-72, Session 10A

Optimization of tubular dielectric elastomer peristaltic pump

Guoyong Mao, Tiefeng Li, Shaoxing Qu, Zhejiang Univ. (China)

Inspired by various peristaltic structures existing in nature, we have developed a dielectric elastomer peristaltic pump composed of short tubular modules with finite deformation. In this study, we use a valid analytical model based on nonlinear field theory to optimize the design of the peristaltic pump. We further focus on the performance and stability of the pump module which are important in the design of the peristaltic pump. These two research priorities of the pump module are investigated in the analytical model. We use the following two parameters, driving pressure ratio and displaced volume ratio to evaluate the performance of the peristaltic pump at certain working conditions. The prestretch, aspect ratio, and voltage play an important role in the performance and stability of pump module which are the main design parameters of the peristaltic pump module. Electromechanical instability has been observed when the individual pump module undergoes finite deformation during operation. This instability can be controlled by rational design of the peristaltic pump and applied proper voltage. This work will be helpful in the future application of soft peristaltic pumps in the field of artificial organs and industrial conveying systems.

9430-73, Session 10A

Kinematics and control of redundant robotic arm based on dielectric elastomer actuators

Francesco Branz, Andrea Antonello, Andrea Carron, Univ. degli Studi di Padova (Italy); Ruggero Carli, Department of Information Engineering - University of Padova (Italy); Alessandro Francesconi, Univ. degli Studi di Padova (Italy)

Soft robotics is a promising field and its application to space mechanisms could represent a breakthrough in space technologies by enabling new operative scenarios (e.g. soft manipulators, capture systems). Dielectric Elastomers Actuators have been under deep study for a number of years and show several advantages that could be of key importance for space applications. Among such advantages the most notable are high conversion efficiency, distributed actuation, self-sensing capability, multi-degree-of-freedom design, light weight and low cost. The big potentialities of double cone actuators have been proven in terms of good performances (i.e. stroke

and force/torque), ease of manufacturing and durability.

In this work the kinematic, dynamic and control design of a two-joint redundant robotic arm is presented. Two double cone actuators are assembled in series to form a two-link design. Each joint has two degrees of freedom (one rotational and one translational) for a total of four. The arm is designed to move in a 2-D environment (i.e. the horizontal plane) with 4 DoF, consequently having two degrees of redundancy. The redundancy is exploited in order to minimize the torque at the joints and/or the force at the end effector. The kinematic design with redundant Jacobian inversion is presented. The selected control law is described along with the results of a number of dynamic simulations that have been executed for performances verification. Finally, an experimental setup is presented based on a flexible structure that counteracts gravity during testing in order to better emulate future zero-gravity applications.

9430-74, Session 10A

Bio-inspired artificial muscle structure for integrated sensing and actuation

Zhihang Ye, Md. Shahnewaz Sabit Faisal, Ramazan Asmatulu, Zheng Chen, Wichita State Univ. (United States)

In this paper, a novel artificial muscle/tendon structure is developed for achieving bio-inspired actuation and self-sensing. The hybrid structure consists of a dielectric elastomer (DE) material connected with carbon fibers, which incorporates built-in sensing and actuation capabilities of DE and mechanical, electrical interfacing properties of carbon fibers. DEs are light weight artificial muscles that can generate compliant actuation with low power consumption. Carbon fibers act as compliant artificial tendons due to their high electro-conductivity and mechanical strength. Bonding materials are used to electrically and mechanically connect the carbon fibers with the DE material. A strip actuator was fabricated to verify the structure design and characterize its actuation and sensing capabilities. A 3M VHB 4905 tape was used as DE material. To make compliant electrodes on the VHB tape, carbon black was sprayed on the surface of the VHB first. Then a 100 nm thick silver layer was sputtered on top of the carbon black to improve the electrical conductivity. To join the carbon fibers to the VHB tape, silver paste was used as electrical bonding material and PDMS was used as mechanical bonding material. Actuation tests have shown that the energy efficiency of the artificial muscle can reach up to 40%. Sensing tests have verified that the structure is capable of self-sensing without extra external sensors.

9430-75, Session 10B

A stretchable soft-touch musical keyboard

Daniel Xu, The Univ. of Auckland (New Zealand); Benjamin M. O'Brien, Todd A. Gisby, StretchSense (New Zealand); Iain A. Anderson, The Univ. of Auckland (New Zealand) and StretchSense (New Zealand)

Recall the first time that you discovered the piano. The delicate touch on the keys and the excitement and curiosity that followed. We are always looking for new and creative ways to express ourselves with music. Dielectric elastomers can be used as large strain sensors, making them ideal for capturing human body motion. Their natural softness gives them the versatility and robustness required for coupling onto complicated structures such as the human hand. This paper describes a musical keyboard made from dielectric elastomer sensors. A custom electronics circuit associates the capacitance change from hand motion to notes on the keyboard. This allows new gesture control dynamics, creating a more intimate playing experience. Since capacitance is also a continuous function of pressure, the musical keys can be programmed to allow volume and pitch control in an analogue manner, enabling an endless possibility of sounds.

9430-76, Session 10B

Transparent and conformal touch sensor

Mirza S. Sarwar, Ettore Glitz, Meisam Farajollahi, Shahriar Mirabbasi, John D. W. Madden, The Univ. of British Columbia (Canada)

Tactile sensors acquire information through physical touch and are typically capacitive, piezo-resistive, piezoelectric, inductive, or opto-electronic. With the increase in interactive devices, modern applications require sensors that are structurally conformal, transparent, require low power and are often of large area. Tactile sensors are also being investigated as artificial skin for robotics applications. Most flexible transparent sensors to date are either capacitive or resistive, require complex readout electronics and may not be conformal to complicated geometries. This work proposes a hydrogel-based sensor technology with multi-touch capabilities and sensitivity comparable to existing technologies with additional benefits that can enable a wide range of applications from flexible hand held devices to electronic skin. Conventional passive sensor technologies in the market require an excitation current or voltage for readout. With a working principle analogous to piezoelectricity, the hydrogel sensor generates a potential difference upon actuation that can be sensed using mainstream cost and power efficient electronic interface circuitry. In addition, it allows for low material cost and large area fabrication of the sensor. Hydrogels are water-insoluble, hydrophilic, gels used in a number of sensing applications including pH and humidity. Being a gel like substance it is conformal to many geometric shapes, and it has a very good transmittance of light.

9430-77, Session 10B

Follicular DEAs for two-way tactile communication

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Follicular structures in the skin combine sensing and actuation in a soft and compliant continuous surface. We have developed a tactile display device inspired by this structure, using a Dielectric Elastomer Actuator (DEA). The soft actuator gives the device inherent compliance, making it suited for wearable devices that conform to and move with the user. The sensing and actuation functionality of DEAs allows for combined tactile sensing and actuation, making two-way tactile communication between the user and the tactile device possible. This is different from the majority of tactile devices to date, that focus on either sensing or stimulation, and opens up a number of possibilities. The device can obtain tactile information about the environment, or a user touching it, and it can simultaneously present tactile information to the user.

In social robotics, for example, the robot would be able to feel a human touching it and give some meaning to the tactile interaction (e.g stroking, petting). It would then be able to respond, presenting the human with some tactile stimulus that could for example express the emotional state of the robot. In industrial applications, the tactile response could alert the user about the current risk level.

We characterise the sensing and actuation properties of the developed bio-inspired tactile display device, and perform classification of different tactile stimuli. We also demonstrate an example of two-way tactile interaction between a user and the device.

9430-78, Session 10B

Dielectric elastomer (DE) based sensors for SHM in composite structures

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Dielectric Elastomer (DE) based sensors for SHM in composite structures.

The use of composite materials for the manufacturing of complex aerospace structures has grown significantly during the last two decades and it is forecasted to further increase fuelled by the growth in civil and military market. However, the diffusion of these materials is still hindered by their low resistance to impacts with foreign objects that tends to generate different kinds of internal flaws that might lead to the dramatic failure of the entire structure. Hence, the development of a system able to monitor the structural integrity of a composite part could guarantee safety and reduce maintenance costs. Based on these premises, the aim of this paper is the design and manufacturing of an in-situ SHM system based on Dielectric Elastomers (DEs) sensors able to measure and evaluate the stress distribution over an entire structure during service and eventually detect the insurgence of an impact event. These electroactive sensors are manufactured starting from a very thin dielectric elastomer film (silicone or acrylic) which is then coated with highly compliant electrodes on both sides, generating a layered structure that acts as a stretchable capacitor. By changing the extension of the coated areas it is possible to modify the distribution of active and passive areas, thus creating a sort of sensors array all over the part under examination. When an external load (such as an impact or shear, bending, compression/tension force) is applied on the structure, because of the high compliance of the sensors, their geometry will change according to the solicitation, leading to a variation in the internal capacitance that can be measured and recorded.

In addition, because of their intrinsic flexibility, the system can be easily integrated in complex structures and are able to detect large deformations, overcoming some of the issues generated by the intrinsic rigidity of traditional piezoelectric sensors.

Keywords: SHM, composite structures, dielectric elastomer, electroactive polymers

9430-79, Session 10B

Influence of design and material properties on the performance of dielectric elastomer compression sensors

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Dielectric elastomer sensors with high sensitivity for compression load were introduced recently. The sensors basically consist of two profiled surfaces between which an elastomer film is stretched upon compression. Due to their flexibility, the sensors can be used on compliant substrates such as seats or beds. Different designs of the compression sensor give rise to very different sensor characteristics in terms of their dependence of electric capacitance on compression force. The design parameters concern the shape of the profiled surfaces. Furthermore, the electrode layers which are charged in the capacitance measurement can be located at different positions. With a special sensor design, an increase of capacitance by a factor of more than ten has been achieved. Another strong impact is caused by the hardness of the elastomer components in the compression sensor. The elastomer profiles as well as the elastomer films for the investigations were prepared with silicone. The hardness of the silicone elastomer was controlled by the degree of crosslinking. With a softer silicone film or with softer silicone profiles, the compliance of the sensor was enhanced. The design of various compression sensors is outlined and the work mechanism is explained. For these compression sensors, the performance is compared and the influence of sensor design as well as elastomer material properties is discussed.

9430-80, Session 11A

Gel chemical transistor

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Gel is a substance which takes the state of belonging in the middle of a solid and a liquid, and changes even to a hard solid from a viscous liquid. In our research group, development and analysis of high transparent shape memory gels are advanced. Shape Memory Gel (SMG) is one of the most interesting unique soft and wet materials. Its shape memory function is due to the crystalline feature of alkyl main chain and alkyl side chain. Both the main chain and the side chain switch their state between amorphous phase and crystalline phase depending on temperature. The elastic modulus of the SMG in water is steeply changed by heating and cooling due to the composite preparation from hydrophilic and hydrophobic monomers (T-switch SMG). Thus the modulus is also changed by the kinds of solvent (S-switch SMG). Here we have an idea that these properties are possibly applied to develop a novel gel chemical transistor, named "Gel-con(ductor)". The Gel-con will be made from the combination of the different kinds of the S-switch gel membranes and will be used as rectifier, amplifier and calculator in chemical circuits, where the solvent molecules behave as electron and hole. In this study, S-switch Gels were produced as the suitable gel membranes for the Gel-con and make the Gel-con. Then solvent content ratio and the permeability property of the prepared S-switch gel membranes were investigated.

9430-81, Session 11A

Dry deposition sequential process for an automated manufacturing of DEAP stack-actuators

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Due to the influence of an electrical field, dielectric elastomers perform a relatively high amount of deformation with considerable force generation. Because single layer polymer films are very thin in order to realize high electric fields with a limited voltage level, novel multilayer actuators are utilized to increase the absolute displacement and force. In case of a multilayer stack-actuator, many actuator films are mechanically connected in series, which elongates in case of a charged EAP capacitance.

This contribution deals with the development, design and realization of a dry deposition sequential process for DEAP stack-actuators. First of all the specific design and topology of the considered multilayer actuator from a single layer actuator film towards the encapsulation of the stack-actuator and afterwards the concept, design and realization of several sub processes of the automated fabrication is presented in detail.

In contrast to known chemical processes, thin DEAP-films are mechanically stacked in series ensuring a low driving voltage due to the electrical connection in parallel. In order to obtain a modular and flexible construction, the whole process is divided into several sub-processes, which can be adapted individually to produce various actuator geometries. At first the liners on the top and bottom surfaces of the processed elastomer from the material supplier have to be removed and the films are folded and afterwards they are stacked, cutted, contacted and encapsulated. By applying this automated process, stack-actuators with reproducible and homogeneous properties are manufactured. The holistic manufacturing will be presented in detail and the fabricated DEAP stack-actuators will be validated experimentally.

9430-82, Session 11A

A dielectric elastomer actuator coupled with water: snap-through instability and giant deformation

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A dielectric elastomer actuator is one class of soft actuators which can deform in response to voltage. Dielectric elastomer actuators coupled with liquid have recently been developed as soft pumps, soft lenses, Braille displays, etc. In this paper, we conduct experiments to investigate the performance of a dielectric elastomer actuator which is coupled with water. The membrane is subject to a constant water pressure, which is found to significantly affect the electromechanical behaviour of the membrane. When the pressure is small, the membrane suffers electrical breakdown before snap-through instability, and achieves a small voltage-induced deformation. When the pressure is higher to make the membrane near the verge of the instability, the membrane can achieve a giant voltage-induced deformation, with an area strain of 1165%. When the pressure is large, the membrane suffers pressure-induced snap-through instability and may collapse due to a large amount of liquid enclosed by the membrane. Theoretical analyses are conducted to interpret these experimental observations.

9430-83, Session 11A

Effect of mass loading on ionic polymer metal composite actuators and sensors

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Ionic polymer metal composites finds applications as actuators and sensors [1] in flapping wing micro air vehicle design due to its advantages such as low power consumption, high strain [2] and large displacements at smaller size. In structural design, the attachment of wing on the IPMC actuators is an important concern as the attached wing increases the mass of actuators thereby affecting the parameters like displacement, stiffness and resonant frequencies. Such IPMC actuators have to produce sufficient actuation force and frequency to lift and flap the attached wing. Therefore, it is relevant to study the influence of attachment of wing on the actuator parameters (displacement, resonant frequency, block force and stiffness) and performance of the actuators. In this study, the performance of high frequency and low frequency IPMCs as actuators and sensors are investigated. The geometric parameters of high frequency actuator (HFA) (20 Hz) and low frequency actuator (8.7 Hz) (LFA) are optimized using modeling by energy based variational method [3]. Experimental studies on IPMCs are carried out for actuation and sensing behaviour and a good match between experimental and simulation results are derived. The mass loading (0.16 gm end mass) to the actuators results in a decrease of deflection, flap angle and block force with the HFA and LFA actuators. The frequency and stiffness are decreased significantly with HFA. However, there is only a slight decrease in the tip deflection. In case of LFA, the end mass reduces the displacement value but the frequency remains almost the same before and after mass loading and the stiffness increased with LFA. In terms of sensing of the parent HFA and LFA actuators, the mass loading increases output voltage with HFA where as the output voltage decreases slightly with LFA. The attachment of IPMC as flapping wings, specifically the HFA-wing and LFA-wing (3.2 cm x 1.2 cm x 200 μ m with HFA and 3.5cm x 0.7 cm x 400 μ m with LFA), to the end of the actuators is done to understand the actuation performance of the flapping wing. The experimental studies reveal that LFA-wing shows increased stiffness and frequency compared to HFA-wing. Also, LFA-wing shows lesser tip deflection and actuation force is almost same to that of HFA-wing at increased input voltage.

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9430-84, Session 11B

Transmission line circuit model of a PPy based trilayer mechanical sensor

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Many efforts have been devoted to modeling the diffusive impedance of conjugated polymer based actuators using their equivalent electrical circuits. Employing the same methodology, CP based mechanical sensors can also be treated by an equivalent transmission line circuit and their overall impedance can be modeled, correspondingly. Due to the large number of resources to study the electrical circuits, this technique is a practical tool. Therefore, in this study, an equivalent RC-circuit model including electrochemical parameters is determined to obtain a better perception of the sensing mechanism of these mechanical sensors. Conjugated polymers are capable of generating an output current or voltage upon an induced mechanical deformation or force. This observed behavior in polymer based mechanical sensors is considered as the reverse actuation process. Many outstanding properties of the conjugated polymer actuators including their light weight and biocompatibility are still retained by these sensors. Sensors with a trilayer configuration are capable of operating in air in response to a mechanically induced bending deformation. However, due to their nonlinear behavior and multivariable characteristics, it is required to propose a systematic approach in order to optimize their performance and gain the optimal values of their constituent decision variable. Therefore, the proposed mathematical model is used to define the output voltage of the PPy based mechanical sensor along with the sensitivity of the model to the applied frequency of the induced deformation. Applying a multiobjective optimization algorithm, the optimization problem was solved and the tracking ability of the proposed model was then experimentally verified.

9430-85, Session 11B

Thin-film dielectric elastomer sensors to measure the contraction force of smooth muscle cells

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The development of thin-film dielectric elastomer strain (DES) sensors for the characterization of smooth muscle cell (SMC) monolayers is presented here. Smooth muscle disorders are an integral part of diseases such as asthma and emphysema. Analytical tools enabling the characterization of SMC function i.e. contractile force and strain, in a low-cost and highly parallelized manner are necessary for toxicology screening and for the development of new and more effective drugs. The main challenge with the design of such tools is the accurate measurement of the extremely low contractile cell forces expected by the SMC monolayer (as low as 1 μ N). Our approach uses ultrathin (\sim 5 μ m) and soft elastomer membranes patterned with elastomer-carbon composite electrodes, onto which our cells are cultured. The cell contractile force is subsequently measured via the resulting in-plane strain of the elastomer membrane, predicted to be in the order of 1%. We discuss the fabrication methods considered and describe our chosen method in detail, demonstrating its ability to produce devices with good pattern resolution. Our process and materials are non-toxic to the SMCs used and are also compatible with the various procedures

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of our experimental protocol, i.e. submersion in culture medium, and cell incubation, patterning and alignment. We succeed in measuring contractile forces in the order of 0.1 μ N with our fabricated devices.

9430-86, Session 11B

Humidity micro switch based on humidity-sensitive polymers

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Remarkably, 70% of all sensors in process control and more than 90% in building automation are sensor switches acting as threshold switches when changes of particular conditions require dedicated actions. For these purposes sensors are required which binary switch between two pre-defined states.

We present a binary threshold sensor based on the binary zero-power sensor (BIZEPS) platform which is able to use the energy provided directly from the measured relative humidity of the ambient air to mechanically switch an electrical micro contact. This zero-power switch behavior is realized by using the humidity-sensitive volume swelling of a polymer layer as the detection element deflecting a mechanical deformable silicon boss structure, thus closing the electrical contacts of the switch. For the humidity-sensitive sensor switch considered here, a humidity-sensitive hydrogel blend of poly(vinyl alcohol) and poly(acryl acid) was used. The sensitive part affected by the measurand is completely separated from the electrical part thus providing long-term stability. By using an inverse silicone stamping technique the polymer layer with a thickness of about 10 μ m was patterned on test structures possessing a thin silicon flexure plate of 3.9 mm x 3.9 mm in size and 20 μ m in thickness. The resulting bimorph sensor setup showed sufficiently large switching forces with an effective swelling pressure of 38 kPa. During several humidity cycles the swelling of the polymer layer showed a good reproducible deformation of the flexure plate of about 10 μ m while the average response time after humidity jumps amounted to about 6 minutes.

9430-87, Session 11B

Development of compact slip detection sensor using dielectric elastomer

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In this paper, We developed a resistance tactile sensor that can detect a slip on the surface of sensor structure. The presented sensor device has fingerprint-like structures that are similar with the role of the human's finger print. The resistance slip sensor that the novel developed uses acrylonitrile-butadiene rubber (NBR) as a dielectric substrate and graphene as an electrode material. We can measure the slip as the structure of sensor makes a deformation and it changes the resistance through forming a new conductive route. To manufacture our sensor, we developed a new imprint process. By using this process, we can produce sensor with micro unit structure To verify effectiveness of the proposed slip detection, experiment using prototype of resistance slip sensor is conducted with an algorithm to detect slip and slip is successfully detected. We will discuss the slip detection properties.

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Monday - Thursday 9 -12 March 2015

Part of Proceedings of SPIE Vol. 9431 Active and Passive Smart Structures and Integrated Systems 2015

9431-1, Session 1

Broadband performance of a patterned piezoelectric energy harvester integrated with a continuous elastoacoustic mirror

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Recent work has demonstrated efficient transformation of structure-borne propagating waves into low-power electricity using metamaterial-inspired mirror configurations. More recently, the design of distributed harvester configurations with patterned piezoelectrics has been proposed and verified experimentally. In this work we explore efficient transformation of broadband wave energy into low-power electricity using patterned polymer piezoelectrics integrated with an Elliptical Acoustic Mirror (EAM) configuration. Spatial and temporal transformation of the wave propagation field into the frequency-wavenumber domain is performed in order to identify the wavenumber content inside the mirror. A frequency-domain Root-Mean-Square (RMS) evaluation is then applied in order to guarantee broadband harvesting characteristics to the resulting Distributed Harvester (DH). Computational modeling and experimental testing are employed to quantify performance enhancement of the presented approach in the 20 - 120 kHz range, where broadband focusing characteristics of the EAM are confirmed by experimental evidence. Various case studies demonstrate performance enhancement of signal amplification and increased piezoelectric power generation for various harvester topologies, design frequency ranges, and material impedances. The effectiveness of the proposed configuration is verified experimentally, where significant improvement of power output over two comparison configurations is reported.

9431-2, Session 1

On the use of nonlinear solitary waves for energy harvesting

Kaiyuan Li, Piervincenzo Rizzo, Univ. of Pittsburgh (United States)

In the last decade there has been an increasing attention on the use of highly- and weakly- nonlinear solitary waves in engineering and physics. These waves can form and travel in nonlinear systems such as one-dimensional chains of particles. One engineering application of solitary waves is the fabrication of acoustic lenses, which are employed in a variety of fields ranging from biomedical imaging and surgery to defense systems and damage detection. In this paper we propose to couple an acoustic lens to a wafer-type lead zirconate titanate transducer (PZT) to harvest energy from the vibration of an object tapping the lens. The lens is composed of a circle array made of chains of particles in contact with a polycarbonate material where the nonlinear waves coalesce into linear waves. The PZT located at the designed focal point converts the mechanical energy carried by the stress wave into electricity to power a load resistor. The performance of the designed harvester is compared to a conventional cantilever beam, and the experimental results show that the power generated with the nonlinear lens has the same order of magnitude of the beam.

9431-3, Session 1

Hydraulic pressure energy harvester enhanced by Helmholtz resonator

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

Hydraulic pressure energy harvesters (HPEH) are devices that convert the dynamic pressure within hydraulic systems into usable electrical power through axially loaded piezoelectric stacks excited off-resonance by the fluid. Within hydraulic systems, the dominant frequency is typically a harmonic of the pump operating frequency. The pressure fluctuations coupled with the piezoelectric stack can be amplified by creating a housing design that includes a Helmholtz resonator tuned to the dominant frequency of the fluid excitation. A Helmholtz resonator is an acoustic device that consists of a cavity coupled to a fluid medium via a neck, or in this case a port connection to the fluid flow, that acts as an amplifier when within the bandwidth of its resonance. The implementation of a piezoelectric stack within the HPEH allows for a Helmholtz resonator to be included within the fluidic environment despite the significantly higher than air static pressures typical of fluid hydraulic systems (on the order of one to tens of MPa). The resistive losses within the system, such as from energy harvesting and viscous losses, can also be used to increase the bandwidth of the resonance; thus increasing the utility of the device. This paper investigates the design, modeling, and performance of hydraulic pressure energy harvesters utilizing a Helmholtz resonator design.

9431-4, Session 1

An experimentally validated contactless acoustic energy transfer model with resistive-reactive electrical loading

Shima Shahab, Michael Gray, Alper Erturk, Georgia Institute of Technology (United States)

This paper investigates analytical modeling and experimental validation of Ultrasonic Acoustic Energy Transfer (UAET) for low-power electricity transfer to exploit in wireless applications ranging from medical implants to underwater sensor systems. A piezoelectric receiver bar is excited by incident acoustic waves originating from a source of known strength located at a specific distance from the receiver. The receiver is a free-free piezoelectric cylinder operating in the 33-mode of piezoelectricity with a fundamental resonance frequency above the audible frequency range. In order to extract the electrical power output, the piezoelectric receiver bar is shunted to a generalized resistive-reactive circuit. The goal is to quantify the electrical power delivered to the load (connected to the receiver) in terms of the source strength. Experimental validations are presented along with parameter optimization studies. Sensitivity of the electrical power output to the excitation frequency in the neighborhood of the receiver's underwater resonance frequency, source-to-receiver distance, and source-strength level are reported. Resistive and resistive-reactive electrical loading cases are discussed for performance enhancement and frequency-wise robustness. Simulations and experiments reveal that the presented multiphysics analytical model for UAET can be used to predict the coupled system dynamics with very good accuracy.

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9431-5, Session 1

Energy scavenging from acousto-elastic metamaterial using local resonance phenomenon

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This article presents the possibility of energy scavenging (ES) utilizing the physics of acousto-elastic metamaterial and use them in a dual mode (Acoustic Filter and Energy Harvester), simultaneously. Traditionally acoustic metamaterials are used in filtering acoustic waves by trapping or guiding the acoustic energy, whereas this letter presents that the trapped dynamic energy inside the soft constituent (matrix) of metamaterials can be significantly harvested by strategically embedding piezoelectric wafers in the matrix. With unit cell model, we asserted that at lower acoustic frequencies maximum power in the micro Watts (~36 μ W) range can be generated, which is significantly higher than the recently reported phononic crystal based metamaterials (~30nW) against same resistive load. Efficient energy scavengers at low acoustic frequencies are almost absent due to large required size relevant to the acoustic wavelength. In this work we propose sub wave length scale energy scavengers utilizing the coupled physics of local, structural and matrix resonances. Upon validation of the argument through analytical, numerical and experimental studies, a broadband energy scavenger (ES) with multi-cell model is designed with varying geometrical properties.

9431-6, Session 2

Fail-safe linear stroke magnetorheological energy absorber using hybrid active-passive electromagnetic circuits

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Wei Hu, Norman M. Wereley, Univ. of Maryland, College
Park (United States)

Magnetorheological energy absorbers (MREAs) are used in vertically stroking crew seats to provide controllable stroking load to protect the lumbar spine during a high sink rate landing or crash event. Existing passive energy absorber designs are optimally designed for a 50th percentile male occupant weight. Using an MREA, the stroking load can be adjusted to accommodate the allowable loads of occupants of varying weight (e.g. from a 5th percentile female to a 95th percentile male), as well as varying crash severity (sink rate). The capability to adjust stroking load is achieved by pushing fluid through a valve where magnetic field is applied. This study focuses on the experimental validation of an MREA design [3] utilizing a hybrid magnetic circuit that combines electromagnets and permanent magnets. The inner bypass MREA consists of two concentric tubes that form an active fluid annular gap (1 mm), which allows for flow of the MRF through the hybrid magnetic circuit (Fig. 1). The damper was tested using a servohydraulic load frame, where a sinusoidal excitation was applied to the MREA, while varying oscillation frequency and applied current. The MREA has the ability to provide a maximum stroking load when maximum current (5.3 A), a mid-range stroking load with no applied current (fail-safe conditions), and minimum stroking loads at maximum negative current (-5.3 A). This study experimentally validates the design analysis and operational concept of the MREA for both vibration and shock mitigation problems.

9431-7, Session 2

A Prosthetic Knee Using Magnetorheological Fluid Damper for Above-Knee Amputees

Jinhyuk Park, Seung-Bok Choi, Inha Univ. (Korea, Republic of)

Prosthetic knee for above-knee (AK) amputee can be categorized into passive and active type, and it has been actively researched. A passive prosthetic knee is generally made by elastic material. Although AK amputee can easily walk by using passive prosthetic knee, knee joint motions are not similar to ordinary persons. On the other hand, The active prosthetic knee can control the knee angle because this type consists of actuator and microprocessor. However the active type needs actuator which can generate large energy for supporting the weight of the body. In order to solve these problems, semi-active prosthetic knee which can control the knee angle should be needed to use less energy than active type. Therefore, this paper presents a semi-active prosthetic knee by using magnetorheological (MR) damper for AK amputees. The proposed semi-active prosthetic knee has the MR damper, servomotor and microprocessor. Not only the MR damper can support the weight of body by using less energy than actuator of active prosthetic but it can also control knee angle by inducing the magnetic field at the time of stance phase. The servomotor controls the knee joint angle similar to ordinary person during swing phase. A mathematical model of human leg is formulated along with working principle. In order to control the knee angle PID control is adopted. Consequently, control performance of the proposed semi-active prosthetic knee is evaluated.

9431-8, Session 2

Behavior of a controllable fluid transport system

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

In this study a flexible fluid transport system utilizing a soft magnetorheological elastomer (MRE) in its actuating valve element is investigated. A time-dependent fluid-solid interaction finite element model under magnetic load is developed for this study. The effect of the geometrical parameters, structural properties, fluid properties and magnetic properties on the performance of the system is analyzed. Results demonstrate the effect of various parameters on the fluid propulsion capabilities. The proposed system is able to achieve the desired flow rate, if the system parameters are properly selected.

9431-9, Session 2

Design of energy-efficient MRF-based clutches with defined fail-safe behavior for integration in hybrid powertrains

 Dirk G. Güth, Jürgen Maas, Ostwestfalen-Lippe Univ. of
Applied Sciences (Germany)

Drag losses in the powertrain of hybrid electrical vehicles are a serious deficiency for an energy-efficient application. A promising approach for fulfilling requirements like efficiency, wear, safety and dynamics is the use of an innovative clutch design for the transmission of power is based on magnetorheological fluids (MRF). MRF are smart fluids with the particular characteristics of changing their apparent viscosity significantly under influence of the magnetic field and are characterized by fast switching times and a smooth torque control in the powertrain. In this paper, a novel clutch concept is presented that facilitates the controlled movement of the MRF from an active, torque-transmitting region into an inactive region of the shear gap. This concept enables complete decoupling of the fluid engaging

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surfaces such that viscous drag torque can be eliminated. Therefore, the simulation based design for such MRF-based clutches is presented, which considers in detail the required magnetic excitation systems for enabling a well-defined safety behavior by the fluid control.

An MRF prototype has been developed which provides a loss-reduced alternative to conventional separation elements in the powertrain. Especially the behavior of the clutch in case of a system failure is demonstrated, so that such clutches can be integrated in electrical or hybrid powertrain. By designing these types of actuators, the arrangement of coils, permanent magnets and shear gaps remains crucial for the magnetic fluid control, which is presented in detail. Simulation and experimental results underline the behavior of the presented clutch and show the potential for the mentioned application.

9431-10, Session 3

Underwater energy harvesting from vibrations of annular ionic polymer metal composites

Youngsu Cha, Shervin Abdolhamidi, Maurizio Porfiri, New York Univ. (United States)

Ionic polymer metal composites (IPMCs) are an emerging class of soft electroactive materials that are receiving considerable attention due to their large compliance, light weight, and ability to work in wet environments. These beneficial characteristics have led to the use of IPMCs as underwater actuators and sensors, and more recently, their application has expanded to include energy harvesting. Here, we investigate underwater energy harvesting from axisymmetric vibration of an in-house fabricated Nafion-based annular IPMC. The inner radius of the IPMC is clamped through copper electrodes to a moving base, while the outer radius is free. The IPMC electrodes are shunted to a resistance, which is systematically varied to understand the possibility of power harvesting. We propose a physics-based model for energy transduction, in which the IPMC is described as a thin annular plate undergoing axisymmetric bending vibrations. Since the encompassing fluid reduces the natural frequencies of the plate by virtually increasing its mass, we model the effect of the fluid using a hydrodynamic function that accounts for added mass. Theoretical predictions for the IPMC vibrations are fed to a lumped circuit model, which is utilized to describe the IPMC electrical response as a function of the mean curvature and, ultimately, to quantify power harvesting. The resulting electromechanical model allows for predicting the harvested power from the annular IPMC as a function of the shunting load resistance and the frequency of the base excitation. Model results are validated against experimental findings that demonstrate the feasibility of power harvesting from annular IPMCs.

9431-11, Session 3

Unified electrohydroelastic investigation of underwater energy harvesting and dynamic actuation by incorporating Morison's equation

Shima Shahab, Alper Erturk, Georgia Institute of Technology (United States)

In this work, Macro-Fiber Composite (MFC)-based piezoelectric structures are employed for underwater mechanical base excitation (vibration energy harvesting) and electrical biomimetic actuation in bending at low frequencies. The MFC technology (fiber-based piezoelectric composites with interdigitated electrodes) exploits the effective 33-mode of piezoelectricity and strikes a balance between structural deformation and force levels for actuation to use in underwater locomotion, in addition to offering high power density for energy harvesting to enable battery-less underwater sensors. Following in-air electroelastic model development, it is aimed to establish semi-analytical models that can predict the underwater dynamics

of thin MFC cantilevers for different length-to-width aspect ratios. In-air analytical electroelastic dynamics of MFCs is therefore coupled with added mass and nonlinear hydrodynamic damping effects of fluid to describe the underwater electrohydroelastic dynamics in energy harvesting and actuation. To this end, passive plates of different aspect ratios are tested to extract and explore the repeatability of the inertia and drag coefficients in Morison's equation. The focus is placed on the first two bending modes in this semi-analytical approach. Additionally, nonlinear dependence of the output power density to aspect ratio is characterized theoretically and experimentally in the underwater base excitation problem.

9431-12, Session 3

Integrated structures for hybrid wind and solar energy harvesting

Punnag Chatterjee, Matthew J. Bryant, North Carolina State Univ. (United States)

In most natural environments, wind flow and solar radiation represent the predominant ambient energy sources. This paper envisages to develop multifunctional compliant structures that can generate electrical power from both incident solar radiation and ambient wind flow. Such a device would be an ideal power source for data collection and remote sensing in environments where sunlight becomes intermittently unavailable but still the device would provide a secondary opportunity for power generation through harvesting the wind kinetic energy. Thus creating a single device that has the capacity to generate power from both these disparate energy sources could provide reliable, year round power both day and night. A few places which would highlight its applicability would be urban canyons and polar region where direct sunlight is unavailable for most of the day to months at a stretch, in the later case, however ample wind energy is present to keep generating power from the device.

We have recently reported on axial flow cantilevered piezoelectric structures that use aeroelastic flutter vibrations to produce large but stable limit cycle oscillations suitable for effective power extraction over a range of flow speeds. This paper will investigate a new design that combines piezo-aeroelastic energy harvesting functionality along with flexible, thin-film photovoltaic cells for capturing solar energy in a single integrated device. Furthermore, the multifunctional energy harvesting concept proposed here will be compact, low-mass, and flexible.

The proposed device consists of an array of thin, flexible solar cells clamped under tension at either end. PZT patches are laminated at the ends of the solar films as shown in Fig. 1. The wind flowing over the device induces transverse flutter vibration which is harvested through the piezoelectric transduction in addition to harvesting solar energy. This paper will discuss experimental development of this novel energy harvester and investigate the effects of varying different parameters like tension, angle of attack, and geometric dimensions of the piezo-solar films on the energy harvester performance.

9431-13, Session 3

Enhancement of galloping-based wind energy harvesting by synchronized switching interface circuits

Liya Zhao, Nanyang Technological Univ. (Singapore); Junrui Liang, ShanghaiTech Univ. (China); Lihua Tang, The Univ. of Auckland (New Zealand); Yaowen Yang, Nanyang Technological Univ. (Singapore); Haili Liu, ShanghaiTech Univ. (China)

Galloping phenomenon has attracted extensive research attention for small-scale wind energy harvesting due to its merits of large-amplitude of oscillations and capability of working in wide wind speed range. In the reported literature, the dynamics and harvested power of a galloping-based

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energy harvesting system are usually evaluated with a resistive AC load; these characteristics might shift when a practical harvesting interface circuit is connected for extracting useful DC power. In the family of piezoelectric energy harvesting interface circuits, synchronized switching harvesting on inductor (SSHI) has demonstrated its advantage for enhancing the harvested power from existing base vibrations.

This paper investigates the harvesting capability of a galloping-based wind energy harvester using SSHI interface, with a focus on comparing its performance with that of a standard DC interface at various coupling strengths. The prototyped galloping-based piezoelectric energy harvester (GPEH) comprises a bimorph cantilever attached with a square-sectioned bluff body made of foam. According to different electrical connections (series, parallel, or single layer), three coupling strengths can be implemented. Equivalent circuit model (ECM) of the GPEH are established respectively. System-level circuit simulations with SSHI and standard interface circuits are performed and validated with wind tunnel tests. Both experiment and simulation demonstrate that SSHI interface circuit can significantly improve the performance of GPEH with a realistic coupling strength. Further comprehensive parametric study based on circuit simulation is conducted to understand the influence of coupling on the aerodynamic behavior of GPEH and the consequences for power output from GPEH.

9431-14, Session 3

A hydrostatic pressure-cycle energy harvester

Michael W. Shafer, Gregory Hahn, Eric R. Morgan, Northern Arizona Univ. (United States)

There have been a number of new applications for energy harvesting with the ever-decreasing power consumption of microelectronic devices. In this paper we explore a new area of marine animal energy harvesting for use in powering tags known as bio-loggers. These devices record data about the animal or its surroundings, but have always had limited deployment times due to battery depletion. Reduced solar irradiance below the water's surface provides the impetus to explore other energy harvesting concepts beyond solar power for use on marine animals. We review existing tag technologies in relation to this application, specifically relating to energy consumption. Additionally, we propose a new idea for energy harvesting, using hydrostatic pressure changes as a source for energy production. We present initial testing results of a bench-top model and show that the daily energy harvesting potential from this technology can meet or exceed that consumed by current marine bio-logging tags. The application of this concept in the arena of bio-logging technology could substantially increase bio-logger deployment lifetimes, allowing for longitudinal studies over the course of multiple breeding and/or migration cycles.

9431-15, Session 3

A new energy harvester for fluids in motion

Corrado Boragno, Gregorio Boccacero, Univ. degli Studi di Genova (Italy)

A new energy harvester, named FLEHAP (Fluttering Energy Harvester for Autonomous Powering), will be presented.

The FLEHAP device is based on the fluttering effect: when a fluid in motion impinges on a structure, an amount of the mechanical energy can be transferred to the structure, inducing large amplitude oscillations. The FLEHAP device is based on a wing connected to a support by two elastomers. The wing can freely rotate around a rigid axis where the elastomers are fixed. When a fluid in motion impinges on such a structure, large amplitude oscillations can be induced if few mechanical parameters are correctly set: mass and shape of the wing, strength of the elastomers, pivot point of the wing. The device can operate in air (wind) or flowing

water. To convert the mechanical energy in electrical energy, two different approaches can be adopted: 1) an electromagnetic coupling EMC or 2) by using electroactive polymers EAP. With a centimeter-size device and EMC, more than 5-10 mW can be available in a wind around 3-6 m/s .

9431-16, Session 4

Fluidic origami cellular structure: Combining the plant nastic movements with paper folding art

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

Inspired by the nastic movement of plants, we propose a new class of multi-functional adaptive structure called fluidic origami. The idea is to connect multiple Miura folded panels along their fold lines into a cellular structure and then fill the space in-between with pressurized fluid of high bulk modulus. The correlation between the fluid volume and the structural deformation is primarily determined by the kinematics of folding. Such correlation can be exploited so that fluidic origami can achieve actuation/morphing by actively changing the internal fluid volume, or stiffness tuning by constraining the fluid volume. Furthermore, bi-stability is also possible because there exists two different folding configurations with the same internal volume. These adaptive functions are analytically characterized by transforming the continuous origami structure into an equivalent truss frame, and can be demonstrated on a 3D printed physical pro-otype. The proposed fluidic origami concept combines the physical principles behind the plant nastic motion and the rich design variety of the paper folding art, thus it has the potential of fostering a new generation of high performance adaptive structures.

9431-17, Session 4

Meso-hydraulic actuation for small legged robots

Edward Chapman, Marc MacLeod, Matthew J. Bryant, North Carolina State Univ. (United States)

While wheels and tracks driven by electromagnetic motors are familiar designs for ground robot locomotion, legged platforms are advantageous for navigating rough terrain, climbing walls, and grasping to small toe-holds. The objective of this work is to investigate robot architectures that utilize lightweight hydraulic power to enable efficient walking or climbing robots. Using hydraulic actuation in a legged robot is an attractive concept, but has received little research attention to date because the size and weight of traditional hydraulic systems are a poor match for small climbing robots. Hydraulic actuation can allow a single electric motor to drive a pump and power several degrees of freedom rather than performing electrical to mechanical transduction with a motor at each joint and limb in the robot. This allows the transducer to be driven at its peak efficiency point while storing fluidic power in an accumulator, rather than operating at constantly changing speed and torque loading and slewing through inefficient regions of the motor's transduction curve.

This paper will develop an electromechanical system model for a closed-loop energy-efficient hydraulic power and actuator system for small robots. The system design consists of an electric motor, hydraulic pump, pressure accumulator, and a network of hydraulic actuators such as fluidic artificial muscles. During operation the electric motor pumps hydraulic fluid into the accumulator, increasing the fluid pressure inside. To perform actuation, a network of valves are triggered and the high pressure within the accumulator forces hydraulic fluid into actuator, generating linear force and motion. In order to maximize the system efficiency, the motor operating point must be optimized throughout the robot actuation and locomotion cycle by sizing the accumulator and system pressure to the actuator fluid flow requirements and locomotion duty cycle. Furthermore, in applications such as small climbing robots, it is important that the hydraulic systems be as compact and low mass as possible.

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The objective of this model is to provide a systematic approach to sizing the individual system components based on the magnitude and desired duty cycle of actuation. The motor, pump, and accumulator can all be sized such that the motor is able to run at maximum efficiency. An analytical model of the system characterizing its performance will be described. Equations describing the behavior of system components such as the battery, motor, pump, accumulator, and actuators have been formulated to generate a system of coupled equations that describe the overall system behavior.

9431-18, Session 4

Nylon muscle actuated robotic hand

Lianjun Wu, Monica Jung de Andrade, Richard S. Rome, Yonas T. Tadesse, Ray H. Baughman, The Univ. of Texas at Dallas (United States)

This paper presents the design and experimental analysis of a biomimetic robotic hand utilizing a new actuation system. The robotic hand is actuated by novel artificial muscles made of twisted and coiled nylon fibers. The proposed design employs symmetric pumping chambers for hot and cold fluids in order to actuate the artificial muscles and provide fast finger movements. In this paper, we investigate the design parameters that provide optimum performance, such as fast hand motion, high force generation, and controllable compliance. The concept design will be validated on the current prototype of the nylon muscle actuated robot hand. We will carry out further experiments to verify the actuation system and study the grasping capability of the robotic hand. The prototype hand will be manufactured using rapid manufacturing technology. This is the first implementation of coiled nylon artificial muscle for robotic hand design. Our goal is to design a cost-effective artificial hand that mimics human hand function with novel artificial muscles and semi rigid structures.

9431-19, Session 5

An investigation on vibration energy harvesting using nonlinear dynamic principles inspired by trees

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

Trees exploit intriguing mechanisms, including particular multimodal frequency distributions and nonlinearities, to distribute and structurally dampen the aerodynamically-induced vibration energies to which they are subjected. In dynamic systems context, these mechanisms are comparable to internal resonance phenomena. Researchers are recently harnessing strong nonlinearities, including internal resonance, to induce new and energetic dynamics to enhance vibration energy harvesting system performance. For trees, the internal resonance-like dynamics are evidently robust. Yet for dynamic systems, studies on internal resonance show narrow operating regimes in which the behaviors are exhibited, and deliberate experimental evaluation of such dynamics for energy harvesting systems remain outstanding. To resolve these unknowns, the aim of this research is to thoroughly examine the opportunities enabled by exploiting nonlinear multimodal behaviors related to internal resonance for improved energy harvesting performance. Two harvester platforms are considered, characterized by either mono- or bistability, and both are developed to exhibit a linear mode proportionality of 1:2. The system dynamics are probed analytically and numerically to develop first insights prior to experimental explorations that evaluate the utility of internal resonance phenomena for energy harvesting. It is found that favorable energetic behaviors due to internal resonance are more readily activated and sustained for bistable systems, which also excite snap-through dynamics to induce significantly larger electrical response than monostable platforms. Finally, the implications of the findings are discussed to assess the viability of exploiting such tree-inspired phenomena in energy harvesting systems.

9431-20, Session 5

Piezoelectric cantilever-based energy harvesting with internal resonance

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

In this research we explore utilizing internal resonances to realize harvesting vibratory energy generated by excitations from multiple directions with the usage of a single piezoelectric cantilever. Specifically, it is identified that by attaching a pendulum to the piezoelectric cantilever, 1:2 and 1:1 internal resonances can be induced based on the nonlinear coupling. Systematic analysis and experimental investigation are carried out to demonstrate this new concept.

9431-21, Session 5

Array of piezoelectric oscillators with an SECE circuit

Ping-Hsien Wu, Yi-Chung Shu, National Taiwan Univ. (Taiwan)

This talk reports the study of an array of piezoelectric energy harvesters endowed with an SECE (synchronized electric charge extraction) interface circuit. Much works have been paid on the investigations of SECE circuits attached to a single piezoelectric oscillator, including to the circuit optimization for maximum power transfer and the extension to bi-stable harvesters for wideband energy harvesting. However, none of them has considered the connection of this circuit to multiple piezoelectric oscillators. As an array structure offers advantages of boosting power output and exhibiting broadband energy harvesting, there is a need for investigating its electromechanical response using the SECE interface. Indeed, the electrical performance of an SECE array system is analytically obtained and compared with the use of standard and SSHI (synchronized switch harvesting on inductor) interface circuits. It is found that the SECE circuit outperforms the other cases for the array systems with medium electromechanical coupling. Precisely, the SECE system not only exhibits better broadband energy harvesting but its harvested power is independent of the external load. The former provides bandwidth improvement and the latter gives advantage in the back-end interface design.

9431-22, Session 5

Chaotic control of a piezomagnetoelastic beam for improved energy harvesting

Daniel Geiyer, Jeffrey L. Kauffman, Univ. of Central Florida (United States)

Linear cantilevered piezoelectric energy harvesters do not typically operate efficiently through a large span of excitation frequencies. Beam theory dictates optimum displacement at resonance excitation; however, typical environments evolve and vary over time with no clear dominant frequency. Nonlinear, non-resonant harvesting techniques have been implemented, but none so far have embraced chaotic behavior as a desirable property of the system. This work aims to benefit from chaotic phenomena by stabilizing high energy periodic orbits located within a chaotic attractor to improve operating bandwidth. Direct use of the piezoelectric voltage in applying the small perturbations needed for OGY control will also be investigated. Special attention will be paid to capture how piezoelectric parameter changes affect the size and shape of the strange attractor. Although chaos in non-autonomous systems is typically associated with harmonic inputs, various alternate inputs will be studied to determine whether real time controller modifications can regularly produce a stabilized periodic orbit. An experimental test stand will be used to verify displacement and power output from the harvester to compare results with common configurations in the literature.

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9431-23, Session 6

Vibration energy harvesting from a nonlinear standing beam-mass system using a two-mode approximation

S. Amir M. Lajimi, Simon Fraser Univ. (Canada); Michael I. Friswell, Swansea Univ. (United Kingdom)

For a nonlinear beam-mass system used to harvest vibratory energy, the two-mode approximation of the response is computed and compared to the single-mode approximation of the response. To this end, the discretized equations of generalized coordinates are developed and studied using a computational method. By obtaining phase-portraits and time-histories of the displacement and voltage, it is shown that the strong nonlinearity of the system affects the system dynamics considerably. By comparing the results of single- and two-mode approximations, it is shown that the number of mode shapes affects the dynamics of the response. Varying the tip-mass results in different structural configurations namely linear, pre-buckled nonlinear, and post-buckled nonlinear configurations. We are investigating the nonlinear dynamics of the system response for vibrations about static equilibrium points appearing upon buckling of the beam. Furthermore, it is demonstrated that the harvested power is affected by the system configuration.

In this work, discretizing the energy expressions using a two-mode approximation, and substituting the results into the Lagrange's equations the governing equations of motion are obtained. We obtain the coupled electromechanical equations for a two-mode approximation of the response and solve the system of equations for the displacement, velocity, and voltage. The results of the analysis are reported in terms of time-histories of the displacement and voltage drop across the resistance load and the phase-portraits. The response is highly nonlinear strongly affected by the magnitude of the tip-mass.

9431-24, Session 6

A diamagnetically stabilized horizontally levitated electromagnetic vibration energy harvester

Sri Vikram Palagummi, North Carolina State Univ. (United States); Junchao Zou, North Carolina State University (United States); Fuh-Gwo Yuan, North Carolina State Univ. (United States)

This paper investigates a diamagnetically stabilized horizontally levitated system for vibration energy harvesting in contrast to the diamagnetically stabilized vertically levitated system recently proposed. In this configuration, two large magnets, alias lifting magnets, are arranged co-axially at a distance such that in between them a magnet, alias floating magnet, is passively levitated at a lateral static equilibrium position. The levitation is stabilized in the horizontal direction by two diamagnetic plates made of pyrolytic graphite placed on each side of the floating magnet. This horizontal configuration mitigates the limitation on the amplitude of the floating magnet imposed in the vertical configuration and exploits the ability to tailor the geometry to meet specific applications. Also, the stabilization conditions are more relaxed and provides with a robust tuning on natural frequency.

This configuration gives rise to a softening frequency response in the vertical direction. A simple circular coil geometry is designed to replace a portion of the pyrolytic graphite plate without sacrificing the stability of the levitation for transduction. An experimental setup validates the theoretical findings; at an input mechanical power of 186.6 μ W and at a frequency of 1.2 Hz, the prototype generated a peak power of 7.2 μ W with a system efficiency of 3.85%.

9431-25, Session 6

Piezoelectric energy harvesting with a nonlinear energy sink

Yu Zhang, Kefu Liu, Lakehead Univ. (Canada); Lihua Tang, The Univ. of Auckland (New Zealand)

This paper reports a novel piezoelectric energy harvester. The objective of the reported study is twofold: vibration suppression and energy harvesting. Different from existing nonlinear energy harvesters, the proposed apparatus is based on the principle of the nonlinear energy sink (NES). It comprises a fixed-fixed beam, a pair of oscillating permanent magnets, and a fixed permanent magnet. The fixed-fixed beam is formed by a thin steel beam, each of whose ends is connected to a piezoelectric transducer that is fixed to the support. The pair of permanent magnets is placed at the center of the beam, acting as the NES mass. The beam is compressed axially to achieve a very low linear stiffness due to buckling effect. The stationary position of the oscillating magnets can be kept at zero by a collinear fixed magnet. The apparatus is placed on a primary structure. To emulate the NES behavior, the linear natural frequency of the NES system is kept much lower than that of the primary system.

Equations of motion and state space model are formulated with identified parameters from the experiment. Simulation is performed to investigate the transient behaviors of the system in terms of energy harvesting and vibration absorption, followed by experimental validation. The proposed apparatus can achieve an essential nonlinearity. It is found that as long as the initial energy reaches the required threshold, the NES will be activated and energy can be efficiently transferred to the NES. In this sense, the proposed energy harvester processes a wideband performance.

9431-26, Session 6

Tunable bistable devices for harvesting energy from spinning wheels

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Bistable systems have recently been employed for vibration energy harvesting owing to their favorable dynamic characteristics and desirable response for wideband excitation. In this paper, we investigate the use of bistable harvesters to extract energy from spinning wheels. The harvester consists of a cantilever beam carrying a tip mass in the form of a permanent magnet and mounted on a rigid spinning hub. Magnetic repulsion forces from an opposite magnet cause the beam to possess two stable equilibrium positions. Interwell lead-lag oscillations caused by rotation in a vertical plane provide a good source for energy extraction. The design also offers frequency tuning, as the centrifugal forces strain the harvester, thereby increasing its natural frequency to cope with a variable rotational speed. This has applications in self-powered sensors mounted on spinning wheels, such as tire pressure monitoring sensors. To this end, a piezoelectric energy harvester in the form of a rotating beam is proposed. An effort is made to select the design parameters to enable the harvester to exhibit favorable interwell oscillations across a wide range of rotational speeds for enhanced energy harvesting. Findings of the present work are verified both numerically and experimentally.

9431-27, Session 7

Spanwise morphing trailing edge on a finite wing

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Morphing seeks to improve the aerodynamic performance of an aircraft by reconfiguring the geometry to adapt to changing flight conditions. Unmanned Aerial Vehicles are prime targets for morphing implementation as they seek high performance over long periods of time at low airspeeds while adapting to locally varying wind conditions. The adoption of morphing mechanisms in UAV design is limited by substantial changes required in the structure of the aircraft during the design process. The Spanwise Morphing Trailing Edge concept allows for local camber variation of the trailing edge of a wing or control surface without altering the load-carrying spar box. Utilizing a modular design of active sections driven by Macro Fiber Composites with compliant mechanisms, spanned by inactive sections of elastomeric honeycombs, the SMTE concept eliminates discontinuities increasing aerodynamic performance. Previous work investigated a representative section of the SMTE concept and investigated the effect of various skin designs on actuation authority. The current work seeks to experimentally evaluate the aerodynamic gains, energy requirements and mass distribution for the SMTE concept for a representative finite wing. Aerodynamic forces for a conventional wing with a similar aileron pattern are identified for several different configurations and flight conditions. Spanwise flow from the tip vortex as well as discontinuities at the flap junctions are shown to significantly impact aerodynamic performance. An identical wing with the SMTE concept is shown to eliminate these discontinuities and dramatically improve control over spanwise flow caused by the tip vortex.

9431-28, Session 7

Modeling and development of a twisting wing using inductively heated shape memory alloy actuators

Robert Saunders, James G. Boyd IV, Darren J. Hartl, Dimitris C. Lagoudas, Texas A&M Univ. (United States)

Wing twisting has been shown to possess a number of characteristics that can improve aircraft flight performance. The potential benefits of the twisting wing system have largely been outweighed by the mass of the system required to twist the wing. Shape memory alloy (SMA) actuators have repeatedly demonstrated abilities and properties that are ideal for aerospace actuation systems. Recent advances have shown an SMA torsional actuator that can be manufactured and trained with the ability to generate large twisting deformations under substantial loadings. The primary disadvantage of implementing an SMA actuator is its slow actuation time compared to conventional actuators. Inductive heating of the SMA actuator allows the actuator to heat in just seconds rather than minutes while still generating a full actuation cycle. The aim of this work is to show a wing being twisted to approximately 10 degrees by using an inductively heated SMA torsional actuator. This study will implement a 3-D electromagnetic thermo-mechanical model of the SMA-wing system and compare these results to experiments to demonstrate the models capabilities.

9431-29, Session 7

Multimodal sensing strategies for detecting transparent barriers indoors from a mobile platform

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There is currently an interest in developing semi-autonomous mobile sensing platforms that fly indoors. The primary goal for these platforms is to be able to successfully navigate a building under various lighting and environmental conditions. There are numerous research challenges

associated with this goal, one of which is the platform's ability to detect the presence of transparent barriers. These barriers could include windows, glass partitions, or skylights. For example, in order to successfully navigate inside of a structure, these platforms will need to sense if a space contains a transparent barrier and whether or not this space can be traversed. This project will focus on developing a multi-modal sensing system that can successfully identify such transparent barriers under various lighting conditions while aboard a mobile platform. It will be critical for this system to be able identify transparent barriers and maneuver accordingly in real-time. The properties associated with the interaction between various frequencies of light and transparent materials will be one of the techniques leveraged to solve this problem.

9431-30, Session 7

Morphing wingtips based on inflatable honeycomb structures

Jian Sun, Harbin Institute of Technology (China); Fabrizio Scarpa, Univ. of Bristol (United Kingdom); Yanju Liu, Jinsong Leng, Harbin Institute of Technology (China)

Morphing wingtip is a typical example of a shape changing structure that improves the lift to drag ratio during climb by effectively changing the length of the wingspan. Additional advantages of using a morphing wingtip consist in the reduction of the induced drag at high speeds, and the reduction of the overall fuel consumption in high altitude long endurance (HALE) flights. This paper describes a morphing honeycomb configuration with negative Poisson's ratio (auxetic) topology, actuated through inflatable tubes. Auxetic configurations feature a volumetric expansion of the solid under tensile loading, and conversely shrinking when the loading is compressive. The type of auxetic honeycomb considered in this work has the classical re-entrant (butterfly) configuration. A demonstrator of a unit cell of the active honeycomb is manufactured and tested, and relations between the input pressure in the inflatable tube and overall deformation of the morphing structures are measured, showing a general satisfactory agreement with the predictions provided by the model. Finally, a morphing wingtip structure was fabricated to demonstrate this concept.

9431-31, Session 7

A robust two-way switching control system for remote piloting and stabilization of low-cost quadrotor UAVs

Francesco Ripamonti, Ferruccio Resta, Andrea Vivani, Politecnico di Milano (Italy)

During the last decade drones and, more precisely, Unmanned Aerial Vehicles (UAVs) gained more and more importance in the scientific community. This because their capabilities have been exploited in a wide range of fields, from aerial imaging to area mapping, from objects delivering to military applications. This opened the way to mass production and the consequent development of specific control logics, suitable for many different vehicle uses and characterized by low costs of implementation.

The aim of this paper is to present two possible control logics for UAV stabilization and remote piloting, that are as robust as possible to physical parameters variation and to impulsive or periodic external disturbances (e.g. wind). Moreover, they can be implemented on low-cost micro-controllers, in order to be attractive for commercial drones. A possible application of the two switching control logics could be facial recognition by means of a camera mounted on the drone. The first control logic (low computational requirements) is used to reach the target. Once it has been acquired, the second logic (higher stability) is activated in order to perform the tasks needed to recognize the subject (maintaining a position, follow a specific path around the subject) in presence of external disturbances. Particular attention is paid to robustness as an essential requirement for these smart structures, so that specific on-site calibration of the control system is not required even in presence of uncountable number of uncertainties.

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9431-32, Session 7

Planform, aero-structural, and flight control optimization for tailless morphing aircraft

Giulio Molinari, Andres F. Arrieta, Paolo Ermanni, ETH Zürich (Switzerland)

No Abstract Available

9431-62, Session PTues

Design of a bidirectional piezoelectric hybrid actuator

Xiao Long Jin, Ngoc-San Ha, Nam Seo Goo, Konkuk Univ. (Korea, Republic of); Tae Heun Kim, Byung Woon Bae, Firstec Co. (Korea, Republic of); Chang Seop Lee, Agency for Defense Development (Korea, Republic of)

Piezoelectric-based hydraulic actuator is a hybrid device of a hydraulic pump driven by piezoelectric stacks which is coupled to a conventional hydraulic cylinder via a set of fast-acting valves. Nowadays, such hybrid actuators are being researched and developed actively in many developed countries by requirement of high performance and compact flight system. In this research, a piezoelectric hybrid actuator was designed and tested. To achieve bi-directional capabilities in the actuator, the commercial solenoid valves were used to control the direction of output cylinder. The experimental testing of the actuator in unidirectional and bi-directional modes was performed to examine performance issues related to the solenoid valves. The results showed that the maximum blocked force was measured by 826.0N when the frequency was 150Hz.

9431-100, Session PTues

Creation of smart discrete-nanostructures using soft materials-derived lithography

Jae Hong Park, National Nanofab Ctr. (Korea, Republic of)

One of the two main processes of engineering nanostructures is the top down method, which is a direct engineering method for Si-type materials using photolithography or e-beam lithography. The other method is the bottom-up method, using nano-imprinting. However, these methods are very dependent on the equipment used, and have a high process cost. They are also relatively inefficient methods in terms of processing time and energy. Therefore, some researchers have studied the replication of nano-scale patterns via the soft lithographic concept, which is more efficient and requires a lower processing cost. In this study, accurate nanostructures with various aspect ratios are created on several types of materials. A silicon (Si) nanomold is preserved using the method described, and target nanostructures are replicated reversibly and unlimitedly to or from various hard and soft materials. The optimum method of transferring nanostructures on polymeric materials to metallic materials using electroplating technology was also described. Optimal replication and demolding processes for nanostructures with high aspect ratios, which proved the most difficult, were suggested by controlling the surface energy between the functional materials. Relevant numerical studies and analysis were also performed. Our results showed that it was possible to realize accurate nanostructures with high depth aspect ratios of up to 1:18 on lines with widths from 300–400 nm.

In addition, we were able to expand the applicability of the nano structured mold by adopting various backing materials, including a rounded substrate. The application scope was extended further by transferring the nanostructures between different species of materials, including metallic materials as well as an identical species of material. In particular, the methodology suggested in this research provides the great possibility

of creating nanostructures composed of various materials, such as soft polymer, hard polymer, and metal, as well as Si. Such nanostructures are required for a vast range of optical and display devices, photonic components, physical devices, energy devices including electrodes of secondary batteries, fuel cells, solar cells, and energy harvesters, biological devices including biochips, biomimetic or biosimilar structured devices, and mechanical devices including micro- or nano-scale sensors and actuators.

9431-101, Session PTues

A spring-roll EAP actuator applied as end-effector of a hyper-redundant robot

Francesco Ripamonti, Gianmarco Errico, Victor Fava, Ferruccio Resta, Politecnico di Milano (Italy)

During the last decade, continuum or hyper-redundant robots have been adopted in many and many applications such as the exploration of hardly accessible areas or the minimally invasive surgery in medical field. They are continuously curving manipulator, similarly to a snake or an arm of an octopus, and they have a very high number of sub-actuated degrees of freedom (dof). They usually mount a device as the end-effector to perform the desired task. For all these reasons, requiring a precise and repeatable positioning system, they represent a challenge from the design and the control point of view.

In this paper a 9 links (18 dof) continuum robot with 12 actuators is shown. The design of the structure, as well as the actuation system, is described in detail. Moreover, particular attention is paid to the end-effector where a video camera is mounted. In order to enhance the robot performances, an Electro Active Polymers (EAP) spring-roll actuator is designed and manufactured as a support for the camera. The 2-dof spring-roll is basically a compression spring on which two pre-strained acrylic films are rolled up. In this case, the EAP represents a very attractive solution thanks to its high strain properties (allowing a rotation of the point of view up to 30-40 degrees) and relative low cost and weight.

9431-102, Session PTues

Design of an innovative magnetostrictive patch actuator

Simone Cinquemani, Hermes Giberti, Politecnico di Milano (Italy)

Magnetostrictive actuators can be profitably used to reduce vibration in structures. However, this technology has been exploited only to develop inertial actuators, while patches actuators have not been ever used in practice. Patches actuators consist on a layer of magnetostrictive material, which has to be stuck to the surface of the vibrating structure, and on a coil surrounding the layer itself. However, the presence of the winding severely limits the use of such devices. As a matter of fact, the scientific literature reports only theoretical uses of such actuators, but, in practice it does not seem they were ever used. This paper presents an innovative solution to improve the structure of the actuator patches, allowing their use in several practical applications.

The principle of operation of these devices is rather simple. The actuator patch is able to generate a local deformation of the surface of the vibrating structure so as to introduce an equivalent damping that dissipates the kinetic energy associated to the vibration. This deformation is related to the behavior of the magnetostrictive material immersed in a variable magnetic field generated by the a variable current flowing in the winding. Contrary to what suggested in the theoretical literature, the designed device has the advantage of generating the variable magnetic field no longer in close proximity of the material, but in a different area, thus allowing a better coupling. The magnetic field is then conveyed through a suitable ferromagnetic structure to the magnetostrictive material.

The device has been designed and tested. Its performance have been compared to traditional solutions and good results have been obtained.

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Results confirm that the new configuration can easily overcome all the limits of traditional devices.

9431-103, Session PTues

Low frequency inertial control strategy for seismic attenuation with multi-stage mechanical suspensions

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Rosario De Rosa, Univ. degli Studi di Napoli Federico II (Italy); Gerardo Giordano, Rocco Romano, Fabrizio Barone, Univ. degli Studi di Salerno (Italy)

This paper describes the application of monolithic folded pendulum sensors to the inertial control of multi-stage mechanical suspensions for seismic attenuation, of the same class of those used in interferometric detectors of gravitational waves, with requirement of $10\sqrt{15}$ m/sqrt(Hz) in the band $0.01 \div 100$ Hz. The experimental results in the band $0.01 \div 10$ Hz demonstrate that this class of mechanical sensors has enough dynamics and sensitivity to introduce no limitations to control systems. Moreover, the full scalability of the sensors allows an easy integration and positioning also on the different stages of multistage mechanical suspensions (seismic attenuators) and inertial platforms. This new application demonstrates not only the feasibility of the proposed inertial control strategy in the low frequency region, but, and it is very relevant, that it is now possible the implementation of very effective state-of-the-art control systems with a large reduction of control electronics, replaced by less noisy optical and mechanical devices, with the further advantage of systems less sensitive to environmental noises. The results of this study, has also lead to develop a more general model for very different applications (platforms and mechanical structure control and stabilization, building controls, etc.).

9431-104, Session PTues

A novel resonant based viscometer for magnetorheological fluid

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Abstract:

A new method to measure the viscosity of magnetorheological (MR) fluid in shear mode using resonance concept is proposed. The viscosity measurement system is designed using the resonant cantilever beam probing with the rotating shaft mechanism. The electromagnetic coil is mounted at the free end of the resonating cantilever beam and the metal core of coil is acts as a probing tip. The gap between the probing tip and the rotating shaft is filled with MR fluid to form a shear mode operation. The cantilever beam is vibrated at resonance using the piezoelectric actuation/sensing techniques and the resonance is maintained using the simple closed loop resonator electronics. The input current to the coil is varied and the magnetic field produced by the coil changes the viscosity of MR fluid, which produces a viscous drag force on the vibrating cantilever beam. The viscous drag force created by the MR fluid induces an additional stiffness to the resonating cantilever beam and alters the initial resonant frequency. The shift in resonant frequency due to the change in viscosity of the MR fluid is measured with help of resonator electronics circuit and its viscosity is related to the field dependent yield stress of the of MR fluid. The proposed measurement system is evaluated experimentally and the results are verified with commercially available viscometer (SSS Lab). The schematic representation of the proposed method is shown in figure 1.

9431-105, Session PTues

Passive vibration control in a building-like structure using a tuned-mass-damper and an autoparametric cantilever beam absorber

Josue Enriquez-Zarate, Hugo F. Abundis-Fong, Gerardo Silva-Navarro, Ctr. de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional (Mexico)

This article considers a theoretical and experimental comparative analysis in the responses of a three-story building-like structure using two different schemes of passive vibration control. These control schemes are designed to reduce the effects of resonant vibrations generated by an electromechanical shaker located in the base of the building-like structure. The first diagram of control consists on the design of a Tuned-Mass-Damper collocated over the third floor of the structure, and the second diagram of control considers the implementation of an autoparametric cantilever beam absorber. The mathematical model of the overall system is obtained using Euler-Lagrange method. In order to validate the frequency response of the main system a Finite Element Model is completed. The performance of the control schemes are validated by means of a stability analysis in the sense of Lyapunov. Some experimental and numerical results are shown of the dynamical control and stability of the overall system.

9431-106, Session PTues

Design and Analysis of an Innovative Combined Magnetorheological Damper-Mount

Phu Xuan Do, Inha University (Korea, Republic of); Ung Jye Chung, Inha Univ (Korea, Republic of); Seung-Bok Choi, Inha Univ. (Korea, Republic of)

This research focuses on development of an innovative mount featuring magnetorheological fluid (MRF). The mount consists of a MR valve structure with moth annular and radial flows and a by-pass channel. With this configuration, on experiencing high frequency excitation with small amplitude, the MRF flows from upper to lower chamber through the by-pass channel, thus high frequency vibration can be isolated. On the other hand, on experiencing low frequency with large amplitude, the MRF is forced to flow from the upper to the lower chamber through the MR valve, thus the vibration at low frequency can be suppressed. Firstly, configuration and working principle of the proposed MR mount is introduced. Based on Bingham plastic behavior of the MRF, the MRF flows in the mount are then analyzed and modeling of the MR mount is performed. Based on the modeling, a prototype MR mount is designed and manufactured. In order to evaluate performance of the prototype MR mount, experimental work on the prototype mount is conducted. From the experimental results, performance characteristics of the prototype mount are obtained and presented.

9431-107, Session PTues

Morphological enhancement of poly(3,4-ethylenedioxythiophene) in alginate hydrogel for electrically controlled drug release

Nophawan Paradee, Anuvat Sirivat, Chulalongkorn Univ. (Thailand)

Transdermal drug delivery (TDD) is a method to transport drug across the skin into blood circulation. However, the drug permeation is limited due to lipophilic skin and drug molecular size. Iontophoresis is used

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to improve the drug permeation by applied electric field. In this work, polyethylenedioxythiophene/alginate (PEDOT/Alg) hydrogel was used as a drug carrier/matrix to study the release behavior and diffusion coefficient of benzoic acid (BA) as anionic drug based on the effect of crosslinking ratio, PEDOT particle size, and electric field strength. The release of BA was controlled by the Fickian diffusion in which the diffusion scaling exponent value was close to 0.5. The diffusion coefficient of BA decreased with increasing crosslinking ratio due to smaller mesh size of hydrogel. In addition, the diffusion coefficient was higher under applied electric field because the electric field induced larger mesh size of hydrogel, reduction reaction of PEDOT, and electro repulsive force between the negatively charged BA and the negatively charge electrode (cathode placed on hydrogel). The diffusion coefficient of BA was highest with the smallest PEDOT particle blended with the alginate hydrogel because it possessed the greatest electrical conductivity. Thus, the PEDOT/Alg hydrogel showed a promising behavior for using in TDDS under electrical stimulation.

9431-108, Session PTues

Hysteresis modeling and experimental validation of a magnetorheological damper

Xian-Xu Bai, Peng Chen, Li-Jun Qian, An-Ding Zhu, Hefei Univ. of Technology (China)

Magnetorheological (MR) dampers, a semi-active actuator with the characteristics of short response time, low power consumption, simple structure, and fail-safe behavior, has been widely applied to/studied in various vibration/shock control systems. However, it's difficult to establish a precise mathematical model of MR dampers due to its intrinsic strong nonlinear hysteretic behavior, and hence the control system may not be controlled accurately, rapidly, and effectively. Sequentially, MR technology is restricted to be widely applied in industrial fields. Phenomenological model based on Bouc-Wen model can be used to effectively describe the nonlinear hysteretic behavior of MR dampers, but the structure of the phenomenological model is complex and the Bouc-Wen model is functional redundant. In this paper, based on the phenomenological model, (1) a normalized phenomenological model is presented using a "normalization" concept, (2) a Bouc-Wen transformed model is proposed and realized by adjusting the structure of the phenomenological model. In order to demonstrate conveniently, a modified genetic algorithm is utilized to identify the parameters of the normalized phenomenological model, Bouc-Wen transformed model, and phenomenological model. The research results indicate that, as compared to the phenomenological model, under the condition of an appropriate accuracy of the models, (1) the normalized phenomenological model and the Bouc-Wen transformed model can effectively decrease the number of the model parameters and complexity of the models is also reduced, (2) physical meaning of several model parameters is more reasonable, and the initial range of the model parameters is more explicit, which is of significance for parameters identification.

9431-109, Session PTues

Design of MR brake featuring tapered inner magnetic core

Jung Woo Sohn, Kumoh National Institute of Technology (Korea, Republic of); Jong-Soek Oh, Seung-Bok Choi, Inha Univ. (Korea, Republic of)

Recently, many research works have been conducted to develop haptic actuator by using smart materials, such as piezoelectric material, electro/magneto-rheological(ER/MR) fluid and electro active polymer, for the effective human machine interface. Especially, MR fluid based clutch and brake system for haptic actuator get a lot of attention for its high actuating force and high system stability. In this work, a new type of MR

brake featuring tapered inner magnetic core is proposed and its braking performance is numerically evaluated. In order to achieve high braking torque with restricted size and weight of MR brake system, tapered inner magnetic core is designed and expand the area that the magnetic flux is passing by MR fluid-filled gap. The mathematical braking torque model of the proposed MR brake is derived based on the field-dependent Bingham rheological model of MR fluid. After optimization of principal design parameters for the proposed MR brake, finite element analysis is carried out to identify electromagnetic characteristics of the optimized MR brake configuration. To demonstrate the superiority of the proposed MR brake, the braking torque of the optimized model is numerically evaluated and compared with that of conventional MR brake model.

9431-110, Session PTues

A novel morphing skin integrating shape memory polymer with anisotropic corrugated laminates

Xiaobo Gong, Liwu Liu, Yanjiu Liu, Jinsong Leng, Harbin Institute of Technology (China)

A novel morphing skin based on shape memory polymer (SMP) /corrugated laminates composite was firstly designed and investigated. The carbon fiber laminates were pre-deformed with a corrugated mold, and a certain amount of SMP glue was then cast into it. The morphing skin was obtained after a successive curing procedure. Due to the integration of corrugated structures and SMP, the morphing skin not only shows extreme anisotropic properties of corrugated structures, but also possesses variable stiffness of SMP. In the parallel (longitudinal) direction, where the skin is incompressible, it could fully withstand the aerodynamic loading no matter the temperature is above or below the glass transition temperature (T_g) of the SMP. And, in the perpendicular (transverse) direction, where the skin is compliant, it could be deformed into a desired temporary shape via a relatively small external force above the T_g . Since corrugated laminates are flexible and springy in the perpendicular direction, they can be considered as springs, which could both enhance the shape recovery force and shorten the shape recovery time. The smart morphing skin integrating SMP with anisotropic corrugated laminates shows great potential to be applied on the future morphing aircraft.

9431-111, Session PTues

Circuit driver for robotic hand

Debalina Ghosh, Poojan D. Khanpara, Yonas T. Tadesse, The Univ. of Texas at Dallas (United States)

In this paper, customizable microcontroller based circuitry for actuation of robotic hand is presented. The robotic hand is actuated by contractile actuators, and the arm and shoulder are articulated by servo motors. Two different actuators i.e. shape memory alloy and nylon fibres are compared and contrasted for the hand in a closed loop control system. MPLAB assembly language has been used to program the sequence of finger movement, ultimately loaded in PIC microcontroller based driver circuit. The closed loop control of the hand was achieved by controlling the shoulder Dynamixel-servos and Power HD servos with Pololu Maestro controller and Robotis CM700 controller. Visual feedback for positioning was obtained through cameras. Various gripping and grasping position have been demonstrated to achieve the capabilities and degree of freedom. This compact, light weight robotic hand can be used as cost effective humanoid hand or prosthetic hand for amputees in the future and also to provide physiotherapy treatment to patients with the hand mounted on a robotic base.

9431-112, Session PTues

Trajectory tracking and vibration control in a space frame flexible structure with a PZT stack actuator

Gerardo Silva-Navarro, Oscar A. Garcia-Perez, Juan F. Peza-Solis, Luis G. Trujillo-Franco, Ctr. de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional (Mexico)

This work deals with the robust asymptotic output tracking control problem of the tip position of a space frame flexible structure, mounted on a rigid revolute servomechanism actuated and controlled with a dc motor. The structure is also affected by undesirable vibrations due to excitation of its first lateral vibration modes and possible variations of the tip mass. The overall flexible structure is modeled by using finite element methods and this is validated via experimental modal analysis techniques. The tip position of the structure is estimated from acceleration and strain gauge measurements. The asymptotic output tracking problem is formulated and solved by means of Passivity-Based and Sliding-Mode Control techniques, applied to the dc motor coupled to the rigid part of the structure, and those undesirable vibrations are simultaneously attenuated by an active vibration control using Positive Position Feedback control schemes implemented on a PZT stack actuator properly located into the mechanical structure. The investigation also addresses the trajectory tracking problem of fast motions, with harmonic excitations close to the first vibration modes of the structure. The overall dynamic performance is evaluated and validated by numerical and experimental results.

9431-113, Session PTues

Wideband piezoelectric energy harvester for low-frequency application with plucking mechanism

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In this study, a design of a piezoelectric vibration energy harvester for low-frequency applications is presented. In this design, a unit cell consisting of an elastic frame and a piezoelectric cantilever oscillator in parallel with a plucking mechanism is used as a building block to synthesize a preferable force-displacement characteristics. In this paper, the design and the performance of the unit cell are mainly focused on. Since the plucking mechanism acts as a mechanical switch that connects/disconnects the elastic frame and the cantilever oscillator, the elastic energy accumulated in the cantilever during the loading phase does not return back to the vibration source but remains inside the unit cell as the mechanical energy of the free vibration of the cantilever, which can be retrieved as electric energy by a high efficiency interfacing circuit such as a synchronized switch harvester on inductor (SSHI). Consequently, the force-displacement characteristics of the unit cell presents a large triangular shape. A prototype of the unit cell is designed, manufactured, and its mechanical performance is experimentally investigated. It will be shown that the force-displacement characteristics of the unit cell depends on the total stiffness of the unit cell, the ratio of the total stiffness to the cantilever stiffness, and the connection/disconnection displacements. Then, the SSHI interface circuit is introduced in the unit cell and the efficiency of the electromechanical energy conversion is investigated.

9431-114, Session PTues

Sensor-less parameter estimation of electromagnetic transducer and experimental verification

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Electromagnetic shunt damping is one of the sensor-less damping techniques by using a single electromagnetic transducer. The series resistor-capacitor shunt circuit, typically used as the shunt circuit, is sensitive to the variation of the parameters of the system. Thus, it is essential to use accurate values of natural frequency, damping ratio of vibrating structure, internal inductance, internal resistance and electromechanical coupling coefficient of electromagnetic transducer.

In this paper, a new parameter estimation method for an electromagnetic transducer embedded in a vibrating structure is proposed. The proposed method requires only electrical admittance measurement in the frequency domain. Then, the method is sensor-less due to measuring only electrical admittance between the terminals of electromagnetic transducer. Therefore, by using the method, parameter estimation and electromagnetic shunt damping can be carried out without any sensors for measurement or any actuators for excitation.

Subsequently, experiments are performed to verify the effectiveness of the proposed method. Testing circuit consists of a resistor for the current measurement and an amplifier which is attached to electromagnetic transducer. The experimental results show that the proposed method is well practical to estimate parameters of electromagnetic transducer without use of sensor. Finally, vibration control experiments are performed to verify the validity of the estimated parameter values.

The shunt circuit is a series resistor-capacitor optimized by the estimated parameter values and is verified to act same as dynamic vibration absorber. The experimental results of the vibration control show that the estimated parameter values have sufficiently high precision.

9431-115, Session PTues

Enhanced piezoelectric energy harvesting of a bistable oscillator with an elastic magnifier

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This paper presents theoretical and experimental investigation on a coupling system consisting of a bistable oscillator with an elastic magnifier (EM) to improve the output performances in vibration energy harvesting. Lumped-parameter nonlinear equations of the coupling system were derived to describe the broadband large-amplitude periodic displacement responses of the coupling system. The effects of the system mass ratio and stiffness ratio on the output performances were also studied. It has been shown that increasing the mass ratio and stiffness ratio can improve the system output performances. The distinct advantage in the coupling system lies in the existence of large-orbit attractor over low level range. With the comparison of the electromechanical trajectories obtained from experiments, it was validated that the coupling system can harvest more power in low excitation level with larger bandwidth as compared to the bistable oscillator without an EM.

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9431-116, Session PTues

Structural health assessment in cryogenic temperatures using piezoelectric transducers

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Structures under extreme environmental conditions require efficient structural health monitoring (SHM) techniques for their applications. Such structures include composite fuel tank, LNG carriers and many aerospace and medical applications. In this study, we use low-temperature piezoelectric device to monitor such structures. For a SHM technique to be effective in such applications, it is critical to have the capability of assessing sensors' health. Therefore, in this study, we extend the impedance-based sensor diagnostic process to extremely low temperatures. The effect of temperature variations in the cryogenic range on the sensing capability of piezoelectric active-sensor and the performance of the impedance-based piezoelectric sensor diagnostics were experimentally studied. The results of this study indicate that the piezoelectric sensor could be used for dynamics and SHM sensing at such low temperatures. Furthermore, the impedance-based sensor diagnostic process is capable of detecting faulty sensors at cryogenic temperatures. In addition, we have experimentally demonstrated that bolted joint monitoring using impedance methods is possible at cryogenic temperatures. This paper summarizes experimental procedures and results, and additional issues that can be used as guidelines for future investigations.

9431-119, Session PTues

Off-road motorcycle performance analysis using a rear semi-active suspension

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The topic of the paper is the solution of a problem in motorbike off-road competitions, in which the suspension limitations cause the tire to lose surface contact and potentially cost an entire race or even cause a mayor accident. The objective of the investigation is to characterize an off-road motorcycle and propose a semi active suspension, as well as its control algorithm capable of offering more comfort and tire adherence compared with a passive approach. The first step was to research the current art in vehicle dynamics and suspension control. BikeSim, a professional two-wheel vehicle simulation software was in conjunction with Matlab and Simulink for the suspension and control algorithms inclusion. A series of experiments were designed to test the vehicle in competition circumstances. The results show that a semi active approach is capable of better tire adherence in comparison with a passive suspension system. The conclusion of the project is that, while the technical solution was developed, the current technology is not capable of delivering the required performance for this particular application.

9431-120, Session PTues

Comparisons of the dynamic characteristics of magnetorheological and hydraulic dampers

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A magnetorheological (MR) damper can adapt its dynamic performance to the vibration environment by controlling the current applied. Compared

to other types of dampers, the MR damper has a wider range of dynamic characteristics. Two different dampers: hydraulic, and MRF dampers were tested under forced sinusoidal excitations of low to high frequencies. Also, different currents were applied on the MR damper to investigate its performance under current. The results reveal that the two dampers have nonlinear dynamic characteristics. The characteristics of the hydraulic damper are different from those of the MR damper. The hydraulic damper provides slight nonlinear damping force whereas the MR damper shows a strong nonlinear property. In addition, the hydraulic damper is designed to provide an asymmetric damping force of rebound and compression whereas the MR damper provides a symmetric damping force. In the experiments conducted, the excitation frequency varies from 1 Hz to 17 Hz and the amplitude from 2.5 mm to 12 mm. For the hydraulic damper, the lowest compression damping force only increases by about 0.87KN while the rebound force increases by about 1.64 KN. In contrast, the variation of compression and rebound forces of the MR damper are 1.73 and 1.51 KN, respectively. Furthermore, the damping force of the MR damper increases as the current increases from 0.5 A to 0.75, 1.00 and 1.25 A.

9431-121, Session PTues

Aerosol deposited PZT actuated 2D scanner system

Wei-Chih Wang, Univ. of Washington (United States)

A new lead-zirconium-titanate (PZT) actuator design for a micro scanning light source is being developed. The scanner can be actuated using high frequency AC signals applied to four PZT pads arranged so that 2-dimensional scanning is possible. The thin PZT film is deposited directly on stainless steel at a rate of ~5µm/hour by using an aerosol deposition machine. The aerosol deposition method enables low-cost, quick, room temperature fabrication while producing high {3-1} mode piezoelectric constants. This research aims to investigate if steel based actuators will yield a higher angular deflection in the waveguide. These scanning devices would be attractive for endoscopic device applications, where inexpensive imaging systems with high resolution would enable disposal devices.

A background for scanning endoscope designs is given, as well as a description of similar previous work. The fabrication procedure for the design is presented. Current tests are underway to explore how impulse poling will improve poling success rates and piezoelectric coefficients. The goal of this research is to compare amplitude of actuation, resolution, and frequency of scanning from this device with previously developed Si based devices using the sol-gel PZT deposition process.

9431-33, Session 8A

A review of piezoelectric-based electrical energy harvesting methods and devices for munitions

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This article provides a review of the state of the art in piezoelectric-based electrical energy harvesting methods and devices and their charge collection electronics for use in munitions. The review will concentrate on devices to harvest energy from the launch and flight environments of gun-fired munitions. In particular, this study reviews the various methods of utilizing such energy harvesting devices to address power and energy requirements of munitions using a systems approach to the management of power and energy.

The Armament Research development Center (ARDEC) and their small business collaborator (Omnitek Partners, LLC) have been developing energy systems that can serve as alternatives to current reserve batteries in certain applications in gun-fired munitions. Harvested energy from the launch and

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the flight of gun-launched munitions is used to charge a storage device such as a capacitor or an ultra-capacitor. The present work reviews the energy harvesting methods and devices developed as part of these as well as other research and development efforts. A system approach is presented for addressing the problem of powering munitions by coupling of the energy harvester output and other sources of electrical energy to achieve optimal munitions powering systems.

The performance of current munitions and the development of future munitions are limited by the size and energy constraints of existing power sources. The methods of extracting energy from the launch and flight environments can be applied to almost all munitions, missiles and rocket systems and can strengthen the industrial base for tactical military power sources.

9431-34, Session 8A

Bimorph disk piezoelectric energy harvester under base excitation: electroelastic modeling and experimental validation

Amirebrahim Darabi, Shima Shahab, Michael J. Leamy, Alper Erturk, Georgia Institute of Technology (United States)

Vibration-based energy harvesting using a disk-type piezoelectric bimorph with thickness poled circular piezoelectric laminates is explored theoretically and experimentally. The bimorph disk consists of two circular laminates electrically connected in series and shunted through the outer surface electrodes to an electrical load for characterizing the power output and piezoelectrically shunted vibration in response to base excitation. The bimorph disk with free edge conditions is mounted to the vibrating base from its center and the focus is placed on the fundamental axisymmetric vibration mode. Electromechanical coupling is introduced to the distributed-parameter model of the thin circular plate and a resistive load is considered across the electrodes. Following a modal analysis-based electroelastic solution, closed-form expressions are obtained for the voltage output and shunted vibration frequency response functions (FRFs) by accounting for the two-way coupling in the presence of a finite electrical load impedance. Experimental validations of the electroelastic model are given for two separate PZT-5A bimorph disks of different diameters.

9431-35, Session 8A

An evaluation of piezoelectret foam in a multilayer stack configuration for low-level vibration energy harvesting application

Chase A. Ray, Steven R. Anton, Tennessee Technological Univ. (United States)

Electronic devices are high demand commodities in today's world, and such devices will continue increasing in popularity. With these devices come the issues of how to power them. Currently, batteries are implemented, which increases waste because batteries eventually need to be replaced. Energy harvesting technology is paramount in the advancement of self-powered electronic devices. This paper is an in-depth study on piezoelectret foam assembled in a multilayer stack configuration and presents results of the stack behavior when excited at low frequencies. The basic dynamic principle of the foam is that it contains charged interval voids, which can be represented as macroscopic dipoles. When the distance between the surfaces of the voids changes, a potential across the material is created. In this work, modeling and experimentation is done to investigate piezoelectret foam as a multilayer energy harvester. An examination of modeling piezoelectret foam in recent years is made. After a review of the past modeling, an assessment is made between those models to deduce which one is most applicable to this experiment. The results from the chosen model are compared to the experimental results to check the fidelity

of the model. Electromechanical testing is performed by compressing the foam stack to obtain output electrical energy; consequently, allowing a relationship between input mechanical energy and output electrical energy to be developed.

9431-36, Session 8B

Force-compensated hydrogel-based pH sensor

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This paper presents the design, simulation, packaging and testing of a force-compensated hydrogel-based pH sensor. In the conventional deflection method, a piezoresistive pressure sensor is used as a chemical-mechanical-electronic transducer to measure the volume change of a pH-sensitive hydrogel. Using the compensation method, the volume of this pH-sensitive hydrogel is kept constant during the whole measuring process, independent of the applied pH value. In order to maintain this balanced state, an additional thermal actuator with a temperature-sensitive hydrogel is added on the sensor to generate the compensation force. In such a configuration, the temperature value from the thermal actuator becomes the actual sensor output signal. Poly-N-isopropylacrylamide (PNIPAAm) with 5 mol% monomer 3-acrylamido propionic acid (AAmPA) was synthesized as the temperature-sensitive hydrogel with a wide range of linear temperature response from 20 to 60°C, while polyvinyl alcohol (PVA) with Polyacrylic acid (PAA) served as pH-sensitive hydrogel. Besides, some organic sealant materials for the liquid encapsulation were studied. The epoxy H70E-2 showed the best technological properties. The curing process of this epoxy was optimized to avoid air bubbles as well as to achieve quasi-hermetic packaging. A thermal simulation was performed to assess the temperature distribution of this sensor. Finally, the sensor performance was characterized by varying pH value of the measuring solution between pH3 and pH6. The response time amounted to about 60s, which was 5 times lower than that of the deflection type sensors. The time-dependent output signal drift was significantly decreased, leading to a higher reproducibility.

9431-37, Session 8B

Integration of fluidic jet actuators in composite structures

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Fluidic Actuated Flow Control (FAFC) has been introduced as a technology that influences the boundary layer by actively blowing air through slots or holes in the aircraft skin or wind turbine rotor blade.

Modern wing structures are or will be manufactured using composite materials. In these state of the art systems, AFC actuators are integrated in a hybrid approach. The new idea is to directly integrate the active fluidic elements (such as SJAs and PJAs) and their components in the structure of the airfoil. Consequently, the integration of such fluidic devices must fit the manufacturing process and the material properties of the composite structure.

The challenge is to integrate temperature-sensitive active elements and to realize fluidic cavities at the same. The transducer elements will be provided for the manufacturing steps using roll to roll processes. The fluidic parts of the actuators will be manufactured using the MuCell® process that provides on the one hand the defined reproduction of the fluidic structures and on the other hand a high light weight index. Based on the first design concept, a demonstrator was developed in order to proof the concept. The output velocity on the exit was measured using a hot-wire anemometer.

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9431-38, Session 8B

Design of a high performance T/R switch for 2.4 GHz RF wireless transceiver in 0.13 μm CMOS technology

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The rapid advancement of CMOS technology, in the recent years, has led the scientists to fabricate wireless transceivers fully on-chip which results in smaller size and lower cost wireless communication devices with acceptable performance characteristics. Moreover, the performance of the wireless transceivers rigorously depends on the performance of its first block T/R switch. This article proposes a design of a high performance T/R switch for 2.4 GHz RF wireless transceivers in 130 nm CMOS technology. The switch exhibits 1- dB insertion loss, 37.2-dB isolation in transmit mode and 1.4-dB insertion loss, 25.6-dB isolation in receive mode. The switch has a power handling capacity (P1dB) of 30.9-dBm. Besides, by avoiding bulky inductors and capacitors, the size of the switch is drastically reduced and it occupies only (0.00296) mm², which is the lowest ever reported in this frequency band. Therefore, simplicity and low chip area of the circuit will trim down the cost of fabrication as well as the whole transceiver.

9431-39, Session 9A

Experimental investigation of bond in concrete members reinforced with shape memory alloy bars

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Conventional seismic design of reinforced concrete structures relies on yielding of steel reinforcement to dissipate energy while undergoing residual deformations. Therefore, reinforced concrete structures subjected strong earthquakes experience large permanent displacements and are prone to severe damage or collapse. Shape memory alloys (SMAs) have gained more acceptance in recent years for use in structural engineering due to its attractive properties such as high corrosion resistance, excellent re-centering ability, good energy dissipation capacity, and durability. SMAs can undergo large deformations in the range of 6-8% strain and return their original undeformed position upon unloading. Due to their appealing characteristics, SMAs have been considered as an alternative to traditional steel reinforcement in concrete structures to control permanent deformations. However, the behavior of SMAs in combination with concrete has yet to be explored. In particular, the bond strength is important to ensure the composite action between concrete and SMA reinforcements.

This study investigates the bond behavior between SMA bars and concrete through pull-out test. To explore the size effect on bond strength, the tests are performed using various diameters of SMA bars. For the same diameter, the tests are also conducted with different embedment length to assess the effect of embedment length on bond properties of SMA bars. To monitor the slippage of the SMA reinforcement, an optical Digital Image Correlation method is used and the bond-slip curves are obtained. Results from experimental tests of SMA bars are compared with the reported bond strengths of other types of reinforcement with concrete.

9431-40, Session 9A

Adaptive and Energy efficient SMA-based Handling Systems

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Julian Kunze, Lehrstuhl für Unkonventionelle Aktorik, Universität des Saarlandes (Germany); Benedikt Holz, Lehrstuhl für Unkonventionelle Aktorik, Universität des Saarlandes (Germany) and ZeMA gGmbH (Germany)

Shape Memory Alloys (SMA's) are known as actuators with very high energy density. This fact allows for the construction of very light weight and energy-efficient systems. In the field of material handling, the avoidance of big moments of inertia in robots and kinematic units is essential. High inertial forces require bigger and stronger robot actuators and thus higher energy consumption and costs. For material handling in assembly processes, many different individual grippers for various work piece geometries are used. If one robot has to handle different work pieces, the gripper has to be exchanged and the assembly process is interrupted, which results in higher costs.

In this paper, the advantages of using high energy density Shape Memory Alloys in applications of material-handling and gripping-technology are explored. In particular, light-weight SMA actuated prototypes of an adaptive end-effector and a vacuum-gripper are constructed via rapid-prototyping and evaluated.

The adaptive end-effector can change its configuration according to the work piece geometry and allows the handling of multiple different shaped objects. SMA wires are used to move four independent arms, each arm adds two degrees of freedom to the kinematic unit.

At the tips of these end-effector arms, SMA-activated suction cups are installed. The flexible membranes of these suction cups are pulled up by SMA wires and thus a vacuum is created between the membrane and the work piece surface. The self-sensing ability of the SMA wires are used in both prototypes for monitoring their actuation.

9431-41, Session 9A

Shape-retainment control using an antagonistic shape memory alloy system

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Since shape memory alloy (SMA) actuators can generate large force per unit weight, they are expected as one of the next generation actuators for aircraft. To keep a position of conventional control surfaces or morphing wings with SMA actuators, the SMA actuators must keep being heated, and the heating energy is not small. To save the energy, an antagonistic SMA system is considered, where any position can be an equilibrium point within hysteresis of stress-strain diagrams. To confirm a feasibility of the system, a fundamental experiment is performed. The experimental apparatus consists of two SMA wires, a linear bearing, an electric power supply, and a laser displacement meter. The SMA wires are heated by applying electric current to the wires. When a pulsed current is applied to the two SMA wires alternately, the equilibrium position changes between two positions alternately, and when a series of pulse whose amplitude increases gradually is applied to one SMA wire, the equilibrium position changes like a staircase. However, just after the pulse the position returns slightly. To investigate such a behavior of the system, numerical simulation is also performed. The one-dimensional phase transformation model [Ikeda, Proc. SPIE 5757 (2005), 344-352] is used for a constitutive model of the SMA wires. The simulated result agrees with the experiment qualitatively, including the overshoot. By examining volume fraction of each phase, it is found that the overshoot is caused by that austenite phase transforms into stress-induced martensite phase during the cooling process after the pulse.

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9431-42, Session 9A

**Self tuning parts in an Erhu instrument
using shape memory alloys**

Huihui Wang, Stephen Cowan, Williams B. Lane, John Leong, Devin Pappas, Jacksonville Univ. (United States)

Self-tuning parts in a prototype of an Erhu instrument using shape memory alloys (SMAs) are designed and developed in this paper. Erhu, a traditional Asian music instrument, has two strings which need to be tuned often. Sometimes it requires to be tuned accurately and quickly during performance. The proposed Erhu prototype can be automatically and precisely tuned by controlling SMAs: smart materials controlled by thermal-mechanical effects. SMA springs in this prototype can be deformed (either stretched or compressed) when a current (-1-2As) is passed through them. In this Erhu prototype, each string is connected with two SMAs (one compressed SMA and one tensioned SMA) which are controlled by circuits. Passing current through the SMA springs deforms them, resulting in the stiffness change of the strings. Therefore, the pitch of the Erhu prototype can be controlled precisely. The body of Erhu prototype is manufactured by a 3D printer with SMAs, a portable power supply, and control circuits integrated into the Erhu body. In the future, a series of self-tuning parts based on SMAs will be developed corresponding to different tones. An Erhu instrument with such self tuning parts based on SMAs can be easily tuned in a short time during performance.

9431-43, Session 9B

**Magnetoelastic metastructures for passive
broadband vibration suppression**

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This paper presents experimental and theoretical components of a novel metamaterial-inspired vibration suppression system. It has been shown in the literature that distributed arrays of small resonators integrated into a host structure can have excellent vibration suppression capabilities. Current metamaterial designs however, are limited to relatively large structures or high frequencies, and only consider narrowband linear local resonators. The proposed research takes advantage of uniquely designed cantilevered zigzag structures that can have natural frequencies orders of magnitude lower than a simple cantilever of the same size. Another key aspect of the proposed vibration suppression system is that the dynamic response of each zigzag structure can be made highly nonlinear with the use of magnets. Literature shows that properly designed nonlinear resonators have a large amplitude broadband response compared to narrowband linear resonators. In the proposed research, arrays of these compact nonlinear zigzag structures are integrated into a larger host structure to form what is referred to here as a metastructure. Experimental modal analysis results will be shown comparing the response of the full nonlinear metastructure to those of both an equivalent linear metastructure and also an equivalent host structure with no vibration suppression. This paper focuses on experimental aspects of the research; however, a brief discussion of the modeling strategies will also be given. Included in the modeling discussion will be details of a simplified Rayleigh-Ritz model and how it was used to design the metastructure systems shown in this paper. It will also be shown how both linear and nonlinear dynamics of the zigzag structures were successfully modeled using Rayleigh's quotient and the well-known Duffing oscillator equation.

9431-44, Session 9B

**Multimodal vibration damping through
a periodic array of piezoelectric patches
connected to a passive network**

Boris Lossouarn, Mathieu Aucejo, Jean-Francois Deu, Conservatoire National des Arts et Métiers (France)

In damping devices involving piezoelectric elements, charge cancellation or vibration node locations induce that a single piezoelectric patch cannot consistently achieve a multimodal control. In order to sense and control vibration on a prescribed frequency range, a solution consists in using an array of several piezoelectric patches being small compared to the smallest wavelength to control. Then, as an extension of the tuned mass damper strategy, a passive multimodal control requires to implement a damping system whose modes are as close as possible to those of the controlled structure. In this way, the electrical equivalent of the discretized mechanical structure represents the passive network that optimizes the energy transfer between the two media.

For one-dimensional structures, a periodic distribution in several unit cells enables the use of the transfer matrix method applied on electromechanical state-vectors. The optimal passive networks are obtained for the propagation of longitudinal and transverse waves and a numerical implementation of the coupled behavior is performed. Compared to the more classical resonant shunts, the network topology induces promising multimodal damping and a reduction of the needed inductances. It is thus possible to create a completely passive electrical structure as it is demonstrated experimentally by using only purely passive components.

9431-45, Session 9B

**Static and quasi-static behavior of an
adaptive system to compensate path
errors for smart fiber placement**

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Smart fiber placement is an ambitious topic in current research for automated manufacturing of large-scaled composite structures, e.g. wing covers. Adaptive systems get in focus to obtain a high degree of observability and controllability of the manufacturing process. In particular, the compensation of layout misalignments as a consequence of vibrational disturbances and material failures has to be studied to significantly increase the production rate with no loss in accuracy of the fiber layout. As one contribution, an adaptive system has been developed to be integrated into the fiber placement head. It decouples the compaction roller from disturbances. Therefore, the smart system axially adapts the position of the compaction roller. Misalignments, time- and spatially-invariant behavior of components and acceleration changes during operation can lead to layout deviations. This paper investigates the behavior of the system to compensate quasi-static deviations from the desired path. In particular, the compensation efficiency of a constant offset, a linear drift with constant gradient and a slightly curved drift is studied. Thus, the test bed with measurement devices and scenarios is explained. At first, the free lift of the adaptive system is carried out as the reference. After that, a defined compaction force is set up to have a contact condition like it is during actual fiber layout. Measurement results are compared to the reference. Based on the knowledge obtained by the experimental data, the paper concludes with a discussion of the proposed approach for its use under operating conditions and further control implementation.

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9431-46, Session 9B

Adaptive passive control of structure-borne noise of rotating machinery using a pair of shunted inertial actuators

Guoying Zhao, Neven Alujevic, Katholieke Univ. Leuven (Belgium); Gregory Pinte, Bruno Depraetere, Flanders' Mechatronics Technology Ctr. (Belgium); Paul Sas, Katholieke Univ. Leuven (Belgium)

In this paper, two Piezo-Based Rotating Inertial Actuators (PBRiAs) are considered for the suppression of the structure-borne noise radiated from rotating machinery. Each inertial actuator comprises a piezoelectric stack element shunted with the Antoniou's gyrator circuit. This type of electrical circuit can be used to emulate a variable inductance. By varying the shunt inductance it is possible to realise two tuneable vibration neutralisers in order to suppress single frequency vibrations of a slowly rotating machine. Also, reductions in the sound radiated from the machine housing can be achieved. First a theoretical study is performed using a simplified lumped parameter model of the system at hand. The simplified model consists of a rotating shaft and two perpendicularly mounted shunted PBRiAs. Secondly, the shunted PBRiA is tested on an experimental test bed comprising a rotating shaft mounted in a frame. The noise is radiated by a plate that is attached to the frame. The experimental results show that a reduction of 11 dB on the disturbance force transmitted from the rotating shaft through the bearing to the housing can be achieved. This also generates a reduction of 9 dB for the plate vibration and the radiated noise.

9431-47, Session 10A

Validating the predictive capability of a stochastic analytical model for a piezoelectric energy harvester under non-stationary random vibration

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Vibration energy can be converted into electric power through a piezoelectric energy harvester (PEH) which generates an electrical potential in response to mechanical strains. An analytical model of the PEH is essential to understand its output performance under a given vibration condition. Despite significant effort in developing the analytical models, most have been derived under the assumption of deterministic excitation and may result in unreliable prediction under a random vibration. Recently, as a novel methodology, the stochastic analytical model using a time-frequency analysis was proposed to quantify electric power under a non-stationary random vibration. This study aims at validating the predictive capability of the stochastic analytical model by comparing the analytical solutions and experimental observations. In this study, the smoothed pseudo Wigner-Ville distribution (SPWVD) is used to estimate the time-varying power spectrum of the non-stationary random vibration. There are two kinds of trade-offs due to the smoothing window in SPWVD as: (i) bias and variance, and (ii) interference and localization. Therefore, it is investigated on how the size and shape of the smoothing window affect the analytical solution of the electromechanical behavior. For base excitation, an input acceleration signal is induced by an electrostatic shaker and its amplitude and excitation frequency are randomly modulated. The tip displacement, voltage, and electric power of the PZT-5A bimorph cantilever plate are measured at various electrical loading conditions. Finally, the weighted integrated factor (WIFac) is used as a correlation metric for time history comparison, which calculates an error between analytical solutions and experimental observations.

9431-48, Session 10A

Embedded piezoelectrics for sensing and energy harvesting in total knee replacement units

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The knee replacement is the second most common orthopedic surgical intervention in the United States, but currently only 1 in 5 knee replacement patients are satisfied with their level of pain reduction one year after surgery. It is imperative to make the process of knee replacement surgery more objective by developing a data driven approach to ligamentous balance, which increases implant life. In this work, piezoelectric materials are considered for both sensing and energy harvesting applications in the total knee replacement implants. This work aims to embed piezoelectric material in the polyethylene tibial component of a knee replacement unit to act as sensors that will aid in the alignment and balance of the knee replacement by providing intraoperative feedback to the surgeon. Postoperatively, the piezoelectric sensors can monitor the structural health of the implant in order to perceive potential problems before they become bothersome to the patient. Specifically, this work will present on the use of finite element modeling coupled with uniaxial compression testing to prove that piezoelectric stacks can be utilized to harvest sufficient energy to power the sensors needed for this application.

9431-49, Session 10A

Cell-structured wideband piezoelectric energy harvester for low-frequency application with synthesized force-displacement characteristics

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In this paper, a design of a piezoelectric vibration energy harvester for low-frequency applications is presented. In this design, a unit cell consisting of an elastic frame and a piezoelectric cantilever oscillator in parallel with a plucking mechanism is used as a building block to synthesize a preferable force-displacement characteristics. First, the force-displacement characteristics of the unit cell is studied. Since the plucking mechanism acts as a mechanical switch that can connect/disconnect the elastic frame and the cantilever oscillator, the elastic energy accumulated in the cantilever during the loading phase does not return back to the vibration source but remains inside the unit cell as the mechanical energy of the free vibration of the cantilever, which can be retrieved as electric energy by a high efficiency interfacing circuit such as a synchronized switch harvester on inductor (SSHI). Consequently, the force-displacement characteristics of the unit cell presents a large triangular shape, which depends on the total stiffness of the unit cell, the ratio of the total stiffness to the cantilever stiffness, and the connection/disconnection displacements. Next, a number of unit cells are connected both in series and in parallel. The overall shape of the force-displacement curve can be tailored to a preferable shape by designing the hysteric characteristics of each cell to maximize the transferred energy from the vibration source to the circuit. Experimental studies will be presented to show the validity of the proposed concept and the performance of the unit cell and a combined system consisting of several cells.

9431-50, Session 10A

A mechanical solution of the self-powered SSHI interface for piezoelectric energy harvesting systems

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Both of the mechanical structure and electrical circuit in piezoelectric energy harvesting (PEH) systems have been extensively investigated for pursuing future self-powered electronics, which can scavenge energy from the ambient vibration. Yet, the mechanical emphasized studies usually take simple electrical equivalence, and vice versa. The synthetic dynamics of mechanical structure and electrical circuit was not thoroughly exposed. On the other hand, in practical applications, both of the mechanical and electrical parts in a PEH system need to be customized for harvesting energy from a given vibration source, in order to cover a specific load power demand, as summarized in Fig. 1. This paper provides an impedance based integrated design approach for PEH systems with a focus on mechanical design, when different interface circuits are utilized. Different piezoelectric cantilevers have been customized according to the selection of either of standard energy harvesting (SEH) or synchronized switching harvesting on inductor (SSHI), under the same harmonic vibration energy supply and power demand. The single degree freedom (SDOF) equivalence reflecting the detailed parameters of the piezoelectric cantilevers is used to model the mechanical part; the nonlinear harvesting interface circuit is modeled as a complex impedance. Comprehensive parametric study on the structure parameters are carried out for deriving the design rules towards the given task. Both theoretical and experimental results show that, compared to using SEH, adopting SSHI enables a significant shrink on the physical size of the system. This structural customization provides a good guidance for the integrated design of practical PEH systems.

9431-51, Session 10B

Damage identification in nonlinear periodic structures utilizing the dynamics of intrinsic localized modes

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Intrinsic localized modes (ILMs) are localized vibrational responses that may occur in a variety of nonlinear periodic systems. Many investigations have characterized the existence and stability of ILMs and they have been realized in systems representing numerous domains and length scales. Previous studies indicate that ILMs strongly interact with an impurity via attraction or repulsion from the defect location. In this research to exploit such phenomena for structural damage identification, we analyze the interaction of an ILM with multiple impurities, where a steered impurity strategically guides the ILM towards another, static impurity representative of damage. We discover and catalog the distinct phenomenological interaction types between steered ILMs and damage. For some interaction types, the ILM propagation rate temporarily exceeds a threshold, a behavior that is shown to consistently coincide with ILM interaction with damage (the static impurity). The quantitatively distinct interaction types are used to devise a method to effectively identify damage in the nonlinear periodic structure. Numerous studies were performed to assess the viability and accuracy of the proposed damage identification method and to examine its robustness to random structural heterogeneity. An experimental system is constructed to realize the concept, and investigations are performed to verify the analytical results. Beyond stiffness change, the proposed method is applicable to monitoring other nonlinear periodic system characteristics, such as changing mass or multifield features, which may be represented as damage or static impurity.

9431-52, Session 10B

Modeling and identification of nonlinear electroelastic and dissipative parameters for PZT-5A and PZT-5H bimorphs: a dynamical systems approach

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Electroelastic and dissipative nonlinearities of most commonly used soft piezoelectrics, such as PZT-5A and PZT-5H (PZT stands for lead zirconate titanate), are pronounced in various engineering applications such as dynamic actuation, sensing, their combined implementations in feedback problems such as vibration control, and most recently, in energy harvesting from dynamical systems. The present work investigates the nonlinear nonconservative dynamic behavior of bimorph piezoelectric cantilevers under low-to-high mechanical and electrical excitation levels in energy harvesting, sensing, and actuation, with a focus on most popular soft piezoceramics: PZT-5A and PZT-5H. A unified mathematical framework we recently developed is analyzed by using the method of harmonic balance to identify and validate the nonlinear and dissipative system parameters for energy harvesting and dynamic actuation based on a set of rigorous experiments for different samples. Brass-reinforced piezoelectric bimorphs samples of different PZT-5A and PZT-5H thickness levels are tested to identify and report their nonlinear electroelastic and dissipative constants.

9431-53, Session 10B

Design optimization of a magnetorheological brake in powered knee orthosis

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Magneto-rheological (MR) fluids have been utilized in devices like orthoses and prostheses to generate controllable braking torque. In this paper, a flat-shaped rotary MR brake is designed as part of the powered knee orthosis to provide adjustable resistance. The MR brake configuration is first discussed, and the multiple disk structure with interior inner coil is adopted for a relative large torque-to-volume ratio. In order to increase the maximal magnetic flux as well as the flux density at the MR fluids, a novel design with smooth transition surface between core shaft and side plates is proposed. Based on this design, a parameterized model of the MR brake is built with design variables representing component geometries and state variables, like weight and output braking torque, evaluated via Finite Element Analysis (FEA). Then the MR brake design is formulated as an optimization problem with multiple objectives and constraints. Besides maximal braking torque and weight, the average power consumption of the MR brake is also considered in the optimization objectives, so that the designed device can fulfill functional requirement, and achieve good wearing comfort and energy efficiency. The optimization is then conducted in ANSYS Workbench utilizing Goal Driven Optimization module. The influence of design variables on the design objectives are discussed, and trade-offs between design objectives are also investigated. As a result, the optimal design is obtained with maximal braking torque 35 Nm, total weight 0.56 kg and average power consumption 7.2 W.

9431-54, Session 10B

Bistability, autowaves, and dissipative structures in semiconductor fibers with anomalous electrical properties

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This work provides a discussion of bistability conditions, switching autowave properties and emergence of dissipative structures in semiconducting fibers with anomalous positive dependence of electrical resistivity on temperature of sigmoid type. An open system thermodynamics approach is utilized for the analysis of this dissipative solid-state system. The approach aims to represent the structure of the solution space of its governing equation in the form of physical phase diagrams, known as nonequilibrium phase diagrams, and two specific binary diagrams have been obtained here. One of the diagrams, where the electrical power density and ambient temperature represent external parameters, shows a wide region with dissipative structures as non-uniform steady-state temperature profiles on the fiber. The possibility of efficient external control over the dissipative structure geometry is also demonstrated.

9431-55, Session 11A

Tactile Device Utilizing a Single Magnetorheological Sponge : Experimental Investigation

Soomin Kim, Inha Univ. (Korea, Republic of); Pyunghwa Kim, Seung-Hyun Choi, Inha University (Korea, Republic of); Jong-Seok Oh, Seung-Bok Choi, Inha Univ. (Korea, Republic of)

In the medical world, new areas have been currently introduced such as robot-assisted surgery and virtual reality. However, the major drawback of these systems is that there is no tactile communication between doctors and surgical sites. When the tactile system is brought up, telemedicine including tele-robotic surgery is enhanced much more than now. In this study, a new tactile device is designed using a single MR sponge cell to realize the sensation of human organs. The magnetorheological (MR) fluid absorbed by a sponge, absorbent open celled polyurethane foam, is used to design the proposed MR sponge cell. The viscous and elastic sensational behaviors of human organs are realized by the MR fluid and foam of the proposed MR sponge cell, respectively. Before developing the proposed tactile device, tactile sensation according to touch of human fingers are quantified in advance. In this work, the finger is treated as beam bundle model (BBM) in which the fingertip is comprised of some elastic beams virtually. Under the BBM, when people want to sense an object using their fingers, the fingertip is investigated by pushing and sliding the object. Accordingly, when several magnitudes of magnetic field input are applied to the manufactured tactile device, the vertical, frictional reaction forces and bending moment of tactile device are measured by using 3-axis force sensor instead of fingertip. These measured data are used to investigate the motion of fingertip, and then compared with the ones of real human organs. It is demonstrated that the proposed MR sponge cell can realize any part of the organ based on the obtained data and finally this method can transfer viscous and elastic sensations to operators so that they can recognize as if they directly touch patient's organs.

9431-56, Session 11A

Impact of viscous effects on the stroking load of magnetorheological energy absorbers

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This study addresses how valve wall surface roughness affects performance of a magnetorheological energy absorber (MREA) under high speed impact. MREAs produce a stroking load that adapts to a range of payload mass and/or impact velocity by applying a magnetic field. When used for impact protection, design goals are: (1) to provide optimal stroking load over a wide range of impact velocities without exceeding the maximum allowable force, which corresponds to the tolerable limit load of the lumbar spine in a vertical stroking helicopter seat, and (2) maintain a high dynamic

range, defined as the ratio of maximum field on force to field off force, at high impact speeds. Thus, it is critical to accurately predict viscous force at high piston velocity. A Bingham Plastic (BP) model with viscous losses was developed that shows how valve wall surface roughness substantially increases stroking load at high velocity. An MREA was constructed and drop tested to obtain data in the field-off state and field-on state. Test data showed that the original BP model assuming smooth walls under predicts stroking load at high velocities. The MREA has coils in the valve that introduce wall roughness. At high Reynolds number, the irregularities in the wall surface increase viscous losses, which are well represented by a rough wall model. The rough wall model assumes a Darcy friction factor that is independent of Reynolds number, and is more accurate at predicting the viscous force in the high speed range where turbulent flow is more likely.

9431-57, Session 11A

Force Modeling for Incision Surgery into Tissue with Haptic Application

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Recently, trend of surgery has gone over from laparotomy surgery to robot-assisted minimally invasive surgery. To reflect this tendency, demand of surgical robot using laparoscope has been increased incredibly. However, it is very hard to comprehend inside situation of patient because only visual information is provided during surgery. This problem came from robot master that could not realize touch of sense in surgical situation. This problem caused other problems, such as excessively long time robot manipulation training for robot operator and furthermore degrading the accuracy of the operation result. Because of these problems, haptic system for realizing touch of sense has been researched actively in many countries. In order to realize a haptic system, it should be considered research of hardware and software. However, no research on both of hardware and software has been revealed. Thus, in this paper, a prediction algorithm related to reaction force of human organ is proposed and then calculated reaction force is realized by haptic device using magnetorheological fluid. This subject has a tremendous importance in developing accurate surgical robot, surgical simulation and surgical planning tool. This predicted force model focused on the deformable feature of tissue with concept of energy to formulating force model. This approach is analyzed into several energy types including energy from external force, elastic potential energy from deformation of tissue, and irreversible dissipated energy by rupture and friction. Each energy is exchanged or dissipated to other type of energy at the each mode in incision process and this process is formulated by model based on the theories and data from experiments. After this procedure, the calculated force model is realized by semi-active control force haptic device using magnetorheological fluid in the experiment. This experiment can show the possibility of practical application of this force model and advantages of semi-active control haptic device using magnetorheological fluid. In addition, psychophysical and statistical method is conducted to evaluate the performance of proposed method and haptic device.

9431-58, Session 11A

Optimization of New Magnetorheological Fluid Mount for Vibration Control of Start/Stop Engine Mode

Jye Ung Chung, Xuan Phu Do, Seung-Bok Choi, Inha Univ. (Korea, Republic of)

The technologies related the saving energy/or green vehicles are currently concentrated. In this tendency, the problem for reducing exhausted gas is in development with various ways. It is directly related to the operation of engine, especially start/stop mode of engine. The auto start/stop of

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car engine is currently as a main stream of auto industry. However, this technology automatically turns on and off engine frequently resulting in transmitting vibration of engine which has large displacement, and torsional impact to chassis. These vibrations which cause uncomfortable feeling to passengers are transmitted through the steering wheel and the gear knob. In this work, a new proposed magnetorheological (MR) fluid based engine mount (MR mount in short) is presented for controlling transmitted vibrations which are occurred at start/stop modes of engine operation. The proposed MR mount is designed to satisfy the low transmissibility at broadband frequency range. The analysis of characteristics in-line four-cylinder engine which is popularly installed in various vehicles is simulated followed by the optimization of MR mount. It is shown that the proposed mount can effectively suppress the vibrations due to the start/stop modes of the engine.

9431-59, Session 11A

Haptic cue control of an MR gear shifting assistance device via Preisach hysteresis linearization

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In recent years, fuel economy becomes more and more important in automobile engineering. Several factors can affect the fuel economy of vehicles such as vehicle weigh, types of engine, aerodynamic drag, regenerative braking, traffic condition and personal driving style. Among them, a gear shifting timing caused by personal driving style is significantly related with fuel consumption. This paper proposes a driver assistance device to notify vehicle drivers an optimal gear shifting timing considering fuel consumption in manual transmission vehicles. The haptic cue function of the proposed gear shifting assistance device is utilizing magnetorheological (MR) clutch mechanism as haptic interface between driver and vehicle. The shear stress level and hysteretic behavior of the employed MR fluid are experimentally observed and identified with the Preisach model. A rotary type clutch mechanism is designed and manufactured with electromagnetic circuit and its transmission torque level is experimentally evaluated according to the applied current. The manufactured MR clutch is integrated with accelerator pedal on which driver's foot is placed to transmit haptic cue signal. In the meantime, a cue algorithm for gear shifting is formulated by considering vehicle engine speed concerned with engine combustion dynamics, vehicle dynamics and driving resistance. The cue algorithm is then integrated with a haptic controller which is a torque model based-compensation strategy regarding Preisach hysteresis linearization of the employed MR fluid. In this work, the haptic cue controller is implemented in discrete manner. Control performances are experimentally evaluated such as haptic tracking responses, cue timing and fuel consumption.

9431-60, Session 11A

Modeling and experimental verification of the prosthetic leg powered by MR fluid and SMA wires

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The paper present the continued work with the prosthetic leg previously designed at the same institution. The leg contains shape memory alloy (SMA) wires in the thigh portion as artificial muscle to actuate the shin portion. Magnetorheological (MR) fluid rotary brake installed at the knee portion plays the role of a brake when the leg needs to withstand a holding torque. The shin portion houses the controlling electronics and battery. SMA wires have been proven to provide highly efficient actuation in comparison with regular electric motors. MR fluid brake can hold a high amount of

torque for a significant time without consuming a lot of energy.

In the present work, mathematical models were derived for the MR fluid brake and the SMA actuator. The equations were then simulated in MATLAB/Simulink to predict the motion of the leg. On the other hand, all components of the leg were fabricated and tested at different conditions of loadings. The data was obtained from the experiments and compared with predictions given by the simulation model. The model parameters were then adjusted based on the correlation between simulations and experiments.

9431-61, Session 11B

Large deformation of thin smart beams with piezoelectric patches under electro-mechanical actuations

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In design of smart compliant and flexible systems, it is necessary to predict response of their components under external stimuli such as mechanical and non-mechanical actuations. Many of non-mechanical actuations are made of smart materials like piezoelectric actuators. Also, flexible systems are often designed to undergo large deformations allowing for various shape reconfigurations. Thin beams integrated with piezoelectric layers or patches are one of examples of smart flexible structures.

This study deals with nonlinear large deformation analysis of a thin beam with multiple piezoelectric patches attached on its top and bottom surface. The beam undergoes large plane deformations due to electric actuations by the patches and mechanical actuation by external force. In formulating governing equations, thickness of the patches is assumed to be much smaller than thickness of the beam so that the effect of patches on stiffness of the beam can be neglected. Two approaches are used to analyze the problem; in absence of mechanical loads and only electric actuation by piezoelectric patches, Reissner's large-displacement finite-strain beam theory is adopted for formulation and by neglecting shear effects, closed form solutions are derived for deflection of the beam. For the case that the smart beam undergoes mechanical load as well, nonlinear shooting and 4th order Rung-Kutta methods are used to solve the boundary value problem numerically. Nonlinear constitutive equations for strain of piezoelectric material in terms of electric field is also considered due to the fact that inducing large deformations requires the actuators to be subjected to large amounts of electric fields.

In the end, by controlling some independent variables like location of patches or magnitude of electric load through some examples, desired deformed shapes for such beams are achieved which can be useful for practical purposes.

9431-63, Session 11B

Removing surface accretions with piezo-excited high-frequency structural waves

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Unwanted accretions on structures are a common machinery maintenance problem, which can pose a serious safety threat if not treated effectively and punctually. The foremost example of a dangerous build-up is aircraft icing. In this paper we investigate the concept of employing piezo-excited structural waves to invoke delamination in waveguides with accretion. We apply a wave-based technique for modelling piezoelectric excitation based on the semi-analytical infinite elements to model the interface shear stress associated with piezo-actuated structural waves. Thanks to this, the analysis is not limited by the assumptions on the dynamics of the actuator and its mutual interaction with the structure. We account for the issues related to electrical power transfer between the ultrasonic source and the

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actuator bringing a more practical perspective on the power requirements of considered systems. For two illustrative waveguides we present the contributions to the interface shear stress of particular propagating waves with reference to driving electrical quantities. Since real world structures exposed to accretions can often benefit from residual reflections from their highly absorptive edge boundaries, we look into the enhancement of the generated interface shear stress associated with decreasing leakage into the supporting host structure. Finally, we present a demonstration experiment in which the patches of a model material are removed from a beam-like waveguide with emulated anechoic terminations using ultrasonic excitation. We support the experiment with numerical simulations, proving the modelling method to be an informative tool for the analysis of ultrasonic structural cleaning systems.

9431-64, Session 11B

Hierarchical compact piezoelectric tripod manipulator

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In this paper, we report a 3-DOF Hierarchical Compact Piezoelectric Tripod Manipulator (HCPTM) actuated by piezoelectric stack actuators. Generally, conventional tripod manipulators applying three actuation linkages which length can be controlled by the piezoelectric stack actuator, offer a small workspace of end-effector under a rotational angle of 1° because of a limited strain (0.1%) of the stack actuators. Also the tripod manipulators take up an excessive amount of space and weight. But the HCPTM can provide relatively large workspace, applying three hierarchical linkages consisting of butterfly-shaped amplification mechanisms with a crisscross series arrangement to amplify the stroke of the piezoelectric stack actuators. Through small size of the amplification mechanisms, proposed tripod manipulator is also compact, light to fabricate and has capacity to be utilized in small-scale applications. The prototype of the HCPTM has a workspace with a rotational angle of 1.2° and linear stroke of 562?, despite its small size (total height of 56.0mm and radius of 24.3mm) and weight (115g).

9431-65, Session 11B

Multiobjective optimization of piezoelectric bimorph actuator with rigid extension

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The tip deflection of a piezoelectric bimorph actuator can be increased either by increasing the length of the piezoelectric layer, or by connecting a rigid extension at the tip of the bimorph actuator. By choosing lighter material for the rigid extension compared to the density of the piezoelectric material, we can make relatively lighter actuator. However, this concept introduces limitation in the performance of that piezoelectric actuator. The concept of a rigid extension at the tip of piezoelectric laminar actuator was introduced by Campolo et al (2003). Wood et al. (2005) fabricated tapered piezoelectric bimorph actuator with rigid extension at its tip and considered first order piezoelectric constitutive equations to model that actuator. Tiersten (1993) proposed second order constitutive equations of piezoelectric materials assuming small strain and large electric field.

This paper presents an electromechanical modeling of a piezoelectric bimorph actuator with rigid extension, considering the non-linear behaviour of piezoelectric material at high electric field. The analysis considers the second order constitutive equations of piezoelectric materials assuming the strain is small and the electric field is large. The paper contains analytical formulation and derives different performance measuring attributes of this actuator. Analytical modeling shows that values of output energy, energy

density and energy efficiency become maximum for certain geometry, and beyond that their values decrease. Thereby, we perform a multi-objective optimization to achieve optimal geometry of the actuator for maximum output energy, output energy density and energy efficiency. This optimal design limits the length of the rigid extension. The analysis considers both series and parallel electrical connection for the results.

Summary:

Analytical model of piezoelectric bimorph actuator with rigid extension is described using second order constitutive equations. This analytical model can capture behaviour of this actuator at high electric field. Performance measuring attributes of the actuator are derived analytically. Then multiobjective optimization is performed to find optimal geometry of the actuator for maximum output mechanical energy, output energy density and energy efficiency.

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9431-66, Session 11B

Effect of material uncertainties on dynamic analysis of piezoelectric fans

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A piezofan is a resonant device that uses a piezoceramic material to induce oscillations in a cantilever beam. Piezofans are popular as a very compact, low power, noiseless air cooling technology for portable electronic devices such as cellphones, DVD players, laptop computers, automobile multimedia boxes etc. Uncertainties are associated with the piezoelectric structure due to several reasons such as variation during manufacturing process, temperature, presence of adhesive layer between the piezoelectric actuator/sensor and the shim stock etc. Presence of uncertainty in the piezoelectric materials can influence the dynamic behavior of the piezoelectric fan such as natural frequency, tip deflection etc. These quantities will also affect the performance parameters of the piezoelectric fan such as electromechanical coupling factor, flow velocity, cooling rate etc. Probabilistic analysis provides a tool for incorporating structural uncertainties of the material properties in the analysis of the structure by generally describing the uncertainties as random variables. In the present study, uncertainty analysis is performed using classical Monte Carlo Simulation (MCS). The MCS is one of the most popular non-intrusive uncertainty analysis techniques that can be performed without any modification or approximation of the governing equations. Furthermore, the growing power of computers has made MCS possible for many engineering problems. In the full paper, structural model used for dynamic analysis of a piezofan will be presented. Full paper will also show the influence of the uncertainties associated with the piezofan structure on the dynamic behavior of the piezoelectric fan.

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9431-117, Session 11B

Nonlinear vibration analysis of the high-efficiency compressive-mode piezoelectric energy harvester

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Power source is critical to achieve independent and autonomous operations of electronic mobile devices. The vibration-based energy harvesting is extensively studied recently, and recognized as a promising technology to realize the inexhaustible power supply for small-scale electronics. Among various approaches, the piezoelectric energy harvesting has gained the most attention due to its high conversion efficiency and simple configurations. However, most of piezoelectric energy harvesters to date are based on the bending-beam structures and can only generate limited power with narrow working bandwidth. The insufficient electric output has greatly impeded their practical applications. In this paper, we present an innovative lead zirconate titanate (PZT) energy harvester, named high-efficiency compressive-mode piezoelectric energy harvester (HC-PEH), to enhance the performance of energy harvesters. A theoretical model was developed analytically, and solved numerically to study the nonlinear characteristics of the HC-PEH. The results estimated by the developed model agree well with the experimental data from the fabricated prototype. The HC-PEH shows strong nonlinear responses, favorable working bandwidth and superior power output. Under a weak excitation of 0.3 g ($g = 9.8 \text{ m/s}^2$), a maximum power output 30 mW is generated at 22 Hz, which is more than ten times better than current energy harvesters. The HC-PEH demonstrates the capability of generating enough power for most of wireless sensors.

9431-68, Session 12A

Active noise control with fast delay-less convolution implemented on rapid control prototyping system

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Adaptive Noise Blocker is a system under development that will be mounted inside a window-opening to reduce the transmission of noise. The system consists of ten microphones, four loudspeakers, a Rapid Control Prototyping (RCP) and analog filters. The latter introduce a delay decreasing the performance of the feedback control. A computational efficient active noise control algorithm allows the RCP to operate at high sampling frequency. Herewith the usage of analog filters with high corner frequency is enabled which leads to less delay. A feedback delay-less partitioned block frequency-domain adaptive filter is implemented on a multitasking RCP.

9431-69, Session 12A

A smart model of a long-span suspended bridge for wind tunnel tests

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Traditional aeroelastic models rely only on good mechanical design and accurate crafting in order to match the required structural properties. This paper proposes an active regulation of their structural parameters in order to improve accuracy and reliability of wind tunnel tests. Following the design process steps typical of a smart structure, a damping tuning technique allowing to control a specific set of vibration modes is developed and applied on the aeroelastic model of a long-span suspended bridge. Depending on the testing conditions, the structural damping value can be adjusted in a fast, precise and repeatable way in order to highlight the effects of the aerodynamic phenomena of interest. In particular, vortex-induced vibration are taken into consideration, and the response of a bridge section to vortex shedding is assessed. The active parameter regulation

allows to widen the pattern of operating conditions in which the model can be tested. The paper discusses the choice of both sensors and actuators to be embedded in the structure and their positioning, as the control algorithm to obtain the desired damping. Experimental results are shown and results are discussed to evaluate the performance of the smart structure in wind tunnel tests.

9431-122, Session 12A

Multifunctional magneto-plasmonic nano-transducers for advanced theranostics: synthesis, modeling and experiment

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In this work, nano-transducers with the superparamagnetic iron oxide (SPIO) core have been synthesized by the preparation of precursor gold nanoseeds loaded on SPIO-embedded silica to form a gold nanoshell. The goal is for such nano-transducers to be used in theranostics to detect brain tumors by using MRI imaging and then assist in their treatment by using photothermal ablation. The iron oxide core provides for the use of a magnetic-field to guide the particles to the target (tumor) site. The gold nanoshell can be easily heat up under incident light and/or alternating magnetic-field. After synthesis of nano-transducer samples, Transmission Electron Microscopy was employed to analyze the formation of each layer [1]. Then, UV spectroscopy experiments were conducted to examine the light absorbance of the synthesized samples [2]. The UV-visible absorption spectra shows a clear surface plasmon resonance (SPR) band around 530 nm, verifying the presence of gold coating nanoshells. Finally, photothermal experiments using a high-power laser beam with a wavelength of 527 nm were performed to heat up the samples. It was found that the temperature reaches 45 °C in 12 minutes.

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9431-70, Session 12B

Electromagnetic damper design using a multiphysics approach

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Electromagnetic dampers (EMD) have been widely studied and applied for the control of vibrating structures. Yet, their use for space applications has been almost negligible, due mainly to their high ratio of system mass over damping force produced. The employment of shunts attached to EMDs, and in particular the development of negative impedances, has allowed higher currents to flow in the device, thus obtaining an increased damping performance. However, the need for a thermal analysis has become important in order to evaluate the power and temperature limits of EMDs, and hence allow a more efficient optimization of the whole device. This paper presents a multiphysics Finite Element Analysis of an EMD in which the thermal domain is integrated with the electromagnetic and mechanical domains. The influence of the temperature on the device parameters and overall performance in the operative temperature and frequency ranges of a space mission is shown. The outcomes of this parametric analysis are then included in the design optimization of an electromagnetic shunted damper

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for 5-kg single-degree-of-freedom system to obtain a maximum dissipated power of 7 Watts. In particular, the analytical results are compared with the typical transfer function of a viscoelastic material. This paper demonstrates the feasibility of achieving the same slope of -40 dB/dec while considerably decreasing the magnitude of the characteristic resonance peak of viscoelastic materials.

9431-71, Session 12B

Optimal resource allocation to multiple piezoelectric patches and inductors for SSDI vibration suppression

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We have performed a study of the performance of semi-active vibration suppression by using piezoelectric patch, called as SSDI, is investigated and optimized from a view point of practical application to satellite structures. This method converts the energy of mechanical vibration into the electric energy. Then the polarity of this charge is inversed according to the phase of mechanical vibration by a switched inductive shunt circuit, so that the piezoelectric patch generates the right polarity of force to suppress the mechanical vibration effectively.

Previously, the authors have experimentally demonstrated that this method can reduce the vibration amplitude of 140kg satellite by 50% by using 80g piezoelectric patches. In that demonstration, it was revealed that multiple piezoelectric patches need to be attached to the actual satellite structure because of the limitation of space where the piezoelectric patches can be attached. It was also shown that the performance in suppressing the vibration heavily depends on the configuration of electrical connection for these devices.

In this paper, we first show that the performance in vibration suppression by using a given amount of piezoelectric material is dominated by a parameter called as inverse ratio. Next, a mathematical model of the characteristics of piezoelectric patches and inductors is established as a function of frequency based on measured data. Subsequently, it is experimentally verified that this model can properly predict the value of inverse ratio. And finally, the optimal resource allocation of the patches and inductors is analytically derived based on this verified mathematical model.

9431-72, Session 12B

Vibration of cantilever piezolaminated beam with extension and shear mode piezo actuators

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Vibration of piezolaminated beams with extension and shear mode piezo actuators subjected to electromechanical loading is studied. A finite element eight node isoparametric element is adopted in the formulation with higher order shear deformation theory. Constitutive law for piezoelectric is considered. In case of the extension actuation mechanism, top and bottom layers of beam are of PZT-5A piezoelectric material and the central core is of Aluminum. Whereas, in case of shear actuation mechanism, top and bottom layers are of Aluminum and the central core is provided with a small patch of PZT-5A piezoelectric material and the rest of the core is a rigid foam material. Frequencies obtained by using present methodology are presented for both extension as well as shear actuation mechanism of piezoelectric material.

For piezolaminated plates two constitutive relationships exist including the effect of mechanical and electrical loading. Variation of temperature effect is neglected in formulation.

Frequencies for the cantilever beams with extension as well as shear mode piezoactuators are found out and are compared further.

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9431-73, Session 13A

Magnetoelastic energy harvester for structural health monitoring applications

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The work presented in this paper includes experimental and theoretical results for an energy harvesting device with the capability to power a structural health monitoring system. This device is a unique adaptation of a previously published zigzag magnetoelastic energy harvester that will be usable in a variety of applications. Cantilevered structure zigzag beams have been shown to have natural frequencies orders of magnitudes lower than traditional cantilever beam geometries of the same size. Literature has also demonstrated that the standard cantilever beam harvester design combined with a magnetic field can be successfully used to introduce nonlinearities in the response, which widen the usable frequency harvesting range of the device. The proposed research introduces a zigzag geometry beam used in conjunction with a magnetic field to create a device capable of integrating with a self-powered wireless sensing platform. This platform will combine broadband energy harvesting, highly efficient power generation, and control electronics to provide self-powered sensing functionality and wireless transmission capabilities in a compact device. These attributes combined with low level computing make the device applicable for a host of sensing applications ranging from temperature sensing to strain measurement. Experimental results will be shown comparing both the linear and nonlinear harvesting and transmission capabilities of the energy harvesting device. Experimental results are the focus of this paper, but a discussion of how Rayleigh's quotient and the Duffing oscillator equation were used to model both the linear and nonlinear dynamics of the structures will also be included.

9431-74, Session 13A

Energy harvesting from building seismic isolation

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A novel electromagnetic transducer shunt circuit is proposed in this paper for dual-functional energy harvesting and vibration control of building seismic isolation. In recent decades, base isolation systems are widely used in low and middle rise buildings. Even though base isolation can filter out high frequency excitation from earthquake, it still necessary to consider higher order modes' vibration in host structure. The new design extends the multi-mode shunt circuit technology in piezoelectric area in order to achieve good vibration suppression into the seismic isolation of multi degree of freedoms (MDOF) of host structure of buildings, and use multi-mode circuit to achieve both energy harvesting and seismic vibration control. A numerical study of simplified two degree of freedom base isolation is presented in this paper. This passive system is also examined by giving recorded earthquake excitation. The stimulation results show that this new design could take advantage both of low-pass filtering capacity of base isolation system

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and resonant vibration reduction of electromagnetic shunt circuit. The experiment results also demonstrate that this new system could achieve good seismic control and energy harvesting at same time.

9431-75, Session 13A

Wireless vibration monitoring system powered by piezocomposite vibration energy harvester for machine condition monitoring applications

Ryota Shimizu, Masahiro Yamaguchi, Kazuhiko Adachi, Kobe Univ. (Japan)

In this study, we have proofed the feasibility of the wireless measured vibration data transmission for a vibration condition monitoring system powered by the authors' proposed vibration energy harvester. It uses a commercial LTC3588 energy harvesting chip with huge external capacitor 54.5mF and the piezo-bimorph cantilever-type energy harvester consists of the surface bonded two Macro-Fiber Composites. The power consumption of the acceleration sensor, MMA7361LC, is typically 1mW, and the driving current is typically 400 microamperes. However, the wireless device, TWE-Lite DIP, requires over 60mW DC driving power. For vibration condition monitoring applications of industrial rotating machinery, we assumed that the typical casing or pedestal vibration amplitude of the rotating machinery was 0.71 mm/sec RMS according to ISO standard. This low intensity excitation condition was the input for experimental evaluation of the developed wireless monitoring prototype system. The prototype system was able to measure the vibration acceleration of approximately 2 seconds under the vibration input of 0.013G (RMS) at approximately 56Hz every 26 minutes. In this prototype system, AC/DC rectifying power loss was reached to 23% that was smaller than the authors' previous experimental result. The experimental results successfully demonstrated the feasibility of the prototype wireless system powered by piezocomposite vibration energy harvester.

9431-76, Session 13A

Implementation of a robust hybrid rotary-translational vibration energy harvester for autonomous self-powered acceleration measurement

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In this paper, a hybrid rotary-translational vibration energy harvester is investigated with the goals of increased output power and robustness. The device in question is examined in multiple configurations and compared with a previously reported device that has been re-tested under the same conditions. The new double coil configuration described in this paper shows a -34% increase in peak output power, from 167 mW to 223 mW, at a frequency of 5.4 Hz with a drive level of 500 mg (where $g = 9.8 \text{ m/s}^2$). An improved peak power density of 7 mW/cm³ is observed for the double coil device, compared to a power density of 5.5 mW/cm³ for the original single coil variant [1]. The root-mean-square (RMS) power is increased from 35 mW to 39.7 mW. Further to this the device is made more robust, and the effects of the wear-mitigation measures are examined. It is concluded by the authors that the configuration choices are beneficial to the operation of the device and demonstrate a clear step towards a viable vibration energy harvester. Finally, as a practical demonstration the harvester is used as a power source for an autonomous self-powered acceleration measurement (SAM) device. Manufacture and performance testing of the SAM device will be discussed.

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9431-77, Session 13B

Earthquake response reduction of mid-story isolated system due to semi-active control using magnetorheological rotary inertia mass damper

Mai Ito, Shohei Yoshida, Hideo Fujitani, Kobe Univ. (Japan); Yusuke Sato, Sanwa Tekki Corporation (Japan)

Mid-story isolated design is useful for buildings with two different structural types or for those constructed in highly populated areas. However, earthquake responses of structures above and below the isolation layer are amplified by the interaction between these structures. Moreover, excessive deformation of the isolation layer and large acceleration in the structures may be caused by resonance with long-period ground motions.

In this paper, the dynamic characteristics of mid-story isolated buildings and seismic response reduction due to semi-active control system are investigated using a three-lumped-mass model that simplifies a sixteen story building with an isolation layer in the sixth story. Semi-active control method using a rotary inertia mass damper filled with magnetorheological fluid (MR fluid) is proposed. The damper has both the mass amplification effect due to rotational inertia and the variable damping effect due to MR fluid. The damping force is controlled by the electric current, which is determined by the proposed semi-active control method based on the relative velocity of the isolation layer to the layer just underneath it.

Simulation results showed that the response displacements of the structure above the isolation layer were reduced significantly, without increasing the response accelerations of the whole structure against near-fault pulse and long-period ground motions. Real-time online hybrid tests using an actual damper and a simulated building model were conducted; the test results were in good agreement with the corresponding simulations. It was confirmed that the proposed semi-active control using MR rotary inertia mass damper is effective for mid-story isolated buildings.

9431-78, Session 13B

Bistable oscillator for efficient target energy transfer

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The targeted energy transfer from a linear oscillator to an attached ground nonlinear oscillator is investigated. The nonlinear oscillator functioned as an energy sink, consisting of a nonlinear spring exhibiting bistability. Numerical studies elucidate the effect of bistability on the overall system performance. The studies focus on energy transfer from the linear oscillator to the nonlinear bistable energy sink (BES) subject to impulse excitation. In general, the results show BES exhibits more efficient damping characteristics for a wider input excitation energy level. This model has been used to study an acoustic resonator and its dissipation. The results may indicate a new acoustic dissipation mechanism.

9431-79, Session 13B

Gradient non-reflective layered media for isolation

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The choice and fabrication of point-wise properties in a gradient design allows for more sophisticated objectives in active and passive smart

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dynamic structural systems. For example by creating a non-reflective layered structure, two parts of a dynamical system may be vibrationally isolated. Here a mathematical technique for design of non-reflective media based on the conversion of the wave equation of a heterogeneous medium, in potential form, to a homogeneous one is presented. This approach utilizes a number of standard techniques in scattering particularly used in quantum mechanical systems. The potential form of the equations is chosen for this particular reason. In scattering problems of quantum mechanics, the reflection and transmission coefficients are derived given a potential (e.g. the field due to another particle). Here we convert the heterogeneity of the layered structure to an equivalent potential. For a particular set of layered designs, the equivalent potential results in no scattering. Therefore, such a layered design is in fact non-reflective. The sensitivity to the frequency of excitation is analyzed. The feasibility of fabrication for this class of layered gradient structures in discussed and potential limitations due to discretization in fabrication and numerical calculations will be addressed.

9431-80, Session 13B

Research on seismic performance of slotted RC shear walls with replaceable damper

Jian Wang, Harbin Institute of Technology (China)

Shear walls are important members of resisting the lateral force in high-rise structures. However, the traditional shear walls are difficult to repair or replace in post-earthquake events. Hence, over the past few years, a research was made of several kinds of replaceable structures such as replaceable coupling beam and replaceable shear wall toe. In this paper, a new seismic energy dissipation shear wall structure is proposed. The new shear wall is one with purposely build-in vertical slits with the wall panel, and steel dampers are installed in the vertical slits so that the seismic performance of the structure can be controlled. Moreover, the steel damper is easy to be replaced in post-earthquake events. The proposed steel damper is with a serial of diamond-shaped holes and designed based on the lateral deformation of the shear wall. The yielding scheme of the steel damper is proposed in order to achieve the ductility and energy dissipation demand of the shear walls. The mechanical model of slotted concrete shear wall is established. Finally, the numerical simulations of the slotted RC shear wall based on the finite element software ABAQUS are presented to validate the effectiveness of the proposed mechanical model.

9431-81, Session 14A

Harvesting under transient conditions: harvested energy as a proxy for optimal resonance frequency detuning

Taylor D. Hynds, Jeffrey L. Kauffman, Univ. of Central Florida (United States)

Piezoelectric-based vibration energy harvesting is of interest in a wide range of applications, and a number of harvesting schemes have been proposed and studied -- primarily when operating under steady state conditions. However, the behavior of energy harvesting systems is rarely studied under transient conditions. This paper will work to develop an understanding of this behavior. Of particular interest here is implementing a vibration reduction technique, resonance frequency detuning, which aims to limit mechanical response at structural resonances as the excitation frequency sweeps through a given range. The system will be analyzed through MATLAB simulation as well as through the development of an analytic expression for the state variables, and the results of each method compared. As these techniques will simultaneously produce the local vibration characteristics as well as the energy harvested, useful correlations between these properties will be investigated, with the intent of determining a method of using the harvested energy as a proxy for vibration characteristics within the scope of the vibration reduction technique

discussed above. The strong coupling between mechanical and electrical properties in vibration-based energy harvesting systems leads to the conclusion that it should be possible to use a measurement of the energy harvested with some minimal processing as a proxy for the vibration profile.

9431-82, Session 14A

Electromagnetic energy harvester using coupled oscillating system with 2-degree of freedom

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This paper presents the design and fabrication of a 2-degree of freedom vibration energy harvesting device for converting kinetic energy into electrical energy using electromagnetic transduction. The relative motion between a magnet and a conductive coil induces an electromotive force. A non uniform magnetic field design is used where an oscillating magnet is suspended by a spring-damper system. In addition the coil is suspended to serve as the second oscillating mass to effectively harvest energy at two different frequencies. The design parameters are elucidated in this paper which describes the effects of voltage cancellation due to coil phase, coil placement for optimal performance and the benefits of separating magnets using material with high permeability. The investigation was performed using multi physics finite element analysis (Comsol) with sinusoidal vibration input. A prototype was developed to demonstrate that practical amount of power can be generated from the design. The resonant frequencies of the prototype harvester were tuned to match the dominant frequencies of the host structure (i.e. heavy haul railcars). Peak output powers of 212 mW and 218 mW are generated from sinusoidal vibration with 0.4 g peak acceleration (where $g = 9.8 \text{ m/s}^2$) at 6.5 Hz and 14.5 Hz respectively.

9431-83, Session 14A

A single-DOF vibration energy harvester for integrating into the parallel mechanism

Gang Yuan, Dai Hua Wang, Chongqing Univ. (China)

In order to realize a six-degree-of-freedom (six-DOF) piezoelectric energy harvester through integrating six single-degree-of-freedom (single-DOF) piezoelectric energy harvesters into a parallel mechanism, which has six sensitive axes and broader bandwidth, a single-DOF piezoelectric energy harvester utilizing a clamped beam configuration is proposed in this paper. It consists of a proof mass and a corrugated clamped beam covered by a polyvinylidene fluoride (PVDF) film, where the proof mass is mounted at the center of the beam. Compared to the conventional energy harvester, the proposed single-DOF vibration energy harvester has two parallelism mounting planes at the support of the beam and the mass, separately, and can be easily integrated into the parallel mechanism. The motion equation of the single-DOF piezoelectric energy harvester is established and analyzed. On this basis, the natural frequency and stress distribution of the harvester are investigated through analytical developments and numerical simulations. Experiments are also conducted to verify the performance of a prototype built according to the proposed configuration. These results show that the proposed single-DOF vibration energy harvester has voltage output with the excitation along its axis, while no voltage outputs with the excitation perpendicular to the axis, and the natural frequency and stress distribution can be accurately estimated by the established theoretical models.

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9431-84, Session 14A

A six-DOF vibration energy harvester based on the six-DOF parallel mechanism

Gang Yuan, Dai-Hua Wang, Chongqing Univ. (China)

The existing vibration energy harvesters can only harvest the vibration energy with single sensitive axial and narrow band, which lead to the problems of low efficiency and high level requirements for installation. This paper proposes a piezoelectric energy harvester for six-degree-of-freedom (six-DOF) vibration energy harvesting utilizing a six-DOF parallel mechanism with cubic configuration. It consists of a proof mass as the upper platform, six flexible legs with two spherical joints connected by a single-degree-of-freedom (single-DOF) harvester, and a foundation support. Compared to the conventional energy harvester, the proposed six-DOF vibration energy harvester has six sensitive axes and broader bandwidth for the proper designed six adjacent natural frequencies, so higher efficiency of energy harvesting can be expected. To investigate the characteristics of the proposed energy harvester, analytical developments and numerical simulations on its natural frequency and modes of vibration are carried out. Experiments are also conducted to verify the performance of a prototype built according to the proposed harvester. These results show that the proposed six-DOF vibration energy harvester has higher output voltage and its bandwidth is much broader than the conventional single-DOF one.

9431-85, Session 14B

Simulating coupled thermal-mechanical interactions in morphing radiators

Christopher L. Bertagne, John D. Whitcomb, Darren J. Hartl, Texas A&M Univ. (United States)

As the field of smart structures matures, increasingly complex morphing components are being considered. The ability of smart materials to provide mechanical work allows external actuation mechanisms to be eliminated. However, smart materials often introduce multiphysical behavior, such as the coupling between temperature, stress, and strain for a shape memory alloy. This requires a corresponding increase in the capabilities of analysis tools used to design smart structures. Although multiphysical simulation tools are sufficient to analyze many smart structures, there are some components which exhibit multiphysical characteristics that have not been rigorously considered. One example of such a component is a shape memory alloy-based morphing radiator. This component exhibits a complex coupling between temperature and geometry, as a result of the shape memory alloy and the radiative heat transfer taking place within the component. This work focuses on developing a finite element analysis (FEA) framework capable of simulating coupled radiation heat transfer problems within a radiator actuated by shape memory alloys. An example problem is provided, and non-FEA numerical solutions are also developed to validate the framework. It is expected that similar approaches will be used to design future morphing radiator components for a wide variety of applications.

9431-86, Session 14B

A passive control methodology for seismic safety enhancement of monumental structures

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A passive control methodology to increase the seismic safety of multi-drum columns is presented. The response of a large scale column-model (3 m)

replica of a multi-drum column from the temple of Parthenon is used for the experimental study. The column-model is placed on a 3 x 5 m shake table and its response is investigated under dynamic excitations. The response of the column to the dynamic loads is obtained from eleven accelerometers attached on the drums of the column. A particle damper in the form of a marble drum is used to replace one of the column's original drums. The response obtained is compared with the response of the column without the damper. The influence of the system parameters on the response of the column is systematically examined. The results obtained are compared with the results from the response of a small scale multi-drum column replica of a multi-drum column from the temple of Hephaestus in Athens. It is found that both models behave in a similar way. The seismic response of the column can be considerably reduced if a particle damper replaces a drum above the mid-height of the column. A small mass ratio (mass of particles with respect to the mass of the column) less than 2% is capable to reduce the motion of the column considerably as long as the particles have enough space to move. Guidelines and a design methodology are proposed to restore and protect monumental structures.

9431-87, Session 14B

On the use of Fiber Bragg gratings sensors to increase the reliability of feedback measurements in smart structures

Simone Cinquemani, Gabriele Cazzulani, Francesco Ripamonti, Politecnico di Milano (Italy)

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.

This paper introduces the use of these sensors to increase the reliability of feedback measurements in smart structures designed to actively control vibration.

As known, one of the main drawbacks of these structures is the robustness of the control when one or more sensors do not work properly. In these cases the performance in reducing vibration can be seriously limited and problems of instability may occur.

The use of FBG sensors can overcome this limit thanks to the large number of available measurements. This paper introduces some different control algorithms to suppress vibration and discusses the reliability of feedback measurements when failures on sensors happened. Theoretical results are supported by experimental tests on a large flexible system made of a thin cantilever beam with 30 longitudinal FBG sensors and six piezoelectric actuators (PZT).

9431-88, Session 14B

Investigation on seismic resistance of high-rising buildings installed with viscoelastic-wall dampers

Min Liu, Yang Wang, Harbin Institute of Technology (China)

Viscoelastic dampers are one of popular vibration mitigation devices applied to tall buildings to reduce seismic and wind-induced vibration. In this paper, a new kind of viscoelastic-wall damper, which could be installed at the shear-wall location of high-rising buildings, is proposed to enhance the energy dissipation ability. The theoretical and experimental investigation on the mechanical properties of the viscoelastic-wall damper is developed. The seismic resistance behaviors of one tall building installed with the viscoelastic-wall dampers are investigated by numerical analysis.

In this paper, the mechanical property tests of the viscoelastic material which is applied to the viscoelastic-wall damper are conducted to exactly identify its characteristic parameters under various exciting frequencies

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and strain amplitudes. According to the testing results, a mathematical model of viscoelastic-wall damper is modeled on the basis of Kelvin model. Based on a 36-floor frame-shear wall high building prototype model, two finite element models of the structure with and without the viscoelastic-wall dampers are built up by using the finite element software ABAQUS. Elastic plastic time-history analysis is carried on to compare the seismic resistance performances of the high-rising building subjected to excitations of frequently occurred earthquake and rarely occurred earthquake. The numerical analysis results indicate that the seismic response of the tall building would be mitigated effectively and the damage level of the structure could be reduced when equipped with the viscoelastic-wall dampers.

9431-89, Session 15A

Simulation and experimental studies of the SMA-activated needle behavior inside the tissue

Bardia Konh, Mohammad Honarvar, Parsaoran Hutapea, Temple Univ. (United States)

Recently, the concept of developing an active steerable needle has gathered a lot of attention as they could potentially result in an improved outcome in various medical percutaneous procedures. In addition, compared to the conventional straight needles, active needles can be bent by the attached actuation component to reach the target locations inside the body more accurately. In this study, the movement of the passive needle inside the tissue was investigated using both numerical and experimental approaches. The passive needle insertion tests were performed using a tissue mimicking phantom. Also a finite element simulation of needle insertion was developed using LS-DYNA software to study the maneuverability of the passive needle. The Arbitrary-Eulerian-Lagrangian (ALE) formulation was used to model the interactions between the solid elements of the needle and the tissue which were modeled by fluid elements. This model was validated for the initial 20mm of insertion which can be extended for the whole 150mm of experimental insertion. This model is intended to be based as a framework to model the active needle insertion in future. Finally, a miniature sized prototype of the SMA-actuated needle was developed using which the improvements in the movement and control was demonstrated.

9431-90, Session 15A

Optimization and testing of a continuous rotary motor based on shape memory wires and overrunning clutches

Eugenio Dragoni, Giovanni Scirè Mammano, Univ. degli Studi di Modena e Reggio Emilia (Italy)

High power density, smooth and silent operation, mechanical simplicity, compatibility with aggressive environments are only a few of the many advantages that make shape memory alloy (SMA) actuators an attractive option in modern industrial applications. A relatively unexplored field of the shape memory technology is the area of rotary actuators, especially for generating continuous rotations. Torsion tubes are the favorite concept for rotary shape memory actuators due to their simple geometry and high output torque. However, unless unrealistically long tubes or multiplying gears are used, the effective rotation is generally low. This paper deals with a novel continuous rotary motor based on SMA wires and overrunning clutches producing high output torque and boundless angular stroke. The concept capitalizes on a SMA wire wound round a low-friction cylindrical drum with backup force provided by a beam spring acting tangentially to the drum. Electrical activation of the wire produces a contraction of the wire followed by rotation of the drum and its supporting shaft. Shaft and drum are connected by means of an overrunning clutch so that during the backup phase, the drum rotates backward while the shaft does not move. Spurious backward rotations of the shaft are contrasted by a second overrunning clutch linking the shaft to the frame and allowing movement only in the

direction of the contracting wires. This paper presents the detailed design of a six-stage miniature actuator and compares the expected performance with the experimental measurements performed on a test prototype.

9431-91, Session 15A

An information indicator based on two-way shape memory alloys (SMAs)

Huihui Wang, Williams B. Lane, Max Orozco, John Leong, Devin Pappas, Jacksonville Univ. (United States); Bryam Duque, Jacksonville University (United States)

A prototype of information indicator based on two way SMAs is proposed in this paper. Such a cubic information indicator will deliver different information by changing its shape. A two-inch cubic with five holes is designed and printed by a 3D printer. Five SMAs are imbedded into five holes covered by 1mm thick layers of Polydimethylsiloxane for comfortable touching. A portable power supply, a sensor and a control circuit are integrated with the cube. Two-way SMAs are thermal effect smart materials which can be deformed when current (1-3As) is passed through them and returning to their original shape when the current is off. When the sensor in the information indicator receives a signal, the control circuit will drive the current going through one or more SMAs which will be deformed based on thermal effect. As a result, the information indicator will be deformed from the original cubic shape to a customized shape which depends on personal definition. When the current is off after a couple of seconds, the indicator will go back to the cubic shape again. With such an information indicator, users can be notified through either vision or haptic interface (force feedback) such as when audio or video interaction is not available.

9431-92, Session 15A

Modeling framework for materials capable of solid-solid phase transformation: application to the analytical solution of the semi-infinite mode III crack problem in an idealized shape memory alloy

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We propose two frameworks for the derivation of constitutive models for solids undergoing phase transformations. Two distinct approaches are considered: the first is based on the assumption that solid phases within the material are finely mixed whereas the second considers the material as a heterogeneous solution of phase fragments and uses the homogenization theory to derive constitutive relations at the macroscale. It is shown that in the case of reversible phase transformation, the energy of the material can be obtained by taking the convex envelope of the energy functions of the constituent phases. It is further shown that for dissipative phase transformation the material behavior can be made stable by deriving the evolution equations of the state variables from adequately chosen dissipation potentials. Some new results of existence and uniqueness of the solution of boundary value problems of structures undergoing phase change are also given. As an application, a schematic model is derived for an idealized shape memory alloy and used to obtain a novel analytical solution for the problem of semi-infinite mode III crack in this material. The derivation of the analytical solution uses the hodograph method to map Cartesian coordinates into the hodograph plane. The resulting boundary-value problem for the mode III crack considered becomes analytically tractable for the idealized shape memory alloy considered and leads to closed-form expressions for the displacement and phase volume fraction fields near the crack tip as well as for the boundaries between different phase regions.

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9431-93, Session 15A

**Experimental investigation on a novel
3D isolator made of shape memory alloy
pseudo-rubber**

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Base isolation technology has been widely theoretically and experimentally investigated, and it has also been verified through many severe earthquakes. Three dimensional isolation technology was proposed several years ago, and the 3-D isolation theory has well developed till now. However, the development of 3-D isolation technology was deeply affected by the 3-D isolator product. Many presented 3-D isolators are generally made up of complicated components, such as rubber, springs, dampers and other connectors. These isolators have some problem in certain extent, such as difficult fabrication process or little energy dissipation ability along the vertical direction. This paper presents a novel 3-D isolator which is made up of martensitic shape memory alloy wires through weaving, rolling, and punching. Mechanical properties of 3-D shape memory alloy pseudo-rubber isolator (SMAPRI) are investigated including compression, shear, and compression-shear loading with different frequencies and amplitude. The mechanical behavior of isolators with different fabrication process and parameters is also compared. Accordingly, the mechanism resulting in the above differences is also analyzed. Experimental results indicated that 3-D SMAPRI has good mechanical properties and energy dissipation ability along both of horizontal and vertical direction. The fabrication process of the proposed 3-D isolator is relatively easy and the mechanism of isolation is clearer than the traditional 3-D isolators. Therefore, this new kind of 3-D isolator has good potentiality in both of seismic isolation for civil infrastructures and industrial isolation for important or precision equipment.

9431-94, Session 15A

**Improvement in performance of reinforced
concrete structures using shape memory
alloys**

Kamalkishor M. Bajoria, Shreya S. Kaduskar, Indian Institute of Technology Bombay (India)

Abstract: Shape memory alloys (SMA) are unique class of materials which can undergo solid-to-solid phase transformation and are finding increasing application in many research areas. SMAs have an ability to undergo large deformation and can also regain its un-deformed shape by removal of stress or by heating. SMAs have distinct thermo-mechanical properties like shape memory effect and superelasticity. This unique property could be effectively utilized to enhance the safety of a structure. This paper includes the fundamental characteristics of SMAs, factors affecting the engineering properties of SMAs and some of the potential applications of SMAs in the civil structures. The aim of this paper is to improve the performance of a moment resistance RC frame by replacing conventional steel with the SMA. In this paper the RC frame reinforced with conventional steel is being replaced fully as well as partially with SMAs. Pushover analysis is done for frames reinforced fully and partially with SMA. The results of both the RC frames (full and partial replacement of conventional steel reinforcement by SMA) are compared with the RC frame reinforced with conventional steel. It is observed that RC frame partially reinforced with SMA shows better performance than fully reinforced with conventional steel and SMA.

Keywords: shape memory alloys, reinforced concrete frame, pushover analysis, performance

9431-95, Session 15B

**Adaptive active vibration control to
improve the fatigue life of a carbon-epoxy
smart structure**

Francesco Ripamonti, Gabriele Cazzulani, Simone Cinquemani, Ferruccio Resta, Alessandro Torti, Politecnico di Milano (Italy)

Active vibration controls are helpful in improving fatigue life of structures through limitation of absolute displacements. However, control algorithms are usually designed without explicitly taking into account the fatigue phenomenon. In this paper, an adaptive vibration controller is proposed to increase the fatigue life of a smart structure made of composite material and actuated with piezoelectric patches. The main innovation with respect to the most common solutions is that the control laws are directly linked to a damage driving force, which is correlated to a fatigue damage model for the specific material. The control logic is different depending on the damage state of the structure. If no crack has nucleated, the controller decreases the nucleation probability by limiting the driving forces in the overall structure. On the contrary, if initiated cracks are present, their further propagation is prevented by controlling the damage driving forces in the already damaged areas. The structural diagnostics is performed online through a vibration-based monitoring technique, while an online periodical adaptation of the controller is adopted to consider damage-induced changes on the structure state-space model and to give emphasis to the most excited modes. Furthermore, the online measured mode shapes are extended with a multilayer perceptron to points without sensors, to have clear strain, stress and damage maps for the whole structure, helping the determination of the proper control effort. The control algorithm has been numerically validated through a FEM model and first experimental results give further support to the work.

9431-96, Session 15B

**Non-linear control logics for vibrations
suppression: a comparison between
model-based and non-model-based
techniques**

Francesco Ripamonti, Lorenzo Orsini, Ferruccio Resta, Politecnico di Milano (Italy)

Non-linear behavior is present in many mechanical system operating conditions. In these cases, a common engineering practice is to linearize the equation of motion around a particular operating point, and to design a linear controller. The main disadvantage is that the stability properties and validity of the controller are local. In order to improve the controller performance, non-linear control techniques represent a very attractive solution for many smart structures. The aim of this paper is to compare non-linear model-based and non-model-based control techniques. In particular the model-based sliding-mode-control (SMC) technique is considered because of its easy implementation and the strong robustness of the controller even under heavy model uncertainties. Among the non-model-based control techniques, fuzzy (FC) and fuzzy model-reference-learning-control (FMRLC) allowing designing the controller according to if-then rules have been analyzed. Moreover, an energy-based (EB) law is taken into account. It defines the controller without a system reference model, offering many advantages such as an intrinsic robustness. These techniques have been tested on a three link flexible manipulator and a comparison between the results is presented.

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9431-97, Session 15B

Investigation of LQR decentralization properties for a clamped-clamped beam

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Vibration control design for flexible structures with a significant number of vibration modes can lead to controllers with very high order. Decentralized control seems to be a promising approach developed recently to deal with these problems. In this paper, we use the finite element method to determine the plate model and partition it in four segments. Eight PZT actuators and sensors have been distributed on the plates. In addition the plate is subject to an external disturbance. We formulate the control problem as optimizing a sum of convex objective functions each corresponding to the local controllers. Each controller will not only 'see' local neighboring sensors but also local neighboring controllers. This process not only aims to minimize its own objective function but also exchange information with neighboring controllers in the system. Simulation results, in both time and frequency domain, are presented. A comparison with previous decentralized H_∞ control design is made in terms of attenuation rate and control effort. Stability issue of our new proposed decentralized control framework is demonstrated. Robustness issue due to random exchanging failure is also investigated.

9431-98, Session 15B

Potential of viscous dampers for vibration mitigation of transmission overhead lines

Asadollah Bassam, Amir Soltani, Sargent & Lundy LLC (United States)

Viscous dampers are one of the tools that can be utilized to mitigate cable vibrations. However, the damping achieved by these dampers is small due to the limitation in attachment location of these dampers. A case study is conducted in this paper to investigate the potential of additional damping provided by a third viscous damper for the case in which two rubber bushings are already attached to the cable near the anchorages. Based on this case study, the dependency between the third damper location and optimum viscosity for maximum vibration mitigation that can be given to a cable with rubber bushings is investigated. The approach used in this study is based on Finite Element (FE) method. The FE model is developed by first formulating an isoparametric cable element which enables modeling a sagged cable. The model is validated by comparing the results of the presented approach with finite series method.

The study shows that although rubber bushings may help mitigating vibrations, they reduce the effect of additional damping devices. However, if the third damper viscosity is selected properly, it can be very effective in further mitigating the vibration amplitudes.

9431-99, Session 15B

Design and investigation of a linear smart actuator

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Traditional linear actuators mainly include hydraulic cylinders, electromagnets and electric linear actuators. The hydraulic cylinder has the advantage of producing large force and output displacement. However, it needs auxiliary equipments such as the hydraulic control valve and pump, which makes the system quite complicated. Electromagnetic and electric linear actuators have been widely used as efficient linear actuator. But it is

difficult to generate significant force when its size and weight are scaled down. Moreover, the electric linear actuators are rotary devices by design, translating rotation into linear motion hence are less efficient than direct linear motion actuators, employs roller screws for the conversion or requires gearboxes and linkages. Although it suits precise positioning applications but inherently exhibits complex design and heavy frictional losses. These drawbacks led to search for innovative actuator technologies, wherein the new revolutionary technology - shape memory alloys (SMA) has proven their worth opening the door for new ideas and designs and with it, what seems unfeasible in the past becomes now challenging.

Shape memory alloys gained increasing attention in recent years, especially in the development of innovative engineering systems such as miniature actuators, valves, etc. They are attractive as actuators and also possess dual functionality of sensing and actuating. Also, the direct drive capabilities and high force to weight ratio of SMA finds them suitable in vast areas of application. The main physical limitation that needs to be overcome is the absolute percent strain that SMAs can achieve. The workable strain is usually around 5 percent i.e., the limitations include the need for a large length of wire to create sizeable linear motion, the small amount of absolute force obtained from one SMA wire, a relatively small bandwidth and low energy efficiency. Various designs of SMA actuators proposed depend on mechanically amplifying the displacement either through the use of long straight fibers or through the use of coils.

The accomplishments reported through this work are as follows:

i. A linear smart actuator system using SMA wires is proposed. A rectilinear (linear) actuator creates motion in a straight line. At its simplest, the linear actuator is a piston-like mechanism. The proposed linear smart actuator design consists of a fixed structural member and a sliding structural member which are engaged with each other along the longitudinal axis by four parallel SMA wires and an axially mounted helical passive spring, to provide linear stroke between the extended state and the contracted state.

ii. A geometrical analysis is carried out to investigate the position of the shaft due to the linear movement of the sliding structural member. Also the maximum force created by the linear smart actuator is computed mathematically using the stroke developed. When subjected to electric current, the SMA wires provide an actuating force to produce a linear movement of the sliding unit.

When the SMA wires are heated above austenitic start temperature, they contract to its original length, thereby applying an actuation force to pull the slider. As the SMA wires are cooled below the martensite finish temperature, they elongate back approximately to its pre-strained length by the virtue of the biasing force provided by the spring. Heating and cooling the SMA fibers result in cyclic contraction and expansion of the actuator.

iii. An open loop experimentation setup is designed to determine the fundamental behavior of linear smart actuator. Figure 2 shows the photograph of the linear smart actuator and the experimental arrangement to acquire the open loop step response i.e., displacement for input voltages in steps of 0.2 V. Corresponding responses are shown in figure 3 for a single and dual set of parallel connected SMA wires.

Larger number of symmetrically fixed parallel SMA wires offer larger magnitude of force and displacement at a faster actuation speed as seen from the figures 4 and 5.

Conference 9432: Behavior and Mechanics of Multifunctional Materials and Composites IX

Monday - Wednesday 9 -11 March 2015

Part of Proceedings of SPIE Vol. 9432 Behavior and Mechanics of Multifunctional Materials and Composites 2015

9432-1, Session 1

Unifying relations in polymer photomechanics

Jonghoon Bin, William S. Oates, Florida State Univ. (United States)

Unusual material mechanisms contributing to surface deformation in azobenzene based polymers has motivated a need to reassess constitutive relations used to predict the transfer of photochemical energy to mechanical deformation. A unified modeling framework is presented that shows how lower order terms within a field coupled constitutive theory can be used to predict a very broad range of deformation states in azobenzene polymers. The results are different than prior models which use the concept of mass diffusion and field gradients. These models breakdown when quantifying bending deformation from uniform light. However, they accurately predict surface relief grating structures. It is shown how certain aspects of Maxwell's equations coupled to electronic structure evolution of the azobenzene can predict bending from uniform light as well as surface relief grating structures from linear or circularly polarized light or vortex beams. A three dimensional microstructure model coupled to mechanics and Maxwell equations is implemented and compared to data to validate the model.

9432-2, Session 1

Thermoplastic polyurethane as a mechanochromic strain sensor

Filippo Cellini, New York Univ. (United States); Sachin Khapli, New York Univ. Abu Dhabi (United Arab Emirates); Sean D. Peterson, Univ. of Waterloo (Canada); Maurizio Porfiri, New York Univ. (United States)

Mechanochromic polymers are a new class of soft active materials that exhibit a detectable change in color upon deformation of their macromolecular backbone. Polymer-dye blends with mechanochromic properties can be obtained through the dispersion of a fluorescent aggregachromic dye within a compatible polymer host. Aggregachromic dyes are characterized by a monomeric state and an aggregate state, with fluorescence emissions at different wavelengths. The color change is associated with shear stresses in the polymer, which induce a transition from an aggregate state to a monomeric phase. Here, we study reversible mechanochromism of thermoplastic polyurethane blended with 0.5 wt % bis(benzoxazolyl)stilbene dye. The material's optomechanical behavior is analyzed during a stress relaxation test performed in a custom-made experimental setup that enables simultaneous acquisition of mechanical and optical responses of the material. Experimental results are interpreted through a modified version of the classical Arruda-Boyce model, which accounts for progressive evolution of the material structure during the deformation cycle. Our results demonstrate a remarkable degree of reversibility of the mechanochromic response of the material, which is expected to aid in the design of mechanical sensors. Moreover, we find that the optical response does not depend on the time-history of the deformation and linearly correlates with the stretch of the polymeric network. We foresee this class of materials to find large application in experimental mechanics and in the design of active non-contact sensors for fluid mechanics and hydrology.

9432-3, Session 1

Mechanical, thermal, and photo-mechanical properties of a novel light activated shape memory polymer

Yingtao Y. Liu, The Univ. of Oklahoma (United States)

Shape memory polymers (SMPs), as a type of important stimuli-responsive polymers, can recover their original (or permanent) shape upon exposure to external stimuli. Intense investigation has been focused on this type of materials due to their novel properties and great potential. However, SMPs have not fully reached their technical potential because of the limitation of activation for the shape memory function. Most published SMPs are thermal active materials which depends on the thermal stimulus to obtain the shape memory function. This paper will synthesize and characterize the mechanical, thermal, and photo-mechanical properties of a novel light activated shape memory polymer. A customized mechanical testing system integrated with optical microscope will be used to characterize the mechanical properties of the proposed SMP. The thermal and photo-mechanical properties will also be investigated. The proposed SMP can be potentially used to design novel shape memory composites in the near future.

9432-4, Session 1

Chemorheological behavior of thermoset shape memory polymers: experiments and modeling

Kannan Dasharathi, John A. Shaw, Alan Wineman, Univ. of Michigan (United States)

Thermo-responsive shape memory polymers (SMPs) rely on the dramatic change in relaxation times across the rubber-glass transition temperature (T_g) to exhibit shape memory behavior. SMPs exhibit three regions of viscoelasticity, namely, glassy (below T_g), leathery (near T_g) and rubbery (above T_g). Additionally, at elevated temperatures (beyond a threshold chemorheological temperature, T_{cr}) SMPs may undergo permanent changes in macromolecular structure, involving scission (breaking of chemical bonds) and recross-linking (reformation of new bonds). Such irreversible microstructural changes can lead to changes in viscoelastic properties and incomplete shape recovery. Thus, chemorheological aging can significantly alter the performance and useful life of the SMP.

In this paper, a multi-network constitutive model is developed for the fundamental (viscoelastic) shape memory behavior combined with the irrecoverable effects of chemorheological aging. Uniaxial tension experiments are performed on two thermoset SMPs, and dynamic mechanical tests are used to calibrate the baseline viscoelastic model. Creep-recovery and thermo-mechanical cycling data are used to quantify the kinetics of chemical aging. The model is then evaluated against experimental data for other, more general, thermo-mechanical histories.

9432-5, Session 2

Electric field responsive origami structures using electrostriction-based active materials

Saad Ahmed, Erika Arrojado, Nirmal Shankar Sigamani,

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Zoubeida Ounaies, The Pennsylvania State Univ. (United States)

The objective of origami engineering is to combine origami principles with advanced materials to yield active origami shapes, which fold and unfold in response to external stimuli. We are investigating the use of P(VDF-TrFE-CTFE), a relaxor ferroelectric terpolymer, to realize origami-inspired folding and unfolding of structures and also to actuate so-called action origami structures. To accomplish this actuation, we have explored different approaches to the P(VDF-TrFE-CTFE) polymer actuator construction, ranging from unimorph to multilayered/stacked configurations. Electromechanical characterization of the terpolymer-based actuators is conducted with a focus on free strain, force-displacement and blocked force. Moreover dynamic thickness strains of P(VDF-TrFE-CTFE) terpolymer at different frequencies ranging from 0.5Hz to 10Hz is also measured. Quantifying the performance of terpolymer-based actuators, as discussed above, is important to the design of action origami structures. Following these studies, action origami prototypes based on catapult, flapping butterfly wings and barking fox are actuated and characterization of these prototypes are conducted by studying impact of various parameters such as electric field magnitude and frequency, number of active layers, and actuator dimensions.

9432-6, Session 2

Characterization of lead zirconate titanate microwires using digital image correlation

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

Lead zirconate titanate (PZT) microwires with applications in sensors, actuators and energy harvesters are produced using hydrothermal synthesis. The synthesized microwires are relatively large with the average length about 400-500 microns and width of 3-4 microns. Each of these individual PZT microwires can be integrated in smart systems as an active phase or be used as an independent smart material. In this paper, the synthesis procedure and characterization of these large microwires is demonstrated. The converse piezoelectric properties of the microwires are measured using digital image correlation after clamping and adding electrodes at each end of the microwire. It has been shown in the literature that digital image correlation can be used as a precise tool for rapid characterization of the piezoelectric materials. Here, it is demonstrated that this technique can be extended for electromechanical characterization of micro/nanoscale piezoelectric materials.

9432-7, Session 2

Effect of carbon nanotubes on properties of cement-sand-based piezoelectric composites

Sun Jung Kim, Ping Zhao, Emmanuel U. Enemuoh, Univ. of Minnesota, Duluth (United States)

A cement-sand based piezoelectric smart composite was recently investigated and developed by the authors; however, there was difficulty in poling the composite because the Lead Zirconate Titanate (PZT) particles did not produce a continuously connected structure, leading to a low piezoelectric effect. In this work, Carbon Nanotubes (CNTs) were dispersed in the composite as a conductive filler to improve its poling efficiency. By introducing a small amount of CNTs, continuous electric networks between PZT particles are created, thus making the composite poling easier. However, too much CNTs can generate short-circuit in the composite, therefore making the amount of CNTs introduced a key design parameter. The optimal quantity of CNTs was evaluated by conducting statistical analysis of the main effects of several CNT quantities ranging from 0 to 1.2 vol.% on the composite's characteristics: piezoelectric coefficients, dielectric constants, loss, and sensing effect. The specimens were prepared

by mixing PZT powders, Portland cement and sand with CNTs, followed by pressing with 100 MPa pressure. The piezoelectric coefficient d_{33} was carried out by an APC d33 tester. The dielectric constant and loss were measured using an impedance analyzer (Gamry Reference 600) under multiple frequencies. The sensing effect of the composite was characterized by conducting compression tests with a universal material testing system. The developed composite generated cyclic voltage when subjected to a sinusoidal compressive wave. The results from this study will have broader impact in civil engineering structures, especially in the performance of the piezoelectric transducers in Structural Health Monitoring systems.

9432-8, Session 2

Poly(vinylidene fluoride)/graphene nano-platelets electrically conductive composite foam for thermoelectric applications

Yu-Chen Sun, Univ. of Toronto (Canada); Daryl Terakita, Alex C Tseng, University of Toronto (Canada); Hani E. Naguib, Univ. of Toronto (Canada)

Thermoelectric effect is known as the electricity or voltage difference generated from some materials when they are being subjected to a temperature difference. The performance of these materials is defined as merit, ZT, and it is a function of material's thermal conductivity, electrical conductivity, and its Seebeck coefficient. In the past, polymer based thermoelectric materials are fabricated from the solvent casting method which usually involves highly toxic solvent and solution. In this paper, we presented the results of poly(vinylidene fluoride) (PVDF) based thermoelectric material with graphene nano-platelets (GNP) and multiwall carbon nanotube (MWCNT) as fillers. The samples are fabricated through melt blending method, which is a cheaper, simpler process and can be easily scale up to industrial level for mass production. Our results indicated that melt blending process can produce either similar or superior results compared to the traditional solvent casting methods. For GNP/PVDF samples, we have found a superior Seebeck coefficient approximately 200% better compared to the value reported from previous studies while the electrical and thermal conductivity shows similar values. In addition, our MWCNT/PVDF samples show a similar trend compared to literature but with a slightly lower thermoelectric performance.

9432-9, Session 2

Strain and voltage analysis of a piezoelectric wafer bonded to thin plate in bending

ZhongZhe Dong, Cassio T. Faria, Siemens Industry Software (Belgium)

Smart materials have been investigated for potential in automotive, aerospace and other industry related applications. In particular, piezoelectric materials are of interest due to its actuator/sensor characteristics that can be implemented in a large number of mechanical applications, for example vibration suppression, active control, damage detection etc. A good prediction capability of the strain and consequently the voltage of a piezoelectric element operating in bending is a very important tool to have in order to enable those applications.

The work presented here focuses on the pure bending coupling of bi-layer plates; an accurate determination of strain in the coupled structure is the main issue at hand, a solution is proposed is based on the classical Kirchhoff plate's hypothesis, using the Ambartsumyan's model, which works for bi-modulus materials. The existence of the elastic neutral layers in the plate's section has been predicted by the Kirchhoff plate theory. Here, the model of the bi-modulus thin plates in bending has been extended to determine the position of the neutral layers. Then, the coupled strain in pure bending is analyzed, so that the voltage in the piezoelectric layer. The results are compared with finite element modeling simulations.

9432-10, Session 3

Characterization and modeling time dependent behavior in PZT fibers and active fiber composites

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

Active fiber composites (AFC) are comprised of lead zirconate titanate (PZT) fibers embedded in a polymer. The PZT fibers are manufactured based on the ALCERU process, which affects their performance in such a way that their effective properties are found to be different than that of bulk PZT. This paper presents both an experimental characterization of the PZT fibers and a constitutive model focused on their time dependent, nonlinear response. The experimental study focuses on time-dependence of various properties by conducting creep, relaxation, mechanical and high electric field cyclic loading under different frequencies. In addition to highlighting differences from bulk behavior, some of the experimental results are used as inputs to the constitutive model. The constitutive model is derived based on a single integral form with nonlinear (electric field) integrand and includes a time dependent polarization constitutive model for predicting nonlinear polarization and electro-mechanical strain responses of these fibers. An 'internal clock' concept is used to incorporate the effect of electric field on the rate of polarization. A third order piezoelectric constant g and/or fourth order electrostrictive constant h that vary with polarization are used to estimate the strain response of the PZT fibers. The developed model of PZT fibers is used in the FEM simulation of AFCs and results of the model are compared to experiments for validation.

9432-11, Session 3

Uncertainty quantification in quantum informed ferroelectric phase field modeling

William S. Oates, Justin Collins, Florida State Univ. (United States)

Uncertainty associated with homogenization of density functional theory (DFT) is studied by computing stress, polarization, and energy for lead titanate using DFT and integration into a phase field finite element model. The assumption of the Cauchy-Born rule is explored through ab initio molecular dynamic calculations for different lattice configurations and compared to affine deformation mapping within the continuum mechanics framework. The uncertainty of this assumption and the uncertainty associated with constructing a Landau energy is developed and integrated into a finite element phase field model. The effect of strain gradients and flexoelectricity is also explored near domain wall structures to quantify its influence on nanoscale ferroelectric material behavior.

9432-12, Session 3

Bayesian techniques to quantify parameter and model uncertainty in nonlinear distributed smart material systems

Ralph C. Smith, 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.

9432-13, Session 3

Electromechanical analysis of tapered piezoelectric bimorph at high electric field

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For same surface areas, piezoelectric bimorph actuators of tapered width can provide better performance compared to actuators of rectangular surface geometry. We find that the tapered width piezoelectric bimorph actuator achieves better block force, output mechanical energy, output energy density and energy efficiency. Many literatures are reported on linear modeling of piezoelectric bimorph. Wang et al. (1999) conducted experiment on piezoelectric bimorph and reported nonlinear behavior of tip deflection and block force at high electric field, which do not agree with their proposed linear model. Tiersten (1993) proposed second order constitutive equations of the orthorhombic piezoelectric materials assuming effect of small strain and large electric field.

This paper contains modeling and electromechanical performance analysis of a tapered width piezoelectric bimorph actuator considering non-linear constitutive equations of piezoelectric material for small strain and large electric field. Consideration of second order approximation can better predict the behavior of tapered width actuator at strong electric field compared to the linear model. The analysis compares performance improvement in tapered width piezoelectric actuator with the rectangular surface geometry. The nonlinear analysis shows that output energy and energy density increase more rapidly at high electric field compared to the prediction by linear model. Considering this nonlinear analytical model, we also find that the energy efficiency, which is predicted to be independent of electric field in linear model, actually increases as the electric field increases. These effects become prominent at high electric field. We consider both series and parallel electrical connection for the results. Part of the analytical results is validated with the experimental results, reported in earlier literature.

Summary:

The paper discusses electromechanical performance of tapered width piezoelectric bimorph actuator at strong electric field and compares its performance with the actuator of rectangular surface. The non-linear analytical model of tapered width actuator can predict its behavior better at high electric field. The non-linear analytical modeling also provides us better insight to design better actuator.

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9432-14, Session 3

Modeling and experimental characterization on fatigue behaviour of 1-3 piezocomposites

Y. Mohan, R. Jayendiran, A. Arockiarajan, Indian Institute of Technology Madras (India)

1-3 piezocomposites are attractive materials in underwater and biomedical applications. These materials may be subjected to high electric field (2kV/mm) under continuous operation leading to deterioration in the

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output parameters such as remnant, saturation polarization and strain. Hence in this work, an experimental study is carried out to understand the fatigue behavior of 1-3 piezocomposites for various fiber volume fraction subjected to cyclic electric field (2kV/mm, 50Hz) up to 106 cycles. A uniaxial micromechanical model is developed to predict the fatigue behaviour of 1-3 piezocomposite. In this model, remnant polarization and strain are chosen as internal variables which is also dependent on the number of cycles. This model is also incorporates the viscoelastic behaviour of 1-3 piezocomposites, since the presence of epoxy matrix may have an influence in the performance of 1-3 piezocomposites. The simulated results are compared with the experimental observations, it is observed that the proposed micromechanical model is able to predict the material degradation with increase in number of cycles of operation. A parametric study is also conducted for various fiber volume fraction of 1-3 piezocomposite as function of fatigue cycle it shows that the amplitude of dielectric hysteresis and butterfly loop decreases with increase in the number of cycles. The fatigue behaviour has an effect in the performance parameters such as coercive field, remnant polarization and the asymmetric strain behavior of 1-3 piezocomposite. This fatigue study explores the utilities of 1-3 piezocomposites in transducer applications by providing insight into the device design.

9432-15, Session 4

Molecular mechanics methods for individual carbon nanotubes and nanotube assemblies

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Since many years, carbon nanotubes (CNTs) have been considered for a wide range of applications due to their outstanding mechanical properties. CNTs are tubular structures, showing a graphene like hexagonal lattice. The carbon atoms are located at vertices of the hexagons and are connected to its three neighbor atoms via covalent bonds.

Our interest in the calculation of the mechanical properties is motivated, inter alia, by the following application. It is known, that CNTs can be spun into fibers. Due to the excellent stiffness and strength of the individual CNTs, these fibers are expected to be a promising successor for state of the art carbon fibers. However, the mechanical properties of the fibers fall back behind the properties of individual CNTs. It is assumed that this gap in the properties is a result of the van-der-Waals interactions of the individual CNTs within the fiber. In order to understand the mechanical behavior of the fibers we apply a molecular mechanics approach.

The mechanical properties of the individual CNTs are investigated by using a modified structural molecular mechanics approach. This is done by calculating the properties of a truss-beam element framework representing the CNT with the help of a chemical force field.

Furthermore we also investigate the interactions of CNTs arranged in basic CNT assemblies, mimicking the ones in a simple CNT fiber. We consider the van-der-Waals interactions in the structure and calculate the potential surface of the CNT assemblies.

The results of these investigations are analyzed and interpreted with respect to the above mentioned application.

9432-16, Session 4

Actuation-mechanisms of CNT-bucky papers and CNT-arrays

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In the fields of smart materials is still a demand for a material providing

high modulus, low density and large strain. Carbon materials catch scientific attention since a while but one sort among these carbon allotropes is of special, structural interest: carbon nanotubes (CNTs). Beside excellent electro-mechanical properties another interesting feature was first mentioned 1999 - the active behavior of paper-like mats (bucky-papers) made of CNTs. The CNT-papers are electrical activated using a double-layer interaction of ions provided by an electrolyte and the charged high surface area of the paper formed by carbon tubes. Until now the mechanism behind the strain/force generation of CNT-based architectures is unknown. But the principle of the mechanism reveals the potential of carbon tubes to be or not to be a resilient smart material in order to use the strong covalent carbon bonds instead of weak van der Waals force as linking between the tubes. This paper presents further investigations about the mechanical composition of CNT-papers as well as vertical aligned CNT-arrays using an actuated tensile test set-up. For better comparison the experiments of both specimen-types are conducted in dry, wet and wet/charged conditions.

Especially in the case of CNT-arrays it is essential to preload the specimens because the curly CNT-structure superimposes the vertical orientation. While the CNT-paper is tested in solution of one molar sodium chloride, the hydrophobic character of CNT-arrays requires ionic liquids (IL) as electrolyte. It is found that the mechanical properties of CNT-papers drop significantly by wetting and further more by charging what indicates an electro-static dominated effect. In contrast the CNT-arrays show similar results regardless of the test-conditions and an active, reversible behavior of tube-elongation by charging. These results indicate strongly a quantum-mechanical effect of the single array-tubes.

9432-17, Session 5

Nonlinear modeling of ferroelectric-ferromagnetic composites based on condensed and finite element approaches

Andreas Ricoeur, Stephan Lange, Artjom Avakian, Univ. Kassel (Germany)

Magnetolectric (ME) coupling is an inherent property of only a few crystals exhibiting very low coupling coefficients at low temperatures. On the other hand, these materials are desirable due to many promising applications, e.g. as efficient data storage devices or medical or geophysical sensors.

Efficient coupling of magnetic and electric fields in materials can only be achieved in composite structures. Here, ferromagnetic (FM) and ferroelectric (FE) phases are combined e.g. including FM particles in a FE matrix or embedding fibers of the one phase into a matrix of the other. The ME coupling is then accomplished indirectly via strain fields exploiting magnetostrictive and piezoelectric effects. This requires a poling of the composite, where the structure is exposed to both large magnetic and electric fields. The efficiency of ME coupling will strongly depend on the poling process. Besides the alignment of local polarization and magnetization, it is going along with cracking, also being decisive for the coupling properties.

Nonlinear ferroelectric and ferromagnetic constitutive equations have been developed and implemented within the framework of a multield, two-scale FE approach. The models are microphysically motivated, accounting for domain and Bloch wall motions. A second, so called condensed approach is presented which doesn't require the implementation of a spatial discretisation scheme, however still considering grain interactions and residual stresses. A micromechanically motivated continuum damage model is established to simulate degradation processes. The goal of the simulation tools is to predict the different constitutive behaviors, ME coupling properties and lifetime of smart magnetolectric devices.

9432-18, Session 5

Dynamic characterization of Galfenol

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This paper summarizes a novel and precise characterization of the constitutive behavior of polycrystalline Galfenol (Fe_{81.6}Ga_{18.4}) under quasi-static (1 Hz) and dynamic (4 to 1000 Hz) stress loadings. Mechanical loads are applied using a high frequency load frame. Quasi-static minor and major loop measurements of magnetic flux density and strain are presented for constant electromagnet currents (0 to 1.1 A) and constant magnetic fields (0 to 14 kA/m). The dynamic stress amplitude for minor and major loops is 2.8 and 30 MPa, respectively. Quasi-static actuation responses are also measured and compared to quasi-static sensing responses; the high degree of reversibility seen in the comparison is consistent with published measurements and modeling results. Dynamic major and minor loops are measured for the bias condition resulting in maximum, quasi-static sensitivity. Eddy current effects are quantified by considering solid and laminated Galfenol rods. Three key sources of error in the dynamic measurements are accounted for: (1) electromagnetic noise in strain signals due to Galfenol's magnetic response, (2) error in load signals due to the inertial force of fixturing, and (3) time delays imposed by conditioning electronics. For dynamic characterization, strain error is kept below 1.2 % of full scale by wiring two collocated gauges in series (noise cancellation) and through lead wire weaving. Inertial force error is kept below 0.5 % by measuring the dynamic force in the specimen using a nearly collocated piezoelectric load washer. The phase response of all conditioning electronics is explicitly measured and corrected for.

9432-19, Session 5

Modeling of thermo-mechanical fatigue and damage in shape memory alloy axial actuators

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The aerospace, automotive, and energy industries have seen the potential of using shape memory alloys (SMAs) as solid state actuators. Thus far, however, these actuators are generally limited to non-critical components or over-designed due to a lack of understanding regarding how SMAs undergo thermo-mechanical or actuation fatigue and the inability to accurately predict failure in an actuator during use. The purpose of this study was to characterize the actuation fatigue response of a precipitate hardened ternary NiTi alloy and, in turn, use this characterization to predict failure and monitor damage in dogbone actuators undergoing various thermo-mechanical loading paths. Calibration data was collected from constant load, full cycle tests ranging from 200-600MPa. Subsequently, damage was monitored and failure predicted for twelve additional loading paths. These loading paths consisted of: constant load with partial transformation (300-500MPa), linearly varying load with full and partial transformation (200-600MPa), and step loads which transition from zero stress to 300-500MPa at various martensitic volume fractions. Thermal cycling was achieved via resistive heating and convective cooling and was controlled via a state machine developed in LabView. Mechanical loads, discrete and full field deformation, as well as discrete and full field temperature were collected during testing. A previously-developed fatigue damage model, which is formulated such that the damage accumulation rate is general in terms of its dependence on current and local stress and actuation strain states, was utilized. This form allows the model to be utilized for specimens undergoing complex loading paths. Agreement between experiments and simulations is discussed.

9432-20, Session 5

Investigation of crystal structures of one-way shape memory Nitinol wire actuators for active steerable needle

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SMA-based actuators are currently being developed for active steerable needle for medical percutaneous intervention applications. The understanding of phase transformation of Nitinol is critical in achieving consistent strain response of Nitinol actuators. In this study the crystal structures of Nitinol wires of various diameters subjected to different thermomechanical conditions have been investigated using X-Ray Diffraction (XRD) method. This thermomechanical conditions are introduced using constant stress and uniaxial tensile tests to understand several behaviors such as unrecovered strain, effect of maximum temperature during thermal cycles, and formation of twinned and detwinned martensite in cooling cycles. XRD patterns reveal the presence of existed phases before and after each thermomechanical condition in terms of the angle and the intensity of characteristic peaks for each different phase. In addition, by comparing the XRD patterns, the strain response behaviors of different wire diameters are investigated. These XRD patterns explain the different strain responses, in particular, the generation of unrecovered strains of Nitinol wires of various diameters.

9432-21, Session 6

Shape-memory polymers for active optical devices: continuously tunable organic semiconductor distributed feedback lasers

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We demonstrate the advantage of shape memory polymers (SMP) for building novel active optical devices based on tunable gratings. Diffractive phase gratings are important tools for various applications in optics, photonics and telecommunications, e.g. they serve as distributed feedback (DFB) resonators for laser applications. By fabricating tunable resonator gratings out of SMPs we built an organic DFB-laser with tunable emission wavelength. SMPs can remember a predefined shape and recover it even after strong deformations as long as they are driven by a proper stimulus. The utilized SMP is the thermally triggered polyurethane Tecoflex®. We used hot embossing to replicate nano scaled one-dimensional 2nd order one-dimensional Bragg gratings onto SMP substrates. After stretching, these gratings feature an increased period which shrinks back to original length as soon as the recovery process is activated. In order to demonstrate the practical applicability of these gratings as useful components for photonic devices, we successfully fabricated continuously tunable DFB-lasers based on SMP resonators with the organic semiconductor Alq₃:DCM serving as laser active material. The device includes a pre-stretched SMP substrate covered with organic material which is optically pumped and then heated with a Peltier element to initialize the recovery process. By changing the resonator's period via the shape-memory effect we achieved a continuously tunable and adjustable shift of the emission spectra in range of 30 nm.

9432-22, Session 6

Shape memory polymer with multistage stimulus and two-way reversible actuation

Wenbing Li, Yanjiu Liu, Jinsong Leng, Harbin Institute of Technology (China)

Nowadays, SMP nanocomposite which can be induced in three ways, two-way reversible shape memory semi-crystalline polymers, and multishape memory polymer nanocomposite have been prepared by some researchers. However, the polymer with the properties of two-way reversible shape memory effect, various stimulus methods, and multistage stimulus at the same time has not been employed yet. Therefore, new SMP nanocomposites that can be induced by several external stimuli and can perform multishape transitions have drawn more and more attention among researchers. In this work, a novel type of shape memory polymer nanocomposite was fabricated using chemically cross-linked poly(?-caprolactone) with allyl alcohol as the

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matrix and Fe₃O₄ nanoparticles decorated conductive multiwalled carbon nanotubes (Fe₃O₄@M) as magnetism and electricity responsive source. The nanocomposite exhibited excellent shape memory performance with a multistage stimulus recovery from a temporary shape to a permanent shape, triggered by an alternating magnetic field, an electric field and hot water, respectively. Uniquely, the nanocomposite also displayed significant two-way reversible shape memory behavior, which was not demonstrated previously. Alamar blue assay was also used to prove that the material possessed good biocompatibility. The results showed that the material could have good potential application foreground in sensors, functional tissue engineering constructs and artificial muscles.

9432-23, Session 6

Shape memory PCL/CNT composite foams and their microwave activated behaviors

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Shape memory foams as well as their composites are a kind of intelligent materials with porous structures, which have attracted great interest because of the advanced properties and special structure. Shape memory foams as promising materials that can deform and recover to their original shapes when exposed upon an external stimulus (e.g., heat, electricity, light, magnetism, moisture and even a change in pH value) are utilized in many fields, covering the actuators, sectors, biomedical devices and energy applications. Microwave technology is an effective way which plays an enormous role in development of heating ways and actuation methods.

In this article, uniform PCL/CNT composite foams are successfully prepared from 30% polycaprolactone (PCL)/ Benzoyl peroxide (BPO) solution with different amounts of CNT via using microwave heating for 30 seconds. The resultant samples are porous and show excellent shape memory effect. The CNT in composite foams not only can influence the mechanical properties but also improve the shape recovery speed comparing with pure PCL foams. The optical microscope was carried out to characterize the structure of carbon composite foams. Differential scanning calorimetric (DSC) and dynamic mechanical analyzer (DMA) was used to analyze the thermal and mechanical properties. The PCL/CNT composite foams can be triggered by microwave and the temporary shape recovers to the original shape within 60 seconds. Microwave heating is considered to be an excellent activated source.

Shape memory PCL foams filled with CNT that are able to be inducted through microwave, shows high speed during the shape recovery process. Microwave-activated way plays an important role in the success of remote control. Quick response method, especially microwave, will bring a wide range of applications in smart materials and structure, which shows significance on development of the porous foam composite materials.

9432-24, Session 6

Experimental characterization of a new class of polymeric-wire coiled transducers.

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Recent research works demonstrated that different kinds of cheap polymeric wires can be successfully employed to produce coiled actuators that show good energy densities and large strokes in response to temperature variations.

A simple and easily repeatable manufacturing process allows to obtain a wide range of mechanical properties. Stiffness, stroke, energy density and other variables can be set by properly choosing the design/manufacturing parameters, such as geometry, material, tensile load during coiling and heat-treatment.

This paper presents the results from the experimental characterization of the mechanical response of a variety of linear transducers based on

polymeric-wire coils.

In particular, the spring behavior at different temperatures has been assessed by measuring the stress-strain response under static and dynamic tensile loads.

Specifically, tests were performed using two materials (nylon and polyethylene), several temperatures for the heat treatment and different coil indices.

Results were used to deduce a series of design criteria for polymeric-wire coiled transducers.

9432-25, Session 6

The effect of cross linker concentration in the physical properties of shape memory gel

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The chemically cross-linked Shape Memory Gel (SMG) was synthesized using N, N-dimethyl acrylamide (DMAAm) and Stearyl acrylate (SA). The DMAAm is a hydrophilic monomer, whereas SA is a hydrophobic monomer. The SMG is a soft and wet material having a shape memory effect. The bulk polymerization process was applied for the preparation of samples. The SMG is swollen with water; therefore, it is a hydrogel. Due to the transparency, shape memory property, low friction, and high water content, the SMG is suitable for biomedical and optical applications. The physical property such as mechanical strength of most hydrogels is not good enough. However, the properties of these hydrogels are easily controlled by changing the polymer concentration, molecular weight and cross linker concentrations. In this study, several samples were prepared by varying the cross linker concentration, whereas the monomer concentrations were remain constant. The effect of cross linker concentration in the physical properties was investigated by several techniques. The swelling ratio strongly depends on the solvent as well as cross linker concentration reflecting the structural changes of the internal network. It is found that the tensile toughness is proportional to the cross linker concentration. The laboratory dynamic light scattering (DLS) called Scanning Microscopic Light Scattering (SMILS) was used to understand the internal dynamic as well as network structure. It is observed that the mesh size is inversely proportional to the cross linker concentration. The frictional properties were also investigated and the results are discussed here.

9432-26, Session 7

Effect of particle size on the properties of polyurea-based composites

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Polyurea is a type of elastomer with excellent properties and a myriad of applications. Especially, the application in increasing the survivability of structures and buildings under impact loading is more attractive. Recently, modifying the properties of polyurea by mixing micro and nano particles into polyurea is becoming a new research hotspot. However, systematic study of the effect of particles size on the properties of polyurea-based composites has not been reported. Hence, in our present work, glass beads with diameters in the range from 3 μ m to 250 μ m were selected and composites with 20% volume fraction of glass beads were prepared. Microstructure of the composites was investigated by Scanning Electron Microscopy (SEM). Physical properties of the composites were then tested by fourier transform infrared spectroscopy (FTIR) and differential scanning calorimetry (DSC). Dynamic mechanical analysis was conducted using a TA

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Instruments DMA Q800 over the temperature range from -80°C to 100°C at 1Hz. The storage and loss moduli master curves for these composites were obtained through application of the time-temperature superposition (TTS).

9432-27, Session 7

Multi-functional composite material base on carbon nanotube paper using for deicing, flame retardancy, thermal insulation and lightning strike protection

Hetao Chu, Jinsong Leng, Zhichun Zhang, Yanjiu Liu, Harbin Institute of Technology (China)

The emergence of carbon nanotube (CNT) has aroused an intriguing new field in the science and technology recently for nano-materials with the continuous growth of research and technological impetus, because both theory and experiment demonstrate individual CNT has excellent properties on mechanics, electrical and thermal conductivity and electrochemistry. So far, most of the reports are mainly focus on the individual nanoscaled materials of CNT from theoretical and microscopic analysis which is extraordinary important for the development of CNT. However, a more intractability issue is how to use CNT in our daily life. Then best approach is transforming the micro-material to macro-material.

Carbon nanotube paper is entangled assemblies of CNT with macro 2D paper-like morphology attached together by electrostatic forces and Van der Waals forces. In this article, multi-functional carbon nanotube paper was fabricated successfully by using commercial carbon nanotube. After that, carbon nanotube paper as the functional layer integrated with epoxy and glass of carbon fiber through vacuum bag pressure method to achieve functional composites using in deicing, heat resistant and lightning protection. As a deicing composite material, carbon nanotube was used directly without pretreatment in fabricating carbon nanotube paper. The conductivities of the carbon nanotube paper and deicing composite were 77.8S/cm and 64.9S/ respectively which measure by four point probe and high sensitive digital multimeter. The porosity of carbon nanotube paper was characterized by BET with pore diameter ranging from 3nm to 100nm. Electrical heating and deicing performance were test by infrared camera with deicing time less than 220s and 450s to melt a certain amount of ice under different ambient condition. Unlike the deicing composite, the heat resistant and lightning protection material was modified by chemicals. CNT was grafted by zirconium(IV) butoxide solution and dimethyl dichlorosilicane to form co-oligomers on the tube surface investigated by Fourier Transform Infrared Spectroscopy (FTIR). The oligomers decompose under a certain temperature to develop an inorganic layer of silicon zirconium oxide characterized by X-ray diffraction (XRD) and Scanning electron microscopy (SEM). The oxidizing temperature of carbon nanotube increases more than 20 ° and the weight loss rate decreases 20% than the untreated carbon nanotube realized by thermal gravity analysis (TGA). Lightning protection material required high electro conductivity, due to the utmost high current in a short time. Therefore, silver nanoparticles were deposited on the surface of carbon nanotube with the diameter around 400nm. The conductivity increased sharply from 84s/cm to 1756s/cm with the mount of 5.9wt% Ag of the modified carbon nanotube paper. The lighting performance of the composite was test under a certain current attract with the lightning simulator. The failure stress composite with silver modified carbon nanotube paper was 83% of the blank sample which was larger than 65% without carbon nanotube paper. In addition, different types and thickness CNTs paper were synthesized successfully by multiple steps of CNTs dispersion and suspension filtration. CNTs papers were characterized by scanning electron microscopy thermo gravimetric analysis nitrogen adsorption isotherms at 77K and so on. The Far-Infrared (FIR) absorption property, wavelength between 3-5 and 8-14 μm was performed by the infrared temperature camera. FIR emissivity was investigated at different atmosphere temperatures in an oven from 43 to 233 ° with the thickness range from 30 μm to 70 μm. The influence variation of types of CNTs, thickness and layers was obtained and according to the results, the infrared emissivity of carbon nanotubes paper decreases gradually as the increase of the atmosphere temperatures.

The results of the above experiments indicated the multi-functional carbon nanotube paper composite material was a promising candidate in the field of deicing, heat resistance and lightning protection.

9432-28, Session 7

3D gel printer for creating order-made meals

Jin Gong, Ryo Serizawa, Chika Sasaki, Masato Makino, Hidemitsu Furukawa, Yamagata Univ. (Japan)

In recent years, aging is progressing in Japan. Elderly people can't swallow the food well. So, the need of soft food is increasing greatly with the aging of the population. There are so few satisfying foods for the elderly to enjoy a meal. An equipment of printing soft food gives the elderly a big dream and is promising. In this study, we aim at developing a 3D edible gel printer in order to make soft food for the elderly. We made a prototype of the 3D edible gel printer. The printer consists of syringe pump and dispenser. The syringe pump extrudes the solution. The dispenser allows to model three-dimensional objects. We use agar solution as the ink to carry out the printing. Agar's gelation deeply depends on temperature. Therefore temperature control of the solution is important to mold optimal shapes because the physical crosslinking network of agar's solution is instable. We succeeded in making the gels and plate-shape gel using the 3D edible gel printer. Further more, in order to increase the gelation speed agar's solution, we changed the dispenser and the printing test is being done now. 4 kinds of soft food prepared from agar and gelatin were printed by the 3D edible gel printer. The compression tests of the printed soft food samples were done and their hardness is measured because the hardness is one of very important factors which influence the food texture greatly. In the future, the viscosity of the agar solution or other food ink should be adjusted to suitable for printing.

9432-36, Session 7

Fabrication and characterization of polyaniline-graphene nanoplatelets composite electrode materials for hybrid supercapacitor applications

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With the current energy challenges across the globe, a novel energy storage device that is capable of delivering high power and energy density is highly desired. All-solid-state supercapacitors provides an attractive alternative with good energy and power storage abilities, and yet comes with a light and less expensive package. Herein, supercapacitor performances of different polyaniline (PANI) based nanocomposites have been evaluated with two-electrode electrochemical setup. Material characterization has been performed with FTIR and TGA, while SEM has been used to characterize the morphologies of the nanostructures. These PANI-based nanocomposite supercapacitor electrodes have been successfully synthesized via in-situ chemical polymerization and solvent casting process. Electrodes under study are namely, graphene/PANI, multi-walled carbon nanotubes (MWCNT)/PANI, aluminum oxide (Al₂O₃)/PANI, and titanium dioxide (TiO₂)/PANI. In all cases, thin stainless steel sheets were used as a current collector. Graphite conductive ink and Polytetrafluoroethylene (PTFE) were used as the binder with the composite powder to fabricate a conductive electrode layer. As high as a 275 F/g of specific capacitance, at a relatively high scan rate of 10 mV/s, has been achieved for 1:4 graphene/PANI composite. FTIR and TGA showed good composition with desired weight percentage of nanoparticles present. SEM showed 3D morphology changes leading to improved charge storage ability as a result of polymer-nanoparticle interactions. With empirical results obtained from this study, combined with previous findings, it is possible to examine the key parameters in the capacitive behaviour of polymeric nanocomposite based supercapacitors to further enhance our understanding of these novel devices, as well as to help open up additional possibilities for future energy research.

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9432-40, Session 7

Effects of interface treatment on the fatigue behaviour of shape memory alloy reinforced polymer composites

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Interfacial properties of Shape Memory Alloy (SMA) reinforced polymer matrix composites can be enhanced by improving the interfacial bonding. This paper focuses on studying the interfacial stresses developed in the SMA-epoxy interface due to various laser shot peening conditions. First, to arrive at certain optimal surface microstructure and resulting phase transformation properties of laser peened SMA wires, the SMA wires are surface treated by laser shot peening at various different wavelengths with constant energy level. The optimal laser peening process is identified through ASTM standard fiber-pullout test and usefulness of phase transformation parameters achieved after these surface modifications. Fiber-pullout tests are carried out on thermal SMA actuator at parent state by stress induced detwinned martensites for verifying strength of bonding with the epoxy system. Fiber-pullout test-setup is designed to understand the role of mechanical bias stress cycling and thermal actuation cycling. Phase transformation is tracked over mechanical and thermal fatigue cycles. A micromechanics based model developed earlier based on shear lag in SMA wire and an energy based consistent homogenization scheme is extended here to incorporate the stress-temperature phase diagram parameters for modeling fatigue. Mechanical bias stress cycling and thermal actuation cycling are performed using DMA equipment. A special test-bed is used in open condition, where the fatigue failure initiation is investigated using thermal imaging under Joule heating. Details of observations on the de-bonding and delamination initiations due to interfacial shear stress are discussed.

9432-35, Session PTues

Effects of interface morphology and TGO thickness on residual stress of EB-PVD thermal barrier coatings

Yang Zhao, Jianwei Chen, Jian Ma, Shandong Academy of Sciences (China)

The residual stress of electron beam-physical vapour deposition (EB-PVD) thermal barrier coatings (TBC) is complex and difficult to be obtained. In this paper, the interface morphology of TBCs subjected to cyclic heating and cooling was observed by SEM. Based on the thermal elastic-plastic finite method, corresponding interface model of TBCs was established. The residual stress of EB-PVD TBCs with different interface morphologies and thermally grown oxide (TGO) thicknesses was calculated using the FE method without regard to the presence of cracks and defects. The result shows that the distribution of residual stress is significantly affected by the interface morphology, and the growth of TGO also has influence on the residual stress of TC and TGO. The result is useful to understand the failure mechanism of TBCs.

9432-37, Session PTues

The friction measurement of functional gel mechanical materials using mechanical fixation

Masato Wada, Hidemitsu Furukawa, Yamagata Univ. (Japan)

Gels have superior inborn functions such as high water content, materials permeability, extremely low friction, and biocompatibility, which are not found in the hard and dry materials, because these functions are due to their soft and wet features. Now artificial gels have become like as natural gels of the human body: the articular cartilage of our knee has both several MPs of mechanical strength and about 0.01 of surface friction. In this study, we aim to develop an original apparatus for surface mechanical properties such as surface friction of gels and study both the surface and bulk properties of the high-strength gels. In this study, we report connections to mechanical fixed law and a change of the friction behavior by the difference of the gel fixation method such as chemical fixation methods. In addition, we show it about a change of the friction behavior by compressing gel machine materials.

9432-38, Session PTues

Study of emissivity dependence upon concentration in CdTe quantum dots

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Due to their unique optical properties, quantum dots (QDs) have received a great deal of interest for their potential applications, such as in quantum computing, photovoltaic cells, and electronics. Characterization of the emissivity of CdTe QDs as a function of concentration was conducted on three commercially available CdTe QDs. All have optimal absorption around 400-500 nm with peak emission wavelengths at 530 nm, 550 nm, and 570 nm, respectively. The QDs were suspended in an aqueous solution at 13 different concentrations ranging from 0.37 mg/ml to 10 mg/ml. The samples were excited at room temperature by a 50 mW diode laser emitting at a central wavelength of 405 nm and the fluorescence of the QDs was measured with a free-space CCD spectrometer. The measured spectra showed a general redshift in peak emission wavelength with increasing concentration. A +5.9 nm per mg/ml shift for the 530 nm QDs was observed when a linear fit with a coefficient of determination (R-squared) of 0.99 was applied. The 550 nm QDs and the 570 nm QDs showed a +8.63 nm per mg/ml shift (R-squared=0.97) and a 10.17 nm per mg/ml shift (R-squared=0.98), respectively. The redshift is attributed to a Förster resonance energy transfer (FRET) which causes energy transfer between two light-sensitive molecules.

9432-39, Session PTues

Stress relaxation behavior in the effect of electric field and degree of crosslinking on gelatin hydrogels: time-electric field superposition

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An investigation has been conducted on stress relaxation functions and the corresponding relaxation time distribution functions of gelatin hydrogels for the effects of degree of crosslinking and the applied electric field strength. Uncrosslinked and crosslinked gelatin hydrogels were prepared by adding a glutaraldehyde solution into a gelatin solution followed by a casting method. The characteristic relaxation time can be estimated by three methods; KWW; the dynamic crossover; and the relaxation time distribution spectrum $H(?)$. For the uncrosslinked, 3 %v/v crosslinked and 7 %v/v crosslinked gelatin hydrogels, the relaxation times decrease with increasing degrees of crosslinking and the applied electric field strengths. This is due to the increase in the molecular connectivity that promotes the capability of the stress relaxation process. The experimental shift factors can be thus obtained from either the stress relaxation functions or the storage and loss moduli. Both approaches yield numerically the same shift factor values which successfully allow the time-electric field superposition of various related functions.

9432-41, Session PTues

Mussel-inspired catecholamine polymers as new sizing agents for fiber-reinforced composites

Wonoh Lee, Jea Uk Lee, Joon-Hyung Byun, Korea Institute of Materials Science (Korea, Republic of)

Mussel-inspired catecholamine polymers (polydopamine and polynorepinephrine) were coated on the surface of carbon and glass fibers in order to increase the interfacial shear strength between fibers and polymer matrix, and consequently the interlaminar shear strength of fiber-reinforced composites. By utilizing adhesive characteristic of the catecholamine polymer, fiber-reinforced composites can become mechanically stronger than conventional composites. Since the catecholamine polymer is easily constructed on the surface by the simultaneous polymerization of its monomer under a weak basic circumstance, it can be readily coated on micro-fibers by a simple dipping process without any complex chemical treatments. Also, catecholamines can increase the surface free energy of micro-fibers and therefore, can give better wettability to epoxy resin. Therefore, catecholamine polymers can be used as versatile and effective surface modifiers for both carbon and glass fibers. Here, catecholamine-coated carbon and glass fibers exhibited higher interfacial shear strength (37 and 27% increases, respectively) and their plain woven composites showed improved interlaminar shear strength (13 and 9% increases, respectively) compared to non-coated fibers and composites.

9432-29, Session 8

Power generation from base excitation of a Kevlar composite beam with ZnO nanowires

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Nanowires with piezoelectricity properties have gained interest in fabrication of small scale power harvesting systems. However, the practical applications of the nanoscale materials in structures with true mechanical strengths have not been demonstrated. In this paper, piezoelectric ZnO nanorods are integrated into the Kevlar composites serving as an active phase to convert the induced strain energy from ambient vibration into electrical energy. Arrays of ZnO nanorods are grown vertically aligned on the Kevlar fibers through a low-cost hydrothermal process. Then, the Kevlar fabric with ZnO nanorods on the surface of fibers is placed between two carbon fabrics as the top and the bottom electrodes. Finally, vacuum resin transfer molding technique is utilized to fabricate these multiscale composites. The fabricated composites are subjected to a base excitation using a shaker to generate charge due to the direct piezoelectric effect. Measuring the generated potential difference between two electrodes showed the energy harvesting application of these multiscale composites in addition to their superior mechanical properties. These results propose a new generation of power harvesting systems with enhanced mechanical properties.

9432-30, Session 8

Study of the electro-mechanical properties of a power storage composite material during long term electro-mechanical loading

Constantin Ciocanel, Cindy Browder, Katherine Caroll, Northern Arizona Univ. (United States)

A carbon fiber based composite material with power storage capability has been developed and its electro-mechanical properties have been previously evaluated under quasi-static conditions. However, as the material is being developed with the goal of being embedded in structures that exhibit long term variable loadings, one has to evaluate the material's behavior under long term electro-mechanical loading. This paper presents preliminary results on the long term evolution of the electro-mechanical properties of the developed power storage composite. The effect of both, axial and bending load modes, superimposed on the electric charge-discharge cycles, has been investigated.

9432-31, Session 9

Aggregation of ionic clusters in thermoplastic ionomers under electrostatic fields

Vishnu Baba Sundaresan, The Ohio State Univ. (United States)

Thermoplastic ionomers demonstrate self-healing behavior due to reversible aggregation of ionic clusters in the polymer matrix during a thermal cycle. The aggregation of ionic species in the polymer under electrostatic fields at temperature greater than its melt temperature provides novel opportunities for designing structural composites with well-defined microstructure and targeted mechanical properties. There is a dearth of knowledge in the aggregation processes at a molecular scale of ionic aggregates in thermoplastic ionomers and this article will discuss first experimental investigation on the effect of electrostatic fields in a thermoplastic ionomers. Surlyn, a ethylene/methacrylic acid (partially neutralized with sodium salt) will be used as a candidate thermoplastic ionomers to investigate the aggregation of ionic groups. The experimental study will investigate electrostatic melt-processing of Surlyn and its composites. Pellets of Surlyn will be melt-pressed in the presence of electrostatic fields using the procedure developed by Sundaresan and coworkers (Smart Coatings, 2010, Smart Materials Research, 2013). The resulting coupons will be characterized by small-angle x-ray scattering to investigate the size of ionic aggregates formed at various electrostatic fields and relationship between processing conditions and molecular structure will be developed. Subsequently, composites of Surlyn containing micron scale piezoelectric additives, nanoscale barium titanate particles will be fabricated with the additives forming 1%, 5% and 10% by volume. The aggregation of additives under high electric fields around ionic aggregates will be investigated by SAXS and their electromechanical coupling (d_{33}) characterized through the work presented in this article.

9432-32, Session 9

Theoretical investigation of ionic effects in actuation and sensing of IPMCs of various geometries

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Ionic polymer-metal composite (IPMC) electromechanical and mechano-electrical phenomena for rectangular, rod, and tube shaped IPMC devices have been examined through simulation and experimental investigation. There is a specific focus on investigating the anion and cation effects in actuation versus sensing to assist in understanding the fundamental differences of these phenomena. Simulations were performed using COMSOL Multiphysics 4.3b with the Transport of Diluted Species, Solid Mechanics, Electric Currents, and General Form PDE physics modules, encompassing the necessary IPMC physics. This model employs the Poisson-Nernst-Planck (PNP) equations with a linear elastic material model. Sample IPMCs were fabricated in lab with the desired geometries by techniques described herein. The sample sizes were roughly 1 mm thick and 20-25 mm in length. Actuation and sensor experiments were performed and compared to simulation results, which exhibit good agreement for voltage and tip displacement. Fundamental differences in the electromechanical and mechano-electrical transductions of IPMCs are highlighted in the simulation results. These results display the negligible effect of anion motion in actuation as compared to during sensing. In actuation, the cation motion is dominated by an electric potential flux, and the anions only move only slightly with the deformed polymer membrane. In sensing, the electric potential is induced by the ionic migration in the polymer, and both cation and anion concentration variations are of similar magnitudes.

9432-33, Session 9

Ionic liquid based multifunctional double network gel

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Gels are a promising class of soft and wet materials with diverse application in tissue engineering and bio-medical purpose. In order to accelerate the application of gels, it is required to synthesize multi-functional gels of high mechanical strength, ultra low surface friction and suitable elastic modulus with a variety of methods and new materials. Among many types of gel ionic gel using ionic liquids (ILs) can propose diverse applications in electrochemical devices and in the field of tribology. IL, a promising materials for lubrication, is a salt with a melting point lower than 100 °C. As a lubricant, ILs are characterized by an extremely low vapor pressure, high thermal stability and high ion conductivity. For developing new gel materials with low friction and unique physico-chemical properties IL based double network (DN) gel can initiate the progress of gel materials in tribological advancement. In this work a novel approach of making double network DN ionic gel using IL has been made utilizing photo polymerization process. A neutral monomer Poly(methyl methacrylate) (PMMA) has been used as a first network and a hydrophobic IL monomer, N, N-diethyl-N-(2-methoxyethyl)-N-methylammonium bistrifluoromethylsulfonate)imide (DEMM-TFSI) has been used as a second network using photo initiator benzophenone and crosslinker triethylene glycol dimethacrylate. The resulting DN ionic gel shows transparency, flexibility, good mechanical toughness and low friction coefficient value which can be a potential candidate as a gel slider in different mechanical devices and can open a new area in the field of gel tribology.

9432-34, Session 9

Observation of the characteristic properties in soft and wet friction of gel engineering materials

Naoya Yamada, Yamagata Univ. (Japan); Jin Gong, M. Hasnat Kabir, Masato Wada, Yamagata Univ (Japan); Hidemitsu Furukawa, Yamagata Univ. (Japan)

Soft and wet materials such as hydrogels have unique properties. Several synthesis methods to make high strength gels point to a possibility that gels are applied as industrial materials and biomaterials. The most effective but simple way was proposed to synthesize double network gels in 2003, whose maximum breaking stress in compression reached about 30MPa. Our group has focused on PAMPS-PDMAAm DN gel, because it possibly has both biocompatibility and permeability, which are good for developing artificial articular cartilage and artificial blood vessel. It is also possibly used for rapid additive manufacturing with 3D gel printing system. Here, we develop a novel apparatus of the ball on disk method to observe the surface friction of the hydrogels. The friction behavior of the gels shows different nature than that of the solid friction behavior. In addition, the friction behavior of gels was changed depending on fixed method. The surface condition and friction of gels is also changed with voltage addition to gels. Various characteristic properties were observed in soft and wet surface in gel friction. Our final goal is to control the gel friction by the external action for practical application. We hope to apply this apparatus for various studies about the tribological behavior of the gels, especially about the effect of external electric field on the gel friction.

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Monday - Tuesday 9 -10 March 2015

Part of Proceedings of SPIE Vol. 9433 Industrial and Commercial Applications of Smart Structures Technologies 2015

9433-1, Session 1

Actuators using piezoelectric stacks and displacement enhancers

Yoseph Bar-Cohen, Stewart Sherrit, Xiaoqi Bao, Mircea Badescu, Hyeong Jae Lee, Phillip E. Walkemeyer, Jet Propulsion Lab. (United States); Shyh-Shiuh Lee, Jet Propulsion Lab (United States)

Actuators are used to drive all mechanisms including machines, robots, manipulators and all others. The actuators are responsible for moving, manipulating, displacing, pushing and executing any action that are needed by mechanisms. There are many types and principles that are responsible for the actuation process ranging from electromagnetic, electroactive, thermo-mechanic and many others. Actuators are readily available from commercial producers but there is a great need for reducing their size, increasing their efficiency and reducing their weight. Studies at JPL has been focused on the use of piezoelectric stacks and novel designs taking advantage of their potential to provide high torque/force density actuation and high electromechanical conversion efficiency. The developed actuators/motors that will be reviewed in this paper are operated by various horn configurations as well as the use of pre-stress flexures that make them thermally stable and increases their coupling efficiency. The use of monolithic designs that pre-stress the piezoelectric stack eliminate the use of stress bolt. These designs enable the embedding of developed solid-state motors/actuators in any structure and the only macroscopically moving parts are the rotor or the linear translator. Finite element modeling and design tools were used to determine the requirements and operation parameters and the results were used to simulate, design and fabricate novel actuators/motors. The developed actuators and performance will be described and discussed in this paper.

9433-2, Session 1

Optimally tuned resonant negative capacitance for piezoelectric shunt damping based on measured electromechanical impedance

Rogério Salloum, Oliver Heuss, Fraunhofer-Institut für Betriebsfestigkeit und Systemzuverlässigkeit (Germany); Benedict Götz, Technische Univ. Darmstadt (Germany); Dirk Mayer, Fraunhofer-Institut für Betriebsfestigkeit und Systemzuverlässigkeit (Germany)

In this paper, a new tuning method for semi-active shunt damping which is based on the measured electromechanical impedance of a piezoelectric system is proposed and its validity is investigated. Initially, the measured impedance is represented through an electrical circuit that takes into account the characteristics of both the piezoelectric transducer and the host structure. Afterwards, an additional series RLC circuit representing the shunt is connected and the Norton equivalent circuit is obtained at the terminals that represent the mechanical mode of interest. During the tuning process, the optimal RLC parameters are found by minimizing the Norton impedance through a numerical optimization. Taking benefit from the analogy between electrical impedance and mechanical mobility, the minimization of different mechanical responses (displacement, velocity or acceleration) is also proposed and the different optimum RLC parameters obtained are compared. In view of real technical applications, this method also allows the integration of a real negative capacitance circuit, i.e. a negative impedance

converter (NIC), rather than an ideal component. It is thus possible to assess the impedance of the NIC by using the electrical characteristics of the operational amplifier and later optimize the resistance values. Since this method is based on one simple measurement, it can be applied to arbitrary structures without the need of complex dynamic tests or expensive finite elements calculations. Finally, an experimental analysis is carried out using a test rig in order to compare the damping performance of the proposed method and conventional analytical methods that minimize a mechanical frequency response function.

9433-3, Session 1

Mapping of power consumption and friction reduction in piezoelectrically-assisted ultrasonic lubrication

Sheng Dong, Marcelo J. Dapino, The Ohio State Univ. (United States)

Ultrasonic lubrication is achieved by superimposing ultrasonic vibrations on the macroscopic sliding velocity between two surfaces. Often related to friction, wear is the displacement of materials from one or both surfaces in contact during sliding. Studies have been conducted to quantify ultrasonic friction and wear reduction. This article investigates the dependence of ultrasonic friction and wear reduction on electrical power consumption for various normal stresses, linear velocities, and material combinations. Piezoelectric actuators are used as a source of ultrasonic vibrations in this study.

A piezoelectrically-assisted tribometer was designed and built for pin-on-disc friction and wear tests. The pin consists of a piezoelectric actuator and a ball at one end. The actuator generates ultrasonic vibrations of different amplitudes in the direction perpendicular to the disc surface. The pin is held by a gymbal assembly, which is also used for applying various normal loads and measuring friction forces. A disc is held in contact with the pin by a lathe chuck, which is driven by a motor. Different levels of rotating speeds, radii and testing durations are chosen to obtain various linear speeds, total revolution counts and travel distances. Instantaneous power consumption is calculated from measured voltages and currents supplied to the piezoelectric actuator.

Friction forces and macroscopic wear were measured. Results show that ultrasonic vibrations can reduce friction by 80% and wear by 73%. The relationship between friction reduction and power consumption is characterized under various conditions, from where power maps are derived. An analytical model is employed to explain the experimental data and conduct parametric studies.

9433-4, Session 1

Geometry adaptive control of a composite reflector using PZT actuators

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With the advancing of space technologies, the radio frequencies used for space observation and communication are continuously increasing.

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Therefore, the geometry precision of a reflector onboard a spacecraft needs to be increased accordingly. Although great efforts have been placed to improve the fabrication precision, geometry adaptive control is becoming more and more necessary. This paper will discuss the on-orbit geometry adaptive control for a composite reflector. The first key technology for the reflector wavefront control is the PZT actuator. Compare to other electroactive materials, PZT has much higher elastic modulus, quick response characteristic, good linear behavior, fine resolution, and excellent controllability. How to use PZT to develop an actuator, which can provide sufficient displacement and actuation force, is a challenge. Another challenge is that the PZT actuator should be able to survive the launch vibration. The second key technology is the system design of the adaptive reflector that includes a composite reflector and a control system. How to minimize the fabrication error as well as in space thermal deformation of a composite reflector are very difficult. To design a system that has sufficient controllability to the geometry of the composite reflector sometimes is contradict to the design of a highly stable composite reflector. These study developed a multidisciplinary analytical model, which includes the composite structure, thermal, thermal deformation and control system, to perform an optimization analysis and design for the adaptive reflector.

9433-5, Session 2

Adhesive-bonded shape memory alloy strip joint for composite fan blade shape changing concept

James B. Min, Tiffany S. Williams, Gary D. Roberts, Lee W. Kohlman, NASA Glenn Research Ctr. (United States)

NASA's Fundamental Aeronautics (FA) Program addresses national challenges in air transportation by enabling advanced technologies that will improve the performance and environmental impact of future air vehicles. As part of the FA, Fixed Wing (FW) Project includes exploring concepts and technologies for dramatic improvements in the noise, emissions, and performance of transport aircraft. Shape Changing Airfoil Concept research has been established in FW to explore the utilization of intelligent control of airfoil shapes by employing shape memory alloy (SMA). The initial phases of the effort are to begin establishing fundamental materials technology and analysis techniques to enable the design and fabrication of lightweight, high-strength shape-changing turbomachinery engine airfoils. Fan blades are the most significant airfoil in size and overall impact to engine performance and fuel burn. To increase aerodynamic efficiency, the airfoil adopts its maximum camber for high speed operation at peak power (at take-off through max climb). At cruise, the blade un-cambers for maximum part power performance. The airfoil actuation concept examined in this study utilizes the thermally induced shape-memory effect on the polymer matrix composite (PMC) fan blade system. The primary objectives of this paper are to determine feasibility of an SMA-PMC adaptive fan blade by evaluating the extent of shape change that can be achieved while maintaining other critical structural requirements of the blade.

9433-6, Session 2

Stress optimization of leaf-spring crossed flexure pivots for an active Gurney flap mechanism

Jon Freire Gómez, Julian D. Booker, Phillip H. Mellor, Univ. of Bristol (United Kingdom)

The EU's Green Rotorcraft programme is pursuing the development of a functional and airworthy Active Gurney Flap (AGF) for a full-scale helicopter rotor blade. Interest in the development of this 'smart adaptive rotor blade' technology lies in its potential to provide a number of aerodynamic benefits, which would in turn translate into a reduction in fuel consumption and noise levels. The AGF mechanism selected employs crossed flexure pivots which provide important advantages over bearings as they are not susceptible to

seizing and do not require any maintenance (i.e. lubrication or cleaning). A baseline design of this mechanism was successfully tested both in a 2D wind tunnel environment and in a fatigue rig at flight-representative deployment schedules. However, finite element analysis of the AGF design under full in-flight centrifugal accelerations, aerodynamic loads and blade deformations suggests that the stresses arising on the flexures would compromise their long-term mechanical integrity. This paper investigates the potential for flexure stress reduction through parametric optimization of the baseline mechanism. A procedure combining a simplified finite element model and a series of optimization algorithms is utilized. From all the parameters required to fully define the mechanism topology, only those deemed to be the most influential were taken as optimization variables. Furthermore, the optimization was carried out in a stepped manner, with a gradual increase in problem complexity. Results show that the optimization approach adopted yields important stress reductions. Future work will assess the scope for further stress reduction by altering additional design parameters.

9433-7, Session 2

Fatigue damage monitoring of an UAV wing under extreme environments

Jun Young Jeon, Hwee Kwon Jung, Gyuhae Park, Chonnam National Univ. (Korea, Republic of); Jaeseok Ha, Chan Yik Park, Agency for Defense Development (Korea, Republic of)

This paper presents the results of active-sensing guided wave based structural health monitoring (SHM) methods applied to a 3.7meter UAV wing that underwent fatigue loading. The wing, which is a CFRP composite empennage, underwent harmonic excitation with steadily increasing loading until ultimately reaching failure. In order to simulate a real-flying situation, the fatigue test was performed under a low temperature condition. A specially designed temperature chamber was built and the fatigue test was performed inside the chamber. Data from the sensors were collected between and during fatigue loading sessions, which were measured using the commercially-available hardware (Metis Designs). The analysis methods implemented were evaluated in conjunction with appropriate damage sensitive features, including scattering and reflections of the waves caused by the fatigue damage. The results of this assessment will inform the selection of appropriate hardware and specific data to be collected and analysis methods to be implemented for efficient SHM of aerospace structure in real flying conditions.

9433-8, Session 2

Regenerative composites for drones

Carolyn Dry, Natural Process Design, Inc. (United States)

Drones have improved life cycle cost improvements by delivering in-theater operational life cycle damage repair technology that will dramatically improve the reliability, on-station availability, and maintenance inspection and repair/sustainment costs of cracking and crash damage on drone skins. Regeneration provides the enhanced platform capability of improved protection from current and emerging threats, without appreciable weight, and maintains all existing aspects of air vehicle integrity and maneuverability during full spectrum operations. The self repairing vehicle skins will be described in the paper.

9433-9, Session 2

Structural analysis of morphing airfoils for camber adaptive wing

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The chord-wise bending airfoil wing could be achieved by employing a kind of active morphing skin which was embedded with pneumatic muscle fibers. The output force and contraction of pneumatic muscle fiber and the morphing skin were experimentally characterized at a series of discrete actuator pressures varying from 0.15 to 0.35 MPa. The test results show that pneumatic muscle fiber could output force reaching 26.77N and contract 0.246 (24.6%) at 0.35MPa and the active morphing skin could output force 69.25N and contract 0.097 (9.7%) at 0.35MPa. This camber morphing structure involves the discipline of structural mechanics which are analysed in this paper. Carbon fiber composite plate is utilized for the upper surface skin of the chord-wise bending airfoil structure, so the approach described in this paper starts from deformation analysis of the upper surface skin based on the classical laminate theory. Energy method was also used for solving the shape function of the upper surface skin which was under the condition of pure bending. While the active morphing skin was actuated at a series of discrete actuation pressures, the fixed geometrical shapes of the chord-wise bending airfoil structure could be obtained.

9433-10, Session 3

Multiphysics modeling and design of Galfenol-based unimorph harvesters

Zhangxian Deng, Marcelo J. Dapino, The Ohio State Univ. (United States)

Magnetostrictive iron-gallium alloys, known as Galfenol, exhibit coupling between magnetic and mechanical energies. This property is used in this study to develop energy harvesting devices that operate in bending mode. Bending or unimorph devices consist of a Galfenol strip bonded to a passive substrate, configured as a cantilever beam vibrating in base excitation mode. Galfenol unimorph harvesters have been studied in the literature, including the characterization of device responses over a range of conditions and temperatures, and the development of simplified device models. The authors developed a 2D finite element model for unimorph harvesters in which Galfenol's response is described by lookup tables constructed from piecewise calculation of fully nonlinear thermodynamic models. This model does not include the external electrical circuits required to store the energy harvested by the device. Further, none of the existing unimorph models considers electrical dynamics. To overcome these limitations, this study first conducts impedance matching experiments for various unimorph beam geometries and load conditions. A voltage regulating circuit is developed to transfer AC output voltages generated by the harvester to DC voltages that are able to charge a battery or capacitor. An accurate and efficient 2D finite element (FE) beam model incorporating magnetic, mechanical, and electrical dynamics is presented and implemented in COMSOL Multiphysics. The new model is validated against the impedance matching measurements. Based on this model, design optimization is presented which considers the geometry of the unimorph beam, bias magnetic field strength, and load.

9433-11, Session 3

Magnetostrictive vibration damper and energy harvester for rotating machinery

Zhangxian Deng, The Ohio State Univ. (United States); Vivake M. Asnani, NASA Glenn Research Ctr. (United States); Marcelo J. Dapino, The Ohio State Univ. (United States)

Vibrations in rotating machinery can cause structural damage and high levels of noise. A proposed solution consists of a PZT-based mechanism that inserts damping into a driveline, without significantly increasing compliance, to reduce unwanted vibration and noise. This device has the appearance of a metal ring that can be mounted between two driveline components like a mechanical spacer. However, the depolarization of piezoelectric materials restricts the cycle life of this device. Although a steel protection cage has been developed to address the brittleness and low tensile strength of PZT, the cage complicates the design, manufacturing and assembly of

the system. Magnetostrictive terbium-iron-dysprosium alloys (Terfenol-D) and iron-gallium alloys (Galfenol) exhibit coupling between magnetic and mechanical energies. As such, these material are attractive for vibration energy conversion. The high hysteresis loss of Terfenol-D can be used to increase vibration damping, but this material is brittle thus requiring a support structure. On the other hand, Galfenol does not exhibit as much magnetic hysteresis but can be placed in the load path on account of its mechanical strength. Further, Galfenol can be machined or formed into complex shapes while also operating a broad range of temperatures. This study first develops a finite element (FE) model incorporating magnetic, mechanical, and electrical dynamics in COMSOL Multiphysics. New ring-shaped damping mechanisms using Terfenol-D and Galfenol are evaluated through the finite element models, considering loss factors, energy conversion efficiency, and force transmissibility. Experiments are conducted to validate the proposed model and guide the development of device designs.

9433-12, Session 4

Integrating electrostatic adhesion to composite structures

Callum J. C. Heath, Ian P. Bond, Univ. of Bristol (United Kingdom); Kevin D Potter, University of Bristol (United Kingdom)

Efficient load bearing structures are, on the most part, optimised for a given load case or operational environment. As a result, off-design point operation produces a performance compromise. Introduction of structural functionality could increase the adaptability of global structures or products and minimise this compromise. One product that could benefit from additional functionality is the alpine ski. Introduction of variable stiffness capability was highlighted as potentially beneficial. All-mountain all-round skis represent the largest type of ski produced by major manufacturers, showing the market for products that can perform adequately on varying terrain. Variable stiffness allows for high stiffness on smooth terrain maximizing perceived grip and response, and for lower stiffness in more varied terrain where increased flex is preferable. Split beam elements can vary the second moment of area of the structure, and thus its bending stiffness. Electroadhesion is a means to control shear stress transfer across split beam interfaces, and switch between multiple configurations. An electroadhesive consists of arrays of electrodes within an insulator surface. By imparting a large potential difference across the electrodes (-3kVDC) the surface of a connection substrate can be polarized, generating a holding pressure. Flexible printed circuit board material is etched producing fine electrode designs on a thin supportive backing. Co-curing this with glass fibre reinforced polymer composite produces an electroadhesive device in a novel manner, with the polyimide backing serving as a thin dielectric coating. Functional elements are thus introduced in a simple manner during the composite manufacture process allowing for in-service stiffness control.

9433-13, Session 4

Adaptive-passive vibration control systems for industrial applications

Dirk Mayer, Tobias Melz, Fraunhofer-Institut für Betriebsfestigkeit und Systemzuverlässigkeit (Germany); Jiri Vrbata, Thomas Pfeiffer, Fraunhofer Institute LBF (Germany)

Tuned vibration absorbers have become common for passive vibration reduction in many industrial applications. Lightly damped absorbers (also called neutralizers) can be used to suppress narrowband disturbances by tuning them to the excitation frequency. If the resonance is adapted in-operation, the performance of those devices can be significantly enhanced, or inertial mass can be decreased. However, the integration of actuators, sensors and control electronics into the system raises new

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design challenges. In this work, the development of adaptive-passive systems for vibration reduction at an industrial scale is presented. As an example, vibration reduction of a ship engine was studied in a full scale test. Simulations were used to study the feasibility and evaluate the system concept at an early stage. Several ways to adjust the resonance of the neutralizer were evaluated, including piezoelectric actuation and common mechatronic drives. Prototypes were implemented and tested. Since vibration absorbers suffer from high dynamic loads, reliability tests were used to assess the long-term behavior under operational conditions and to improve the components. It was proved that the adaptive systems are capable to withstand the mechanical loads in an industrial application. Also a control strategy had to be implemented in order to track the excitation frequency. The most mature concepts were integrated into the full scale test. An imbalance exciter was used to simulate the engine vibrations at a realistic level experimentally. The neutralizers were tested at varying excitation frequencies to evaluate the tracking capabilities of the control system. It was proved that a significant vibration reduction is possible.

9433-14, Session 4

Design and testing of a dynamically-tuned magnetostrictive spring with electrically-controlled stiffness

Justin J. Scheidler, Marcelo J. Dapino, The Ohio State Univ. (United States)

This paper details the development of electrically-controlled, variable stiffness spring components, using either magnetostrictive or piezoelectric transducers. The devices can be applied as semi-active vibration isolators or switched stiffness vibration controllers for reducing transmitted vibrations. The magnetostrictive transducer is designed using 1D linear models based on electroacoustics theory and stress-induced magnetic diffusion. Stiffness changes as a result of applied stress and magnetic field control. Modeling results highlight differences in the electrical and magnetic responses of Galfenol- and Terfenol-D-based components. The results also motivate the use of laminated Terfenol-D rods for a greater stiffness tuning range and increased bandwidth. The piezoelectric device is designed by taking advantage of the relationship between stiffness and load capacitance, as derived by 1D linear theory. Methods of implementing variable capacitance are considered and a stability analysis is presented for the selected method. The behavior of each component is examined under vibratory excitation up to 15 MPa and 1 kHz using a dynamic load frame. First, the dynamic elasticity and loss factor are characterized over the range of static control inputs (bias magnetic field or load capacitance). Subsequently, each device is controlled to achieve stiffness switching and continuous variation of stiffness.

9433-15, Session 4

Approach to prevent locking in a spring-damper system by adaptive load redistribution in auxiliary kinematic guidance elements

Christopher M. Gehb, Technische Univ. Darmstadt (Germany); Roland Platz, Fraunhofer-Institut für Betriebsfestigkeit und Systemzuverlässigkeit (Germany); Tobias Melz, Technische Univ. Darmstadt (Germany)

In many applications, kinematic structures are used to enable and disable degrees of freedom. The relative movement between a wheel and the body of a car or a landing gear and an aircraft fuselage are examples for a defined movement. In most cases, a spring-damper system determines the kinetic properties of the movement. However, unexpected high load peaks may lead to maximum displacements and maybe to locking. Thus, a hard clash between two rigid components may occur, causing acceleration peaks. This may have harmful effects for the whole system. For example a hard landing

of an aircraft can result in locking the landing gear and thus damage the entire aircraft.

In this paper, the potential of adaptive auxiliary kinematic guidance elements in a spring-damper system to prevent locking is investigated numerically. The aim is to provide additional forces in the auxiliary kinematic guidance elements in case of overloading the spring-damper system and thus to absorb some of the impact energy. To estimate the potential of the load redistribution in the spring-damper system, a numerical model of a two-mass oscillator is used, similar to a quarter-car-model.

In numerical calculations, the reduction of the acceleration peaks of the masses with the adaptive approach is compared to the acceleration peaks without the approach, or respectively, when locking is not prevented. In addition, the required force of the adaptive auxiliary kinematic guidance elements is calculated as a function of the masses of the system and the drop height or, respectively, the impact energy.

9433-16, Session 5

Computational design optimization of a SMA-based active steerable needle

Bardia Konh, Parsaoran Hutapea, Temple Univ. (United States)

Shape memory alloy (SMA) actuated needle is currently being developed for percutaneous interventional procedures to assist surgeons/physicians. The proposed active surgical needle can potentially compensate the possible misplacements of the needle tip in the tissue benefiting from the improved navigation provided by the SMA wire actuators. In this study finite element tools have been utilized in order to maintain an optimum design of the active needle configuration. There are several parameters involved in the design affecting the active needle's applicability and maneuverability. Among them are the length, diameter and the maximum residual strain of the SMA wires, the stiffness and diameters of the surgical needle and the offset distance between the needle and the actuator. For analyzing the response of the active needle structure a parametric model was developed in ANSYS. This model was linked to the automated optimization tools for improved needle designs. The most sensitive parameters affecting the active needle's steerability were found to be the offset distance and the length of the needle's diameter. Based on the results of this study and considering clinical limitations, a practical design of the active needle was proposed and presented.

9433-17, Session 5

Intelligent driving assistance system using shape memory alloy as variable impedance actuator

Josephine Selvarani Ruth D., Kaliyaperumal Dhanalakshmi, Sunjai Nakshatharan S., National Institute of Technology, Tiruchirappalli (India)

Variable Impedance Actuators (VIA) have received increasing attention in recent times as seen from the latest novel applications involving interactions between the human and dynamic environment. This work proposes an intelligent driving assistance system with impedance feedback for an accelerator pedal. In a vehicle it is important to sense the position of the accelerator pedal and it will be highly useful if the same is used for driver assistance system as haptics pedal, thus presenting a human machine interaction between the driver and driving environment. The methodology of this newly proposed system senses the position and also sends a force reflection signal to the accelerator pedal to provide a reaction force (force feedback) that aids the driver to take appropriate action in harmony with the road's condition. The system has been developed and tested by simulating the vehicle dynamics and essential control system architecture integrating virtual reality with real traffic scenario. This kind of action is brought out by variable impedance actuation using a smart

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material, the shape memory alloy (SMA) which does an integrated sensing (position sensor) and actuation (haptics - force feedback) through suitable design of the mechanism. The mechanical simplicity and compactness (miniaturisation possibilities) of SMA actuators reduce the scale, weight and number of components in the pedal module, thereby reducing the cost of automotive components and also provide substantial performance benefits. Experimental implementation of the proposed scheme is carried out which proves the dexterity of the recommended concept. The application of VIA controlled pedal make the driving easier and also facilitates safe driving.

9433-18, Session 6
SMA actuators: a viable practical technology (*Invited Paper*)

Alan L. Browne, Consultant, Retired (United States);
Jeffrey Brown, Dynalloy, Inc. (United States); Darel E.
Hodgson, Nitinol Technology, Inc. (United States)

Diverse products either based solely on or incorporating Shape Memory Alloys (SMA) have and are being made in a wide range of industries, and IP is being captured.

Why then compared to SE (superelastic) Nitinol, and especially conventional technology, do so few ideas reach production?

This presentation delves deeply into this topic in reaching the final assessment that SMA actuators are indeed now a viable practical technology.

The presentation begins with an introduction to and description of the fundamental basis of SMA actuator technology. Examples of multiple commercially available geometric forms of SMA actuators are given and the functionalities that they provide are described. This is followed by examples of multiple commercial products incorporating such SMA actuators.

Given that there are literally millions of commercial products incorporating conventional actuator technologies, indications are given as to why there are their less than 1000 that utilize SMA. Experience based challenges to the commercial use of SMA actuators are described. Besides having to compete with existing non-SMA technology which is quite mature additional challenges that are unique to SM actuators are indicated these including a wider than expected set of technical engineering problems and challenges and that a broader scope of dynamics is required.

9433-19, Session 6
Large-strain bistable actuation: BSEP polymer materials, actuators, and applications (*Invited Paper*)

Gibing Pei, Univ. of California, Los Angeles (United States)

A smart material capable of producing electrically induced, bistable, large actuation strain could enable a variety of new functional devices and smart structures. Conducting polymers are bistable, but the achievable strain is small. Large deformations have been achieved in dielectric elastomers at the sacrifice of storage modulus. The soft dielectric elastomers generally have elastic moduli less than 10 MPa. The deformed polymer relaxes to its original shape once the applied electric field is removed. Bistable electroactive polymer (BSEP) has been introduced to large-strain bistable actuation. The polymer is rigid, but transforms into an elastomer above glass transition. At the softened state, the polymer could be actuated to strains as much as 580% (area expansion) determined by the applied electric field. The deformation is locked in as the polymer is allowed to cool below glass transition. Reheating would return it to the original shape thanks to shape memory effect. New results in polymer design to tailor the transition temperature, narrow the transition temperature range, and enhance the actuation stability will be presented. Applications of the BSEP for new transducers and systems including refreshable Braille displays will also be presented.

9433-20, Session 6
Magnetorheological energy absorbers and applications to occupant protection systems (*Invited Paper*)

Norman M. Wereley, Univ. of Maryland, College Park (United States); Gregory J. Hiemenz, InnoVital Systems, Inc. (United States)

Magnetorheological energy absorbers (MREAs) have been deployed in occupant protection systems to protect against potentially injurious shock, crash or blast loads. MREAs operate at shear rates upwards of 25,000 s⁻¹, but magnetorheological fluids (MRFs) are typically characterized for shear rates up to 1,000 s⁻¹ in parallel counter-rotating disk rheometers. Because of the lack of data at the required high shear rates in the literature, a Searle-type magnetorheometer was designed and fabricated. Using this magnetorheometer, commercial MRFs were characterized over the shear rate range of 0 - 25,000 s⁻¹. It is shown that the rheometer successfully replicates characterization data taken at low shear rates, as well as quantifying high shear rate behavior as a function of applied field. Experimental data demonstrate that an increase in field dependent shear stress can be realized over this entire shear rate range, so that commercially viable MREAs can be designed using data taken with the magnetorheometer. Finally, the Mason number, which has been shown to be a useful non-dimensional number at low shear rates, provides a useful physical interpretation at high shear rates as well. Apparent viscosity plotted versus shear rate can be collapsed at various conditions can all be collapsed to a single curve if the normalized apparent viscosity is plotted versus Mason number. Lessons learned in commercializing MREAs to high speed impact problems are examined for mine blast protection, crashworthy crew seats and other impact control problems.

9433-21, Session 7
Ephraim Garcia: student and postdoc (*Invited Paper*)

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

Prof. E. Garcia started out as a sophomore in one of my classes. He became a summer "intern" in our lab and at the conclusion of his BS joined our group as an MS student funded by the NASA GSRP program out of NASA Langley Research Center, funding that continued through his PhD. During this time we also started a company together, GARMAN Systems, wrote some fantastic proposals and papers. These events and others, including some interesting social situations, are highlighted in this talk.

9433-22, Session 7
From ASMS to TANMS: what I learned from Ephraim (*Invited Paper*)

Gregory P. Carman, Univ. of California, Los Angeles (United States)

This presentation describes some my interactions with Professor Ephraim Garcia on research and personal topics during the past 20+ years. The history dates back to the first Adaptive Structures and Materials Systems meeting of ASME in 1992 and continues through our interaction in the new NSF Engineering Research Center entitled Translational Applications for Nanoscale Multiferroic Systems

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9433-23, Session 7

**Sparking innovation in defense research:
Ephraim Garcia's contributions to smart
structures and materials** *(Invited Paper)*

Jayanth N. Kudva, NextGen Aeronautics, Inc. (United States)

Sparking innovation in any field requires technical vision and enlightened leadership. In multiple roles - student, academic, company founder, DARPA PM, community mentor - Dr. Garcia has amply demonstrated both. In particular, he was instrumental in seeding innovative ideas and guiding them to technical maturity in the areas of morphing aircraft, compact actuators, and bio-mimetic systems.

This talk will trace his leadership roles in as well as technical contributions to our field and community over two decades. The talk will illustrate his contributions in the light of programs the author has worked on, sponsored by Ephraim while he was at DARPA.

9433-24, Session 7

**Actuation fatigue induced damage and
fracture of SMAs** *(Invited Paper)*

Dimitris C. Lagoudas, Texas A&M Univ. (United States)

No Abstract Available

9433-25, Session 7

**On the use of smart materials for self
sensing** *(Invited Paper)*

Alison B. Flatau, Univ. of Maryland, College Park (United States)

No Abstract Available

9433-26, Session 8

**Ephraim Garica: a visionary, a leader, and
a friend** *(Invited Paper)*

Brian Sanders, Embry Riddle Aeronautical Univ. (United States)

Ephraim Garica's contributions to technology, exploration, development, and application are enduring, but perhaps the most interesting aspects of him were his personal characteristics to include creativity, resilience, and boldness. These are the qualities that drove him to be one of the great members of our community. He used these fundamental characteristics to achieve incredible success in his career as a student, professor, and program manager at the Defense Advance Research Projects Agency (DARPA). My talk will address a behind the scenes look at how Ephraim handled himself in multiple leadership roles throughout his career and highlight attributes of his outstanding character that we can all hope to emulate in our own lives.

9433-27, Session 8

**To slew or not to slew: Ephraim's
influence on my career** *(Invited Paper)*

Donald J. Leo, The Univ. of Georgia (United States)

No Abstract Available

9433-28, Session 8

Top 10 Ephraim-isms *(Invited Paper)*

Diann E. Brei, Univ. of Michigan (United States)

No Abstract Available

9433-29, Session 8

**Bioinspired artificial muscle actuators
for robotics and aerospace applications**
(Invited Paper)

Norman M. Wereley, Univ. of Maryland, College Park (United States)

No Abstract Available

9433-30, Session 8

**Diode-less rectification technique for
energy harvesting** *(Invited Paper)*

Rashi Tiwari, The Dow Chemical Co. (United States); Alex D. Schlichting, The MITRE Corp. (United States)

Loss of power in the traditional diodes is a prevalent issue in low power energy harvesting using smart materials in general. Various techniques and methodologies for increasing power extraction has been reported in literature. This paper describes a new mechanical rectification scheme, designed using reed switches, in a full-bridge configuration that shows the capability of working with signals from millivolts to a few hundred volts with extremely low losses and can be beneficial for energy harvesting systems in general. The methodology has been tested for piezoelectric energy harvesters undergoing mechanical excitation.

9433-31, Session PTues

**Energy harvesting to power embedded
condition monitoring hardware**

Kevin M. Farinholt, Luna Innovations Inc. (United States)

The shift toward condition-based monitoring is a key area of research for many military, industrial, and commercial customers who want to lower the overall operating costs of capital equipment and general facilities. Assessing the health of rotating systems such as gearboxes, bearings, pumps and other actuation systems often rely on the need for continuous monitoring to capture transient signals that are evidence of events that could cause (i.e. cavitation), or be the result of (i.e. spalling), damage within a system. In some applications this can be accomplished using line powered analyzers, however for wide-spread monitoring, the use of small-scale embedded electronic systems are more desirable. In such cases the method for powering the electronics becomes a significant design factor. This work presents a multi-source energy harvesting approach meant to provide a robust power source for embedded electronics, capturing energy from vibration, thermal and light sources to operate a low-power sensor node. This paper presents the general design philosophy behind the multi-source harvesting circuit, and how it can be extended from powering electronics developed for periodic monitoring to sensing equipment capable of providing continuous condition-based monitoring.

**Conference 9433: Industrial and Commercial
Applications of Smart Structures Technologies IX**

9433-32, Session PTues

**Free forming of the gel by 3D gel printer
SWIM-ER**

Koji Okada, Hidemitsu Furukawa, Masaru Kawakami, Jin Gong, Masato Makino, Azusa Saitou, Yamagata Univ. (Japan)

Gels, soft and wet materials, have unique properties such as material permeability, biocompatibility and low frictional properties, which are hardly found in hard and dry materials. These superior characteristics of hydrogels promise to expand the medical applications. In recent years, the optical 3D gel printer named SWIM-ER (Soft and Wet Industrial - Easy Realizer) was developed by our team in order to fabricate tough gels with free form. We are aiming to create artificial blood vessel of the gel material by 3D gel printer. Artificial blood vessel is expected to be used for vascular surgery practice. The artificial blood vessel made by 3D gel printer can be create to free form on the basis of the biological data of the patient. Therefore, we believe it is possible to contribute to increasing the success rate and safety of vascular surgery by creating artificial blood vessel with 3D gel printer. The modeling method of SWIM-ER is as follow. Pregel solution is polymerized by one-point UV irradiation with optical fiber. The irradiation area is controlled by computer program, so that exact 3D free forming is realized. In this study, synthesis conditions are re-examined in order to improve the degree of freedom of fabrication. The dimensional accuracy in height direction is improved by increasing the cross linker concentration. We examined the relationship of resolution to the pitch and UV irradiation time in order to improve the modeling accuracy.

9433-33, Session PTues

**A smart guidewire for smooth navigation
in interventional radiology**

Yanfei Chen, Matthew M. Barry, Mahdis Shayan, Univ. of Pittsburgh (United States); Brian T. Jankowitz, UPMC (United States); Xinjie Duan, Anne M. Robertson, Youngjae Chun, Univ. of Pittsburgh (United States)

A smart guidewire using nitinol materials was designed, manufactured and evaluated the device functionality, such as bending performance, trackability, thermal effects, and thrombogenic response. Two types of nitinol material were partially used to enhance the guidewire trackability. A proposed smart guidewire system uses either one- or two-way shape-memory alloy nitinol (1W-SMA, 2W-SMA) wires (0.015", 381µm nitinol wire, NCD, CA, USA). Bending stiffness was measured using in vitro test system, which contains the NI USB-9162 data logger and LabView™ Signal Express 2010 (National Instruments, TX, USA). Temperature distribution and displacement were evaluated via recording a 60Hz movie using a SC325 camera (FLIR Systems, Australia). Hemocompatibility was evaluated by scanning electron microscopy after one heating cycle of nitinol under the Na-citrate porcine whole blood (Lampire Biological Lab., PA, USA) circulation. Prototypes have been successfully developed and tested. A smart guidewire showed 30 degrees bending after applying or disconnecting electrical current. While the temperature of the nitinol wires increased more than 70°C, the surrounding temperature with the commercially available catheter coverings showed below human body temperature showing 30-33°C. There was no significant platelet attachment or blood coagulation when the guidewire operates. This novel smart guidewires developed using shape memory alloy nitinol may represent a novel alternative to typical commercially available guidewires for interventional procedures.

9433-34, Session PTues

**In-service demonstration of
electromagnetic vibration energy
harvesting technologies for heavy haul rail
applications**

Chandarin Ung, Monash Univ. (Australia); Scott D. Moss, Defence Science and Technology Organisation (Australia); Wing K. Chiu, Monash Univ. (Australia); Owen R. Payne, Luke A. Vandewater, Steve C. Galea, Defence Science and Technology Organisation (Australia)

The dominant vibration frequencies exhibited by heavy haul railcars (operating in remote regions of Western Australia) are found to be 5.8 Hz and 14.6 Hz for loaded and unloaded trips respectively. This paper describes the in-service demonstration of three electromagnetic vibration energy harvesting technologies designed to generate power from these railcar vibrations: (i) a coupled two-degree of freedom (2-DoF) device capable of capturing both dominant frequencies of the railcar, (ii) a hybrid rotary-translational harvester device based on a magnetic sphere capable of harvesting from ~6 Hz, and (iii) a steel ball-bearing/permanent-magnet device capable of harvesting from ~15 Hz. The three devices were laboratory tested prior to mounting on a heavy rail car for in-service demonstration. Within the laboratory the coupled 2-DoF device was found to produce a maximum peak output power of 350 mW from 0.4 g root-mean-square (rms) acceleration at 15 Hz and 230 mW from 6 Hz. The hybrid rotary-translational device based on an oscillating magnetic sphere can produce ~138 mW from host vibration of 0.4 g rms at 5.4 Hz. The third design using a steel ball bearing and separate permanent magnet was able to generate a maximum output power of 16.4 mW from 0.4 g excitation at 14.2 Hz. This paper will discuss and compare the performance of the three prototypes, both within the laboratory and during the in-service demonstration on a heavy haul railcar.

9433-35, Session PTues

**Evaluation of conductive concrete for anti-
static flooring applications**

Sherif Yehia, Nasser Qaddoumi, Mohamed Hassan, Bassam Swaked, American Univ. of Sharjah (United Arab Emirates)

No Abstract Available

Conference 9434: Nano-, Bio-, Info-Tech Sensors and Systems

Monday - Wednesday 9 -11 March 2015

Part of Proceedings of SPIE Vol. 9434 Nanosensors, Biosensors, and Info-Tech Sensors and Systems 2015

9434-1, Session Key

Nano devices and concepts for condition-based maintenance of military systems *(Keynote Presentation)*

Eugene Edwards, Christina L. Brantley, U.S. Army Research, Development and Engineering Command (United States); Paul B. Ruffin, Alabama A&M Univ. (United States); Sihon H. Crutcher, U.S. Army Research, Development and Engineering Command (United States)

There is a continuous need for the Department of Defense (DoD) and its associate weaponry supply organizations to consistently evaluate the usability of weapons that exhibit deteriorative characteristics over a period of time. Along the same lines, enhanced condition-based maintenance evaluation procedures are necessary to mitigate the risk and reduce the cost of catastrophic failure of varying inventories of military systems. One significant area of research is the verification of the existence of sufficient concentrations of propellant stabilizer in the motor of stored missiles. Results from developed apparatuses can help collect degradation information to establish indicators that the missile's double-based solid propellant is still functional after long-term storage. Other mechanisms are being developed for the assessment of degradation in gun barrel rifling. The research outlined in this paper summarizes the Army Aviation and Missile Research, Development, & Engineering Center's (AMRDEC's) investigative approaches relative to the use of spectral-optical and acoustical methodologies for detecting deteriorations in both propellant and the apparatus that engages munitions. A spectral-optical sensing approach is presented that is based on distinctive light collecting optical fiber -based developments designed to detect the concentration of propellant ingredients. The use of diagnostic acoustic sensing mechanisms is delineated to include the use of commercially available transducer-based readers to collect information that is indicative of the distance that acoustic waves travel through weaponry components. In collaboration with several AMRDEC industry and academia supporters, this paper outlines sensing methods that are under consideration for implementation onto weapon systems. Conceptual approaches, experimental configurations, and laboratory results are presented for each initiative. Cost-savings and improved weaponry health monitoring capabilities are expected to derive from each sensing mechanisms.

9434-2, Session 1

A tactile sensor made of graphene-cellulose nanocomposite *(Invited Paper)*

Abdullahil Kafy, Kishor Kumar Sadasivuni, Seongcheol Mun, Jaehwan Kim, Inha Univ. (Korea, Republic of)

Development of tactile sensing technology has promoted intelligent human-machine interaction and recently has evolved out as one of the most promising area of electronics. Here in this paper, we fabricated a tactile sensor material using cellulose nanocrystal modified with graphene by isocyanate grafting. The new material is transparent and ecofriendly and integrated the capability of tactile sensing with fast response, high stability and high reversibility. Various materials from conducting metals to a human hand were checked for proximity sensing capability. Combining the results, the discrete, flexible dual-mode tactile sensor fulfilled the technical and its feasibility in robotics is also derived.

9434-3, Session 1

Design of an Integrated Sensor System for the Detection of Traces of Different Molecules in the Air *(Invited Paper)*

Drago Strle, Univ. of Ljubljana (Slovenia); Igor Muševič, Institute Josef Stefan (Slovenia)

Detecting vapor traces of different molecules in the atmosphere with simple and cheap instrument is very useful in different areas: medicine, security, environmental control, food production, science, etc. At the moment different bulky and expensive instruments exists for that tasks (for example mass spectrometer). Measurements take a lot of time, trained operator is necessary and false detection is very often because number of targeted molecules in the atmosphere is usually very low (density 10⁻⁹ to 10⁻¹⁴). Molecular detection is based on the adsorption of target molecules to the receptor molecules attached to the surface of the sensors. Targeted molecules are usually very small, their surface coverage is incomplete and the electric signals from sensors are usually weak. We have recently demonstrated that concentrations as low as 3 molecule of TNT in 10⁺¹² molecules of N₂ can be measured using differential pair of chemically functionalized COMB micro-capacitors and a low noise detection electronics. In this article the continuation project results are described which aim to increase the sensitivity by up to two orders of magnitude, therefore we want to discern a capacitance changes in the range of 10 Zepto-farad (10⁻²¹F). In addition, we are looking for a solution of the inherent problem of poor chemical selectivity of the system by introducing an integrated array of up to 16 chemically differently functionalized capacitive sensors (for now only four), thus mimicking the architecture of dog's nose; different molecules adsorb differently on differently functionalized surfaces, changing its dielectric constant and this will imprint a unique signal fingerprint to the array of micro-sensors.

9434-4, Session Key

Analysis of advanced thermoelectric materials and their functional limits *(Keynote Presentation)*

Hyun Jung Kim, National Institute of Aerospace (United States)

The efficiency of a TE material for both power generation and cooling is determined by its dimensionless figure of merit (ZT): $ZT = S^2T/\rho\kappa$. The Seebeck coefficient, electrical conductivity, and thermal conductivity are not independent, but intrinsically intertwined since they are determined by the transport properties of electrons. Traditionally, research on TE materials has focused on synthesizing materials which show low thermal conductivity while keeping high electrical conductivity. Such a research approach encompasses a technical controversy unintentionally due largely to the slow-down of thermal energy flow into a domain of TE conversion.

Now it is a time to review whether there is any potential room or opportunities possibly available to enhance TE performance. We obviously need to revisit and review the very fundamental level of physics on each parameter whether we are able to decouple or dissociate these parameters using new physical approaches. What is the functional limit of the transmission of lattice oscillation or energetic electron in thermal conductivity? Is the Seebeck coefficient indeed unbreakable intrinsic parameter? The talk will review and ponder about the current trend of TE research to optimize the ZT and discuss about new arguments on ZT with functional limits of each parameter.

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9434-5, Session 2

Flexible pressure sensors for burnt skin patient monitoring *(Invited Paper)*

GwangWook Hong, Sehun Kim, Joo-Hyung Kim, Inha Univ. (Korea, Republic of)

Pressure garments have been used for the hypertrophic scar treatment to suppress the treatment resistance. However, the treatment effect varies with the applied pressure and the pressure garments is also required proper local pressure measurement system. In general, the pneumatic type pressure gauge in the medical field cannot measure the correct pressure level of local area pressure on the patient skin. Recently, flexible pressure sensor has been received much attentions in the healthcare industries. In this study, polydimethylsiloxane (PDMS) with patterned multi-walled carbon nanotubes has been investigated for flexible pressure sensor. The designed flexible pressure monitoring with wireless monitoring is demonstrated for multi-points monitoring from the burnt patient's skin.

9434-6, Session 2

PPG sensor and device for noninvasive mobile health monitoring

Armen R. Poghosyan, Vahram Mouradian, Levon Hovhannisyan, Sensogram Technologies Inc. (United States)

We are presenting a novel photoplethysmographic (PPG) optical sensor and device with ambient optical, electrical and electromagnetic noises cancellation, thus allowing only the useful optical signals to be received by the health monitoring device. We are also disclosing a new processing technique for canceling the ambient noises contributed by optical, electrical and electromagnetic artifacts in the measured PPG signals. Such a device and method allow the enhancement of the performance of the PPG sensors compared to conventional apparatus and methods. The presented sensor and methodology have been integrated into a prototype device for noninvasive, continuous, wearable, remote and mobile monitoring of human vital signs, such as heart rate, oxygen saturation, blood pressure, respiration rate, etc. This small device allows the user to read, store, process and transmit all the measurements made using the PPG optical sensor and the electronic unit to a remote location.

9434-7, Session 2

Wireless nanosensors for monitoring concussion of football players

Vijay K. Varadan, The Pennsylvania State Univ. (United States)

No Abstract Available

9434-8, Session 3

Probe-pin device for optical neurotransmitter sensing in the brain *(Invited Paper)*

Min Hyuck Kim, Kyo D. Song, Hargsoon Yoon, Norfolk State Univ. (United States); Yeonjoon Park, Sang H. Choi, NASA Langley Research Ctr. (United States); Dae-Sung Lee, Kyu Sik Shin, Hak-In Hwang, Korea Electronics Technology Institute (Korea, Republic of)

Development of an optical neurotransmitter sensing device using nano-plasmonic probes and a micro-spectrometer for real time monitoring of neural signals in the brain is underway. Clinical application of this device technology is to provide autonomous closed-loop feedback control to a deep brain stimulation (DBS) system and enhance the accuracy and efficacy of DBS treatment. By far, we have developed an implantable probe-pin device based on localized field enhancement of surface plasmonic resonance on a nanostructured sensing domain which can amplify neurochemical signals from evoked neural activity in the brain. In this presentation, we will introduce the details of design and sensing performance of a proto-typed microspectrometer and nanostructured probing devices for real time measurement of neurotransmitter concentrations.

9434-9, Session 3

Nanosensor system for monitoring brain activity and drowsiness

M. Ramasamy, Vijay K. Varadan, The Pennsylvania State Univ. (United States)

No Abstract Available

9434-10, Session 3

Miniaturized neural sensing and optogenetic stimulation system for behavioral studies in the rat

Min Hyuck Kim, Ilho Nam, Norfolk State Univ. (United States); Youngki Ryu, Sun Moon Univ. (Korea, Republic of); Laurie L. Wellman, Larry D. Sanford, Eastern Virginia Medical School (United States); Hargsoon Yoon, Norfolk State Univ. (United States)

Real time sensing of localized electrophysiological and neurochemical signals associated with spontaneous and evoked neural activity is critically important for understanding neural networks in the brain. Our goal is to enhance the functionality and flexibility of a neural sensing and stimulation system for the observation of brain activity that will enable better understanding from the level of individual cells to that of global structures. We have thus developed a miniaturized electronic system for in-vivo neurotransmitter sensing and optogenetic stimulation amenable to behavioral studies in the rat. The system contains a potentiostat, a data acquisition unit, a control unit, and a wireless data transfer unit. For the potentiostat, we applied embedded op-amps to build constant amperometry for electrochemical sensing of glutamate. A light emitting diode is controlled by a microcontroller and pulsed width modulation utilized to control optogenetic stimulation within a sub-millisecond level. In addition, this proto-typed electronic system contains a Bluetooth module for wireless data communication. In the future, an application-specific integrated circuit (ASIC) will be designed for further miniaturization of the system.

9434-45, Session 3

Effect of temperature and UV light on charge transport mechanism in DNA

Alaleh Golkar Narenji, Noah Goshi, Chris Bui, John Mokili, Sam Kassegne, San Diego State Univ. (United States)

Research in the use of DNA molecule as a nanoelectronics as well as nano systems component continues. Our group has reported significant conductivity in DNA through direct and indirect measurements

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involving high-aspect ratio electrodes that eliminates the effect of the substrate. Our results demonstrated that, specifically, at moderate to high frequencies, DNA molecular wires show low impedance, which may have significant implications to the field of DNA-based bionanoelectronics. Both circuit modeling and FEA simulation supported the results from the experiments. In addition, in order to prove that the conductivity is indeed from DNA bridge, we studied the effect of temperature, UV, and DNA GC content on DNA molecular wire conductivity. The temperature results showed that DNA molecular wires have differing impedance responses at two temperature regimes: impedance increases between 40°C and 40°C and then decreases between 40°C and melting point (-110 °C), after which DNA denatures resulting in no current transduction. This hysteric and model behavior make DNA a candidate for nanoelectronics components like thermal transistors and switches. The data from UV exposure indicating decreased conductivity of DNA molecular wires as it causes damage to GC base-pairs and phosphate groups reducing the path available both for hopping and short-range tunneling mechanisms. The lessons learned from conductivity experiments and the different charge transport mechanisms in DNA can be applied to conjugated cross-linked synthetic molecular wires for construction of nano electronic devices.

9434-12, Session Key

Nanomaterials and nanotechnology for numerous applications: biotechnology to energy *(Keynote Presentation)*

Aswini K. Pradhan, Norfolk State Univ. (United States)

The development and implementation of nanotechnology for biomedical diagnostics, sensing and energy applications have tremendous societal impact. These research directions represent leading edges of the fast-moving development in nanotechnologies with strong insight into the understanding of both fundamental and applied aspects of nanoscience and nanotechnology. In this talk I would discuss where the nanotechnology has made an impact as well as currently making a huge progress. I would exclusively discuss the future of the nanotechnology and nanomaterials in our day-to-day life to "Nano-Revolution" in every sphere of the society. I would provide some examples on biomedical implications and energy applications: two hot fields of current and future research.

9434-13, Session Key

Properties of RNA nanotubes and their applications

Roderick V. Melnik, Shyam Badu, Wilfrid Laurier Univ. (Canada); Sanjay Prabhakar, Wilfrid Laurier Univ (Canada)

RNA molecules are very flexible in nature. This feature allows us to build various motifs which are essential in bio-nanotechnological applications. Based on the previous studies on RNA nanorings, in this contribution we analyze the structure and properties of RNA nanotubes, where we focus on nanotubes consisting of up to five nanorings of around 20nm in diameter. We have developed a molecular dynamics (MD) method and implemented it by using the NAMD and VMD packages to study the structural and thermal properties of the nanotube in physiological solutions. In particular, we have analyzed such characteristics as the Root Mean Square Deviation (RMSD), the radius of gyration, the number of hydrogen bonds per base pairs, and the radial distribution function for the different nanoclusters in nanotubes of various sizes. The variations of energy and temperature with simulation time have been studied for all sets of simulations. Variations in RMSD, radius of gyration and the radial distribution function with temperature have been analyzed in detail. Furthermore, the number of 23Na⁺ ions around the nanotubes within the distance of 5Å at two different temperatures has also been studied. It has been found that the number of ions accumulated around the nanotubes within the specified distance is growing with increase in temperature from 310K to 510K. The final configurations of the systems simulated at 510K have been considered as the starting point for further

MD simulations at 310K. We confirmed the process of ion evaporation with temperature decrease. This is due to the phenomenon of self-stabilization, first reported in Phys.Biol. 2009, 6, 046003.

9434-14, Session 4

Ultrasonic matrix transducer for real time volumetric cardiac imaging *(Invited Paper)*

Yongrae Roh, Yeonsue Park, Haejune Park, Hyunki Kim, Kyungpook National Univ. (Korea, Republic of)

3-D ultrasound imaging permits better visualization and allows a more accurate diagnosis to be made, thus the volumetric ultrasound images provide clinicians with more confidence in the diagnosis of disease and add knowledge of complex pathology. The 3-D ultrasound imaging technology has benefitted from the development of the transducers that are in direct contact with patients, which has expanded the possibilities for maximizing patient diagnostic information. In this work, an ultrasonic matrix transducer has been developed for cardiac imaging in 3D.

Typical ultrasonic matrix array transducers have a large number of channels. In order to alleviate the difficulty in fabricating so many channels, most of the matrix array transducers reported so far have been made to consist of several sub-array modules. However, even if sophisticated processes were employed to align and bond the modules in an exact pattern, the effects of the gap between the modules are inevitable. In this work, a new conductive backing has been developed to resolve the fabrication difficulty and to improve the transducer performance by machining the whole matrix array on a piezoelectric plate as a single unit.

Conductive pillars were molded in polymeric matrix following the processes similar to those for fabricating 1-3 piezocomposites. Fabricated 64x64 channel matrix transducer has a center frequency at 3.5 MHz and fractional bandwidth of 75%. In terms of sensitivity uniformity, standard deviation over the entire 4,096 array was 0.81dB at maximum without tuning circuits, which is significant improvement over the module type transducer.

9434-15, Session 4

Cellulose nanocrystals, nanofibers, and their composites as renewable smart materials

Jaehwan Kim, Lindong Zhai, Seongcheol Mun, Hyun-U Ko, Young-Min Yun, Eun Byul Jo, Inha Univ. (Korea, Republic of)

Cellulose is one of abundant renewable biomaterials in the world. Over 100 billion tons of cellulose is produced per year in nature by biosynthesis, forming microfibrils which in turn aggregate to form cellulose fibers. Using new effective methods these fibrils can be disintegrated from the fibers to nanosized materials, so called cellulose nanocrystal (CNC) and cellulose nanofiber (CNF), which can be a new building block of new materials. The CNC and CNF have extremely good strength properties, dimensional stability, thermal stability and good optical properties on top of their renewable behavior. The bio-based one dimensional CNCs and CNF are versatile materials since it can be applied in many different fields, for example, new lightweight composite materials to be used in transport, electronic applications but they can also be used in food, cosmetics, medical, packaging and many other applications.

This paper represents recent advancement of cellulose nanocrystals and cellulose nanofibers, followed by their possibility for smart materials. Natural behaviors, extraction, modification of cellulose nanocrystals and fibers are explained and their synthesis with nanomaterials is introduced, which is necessary to meet the technological requirements for smart materials. Also, its challenges for smart materials will be addressed.

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9434-16, Session 4

Implementation and characterization of meta-resonator antennas (*Invited Paper*)

In Kwang Kim, Nextivity, Inc. (United States) and Univ. of Arkansas (United States); Vasundara V. Varadan, Univ. of Arkansas (United States)

Metamaterials are artificially engineered microstructures that have strong resonance behavior although their electrical size is very small (?0.1?). Meta-resonator (metamaterial resonator) antennas use the resonance of the metamaterials to reduce the size of radiators and design multiband antennas. A split-ring resonator (SRR) is a well-studied metamaterial structure which obtains negative permittivity and/or permeability in a narrow frequency region. In this paper, several 2D/3D meta-resonator antennas with SRRs are designed, fabricated and characterized. Metamaterial structures and meta-resonator antennas are designed and simulated using a full wave simulator. 2D meta-resonator antennas are fabricated by photolithography and 3D meta-resonator antennas are fabricated by LTCC (Low-Temperature Co-fired Ceramic) technique. A free space measurement system is used to characterize metamaterial and meta-resonator antenna samples.

9434-17, Session 4

Efficient light scattering in plasmonic light trapping designs for thin film solar cells

Liming Ji, Vasundara V. Varadan, Univ. of Arkansas (United States)

Plasmonic structures have been proposed for enhancing light absorption in thin film solar cells, for which insufficient light absorption is a limiting factor for further improvement of efficiency. The optical path of light in the absorber layer of a solar cell is increased due to the enhanced light scattering by plasmonic structures at resonance. This process involves two steps of energy conversion: light-electron and then electron-light. The first step couples optical energy into the kinetic energy of collective electron motions in plasmonic structures, forming oscillating current. This step is easy to implement as long as plasmonic structures are at resonance. The second step releases the energy from electrons to photons. An efficient release of photon energy is a must for solar cell applications and it is dependent on the two competing effects: light scattering and field localization that results in heat loss. Theoretical discussions and simulation work are provided in the paper, showing that electrically connected plasmonic structures tend to be more efficient in light scattering than discrete structures. The two types of structures were compared by simulation and following field analysis in this paper. The effect of field coupling is also discussed. Simulation work shows that thin film solar cells with electrically connected structures are more likely to have the real enhancement of light absorption in the absorber layer while discrete structures tend to cause field location, in which case the energy of extra light absorption by a plasmonic resonance is dissipated as heat.

9434-18, Session 4

Piezocomposites for unmanned underwater vehicle application

Woosuk A. Chang, National Univ. of Singapore (Singapore)

This paper reviews tailored design and manufacturing method of piezoceramic-polymer transducer for unmanned underwater vehicles(UUV). UUV requires high electro-acoustic coupling sensitivity, wide operation frequency band, strong structural robustness, low density and long endurance in underwater condition, with reasonable price. Numerous polymers are considered with various volume fraction ratio to find optimum point for high receiving sensitivity and wide operation frequency range. Powder injection moling approach was introduced to meet price

requirement by mass production method. A receiving sensor array is designed and manufactured and tested. The advantage of the suggested piezo material is verified in comparison with conventional spherical hydrophones.

9434-19, Session 5

Cellulose/PDMS hybrid material for actuating lens (*Invited Paper*)

Kishor Kumar Sadasivuni, Eun Byul Jo, Xiaoyuan Gao, Asma Akther, Seongcheol Mun, Jaehwan Kim, Inha Univ. (Korea, Republic of)

Miniaturization of optical systems has promoted a revolution in microlens technology and this emerging field has much interest for medical practitioners as well as electronic engineers. Here we demonstrate a microlens consisting of a transparent elastomer liquid composite containing organo modified cellulose nanocrystals and this composite focal length can be adjusting by varying applied voltage. The actuator with the working voltage of only up to 0.8 kV was capable and thereby altering the curvature of the microlens reversibly in few seconds. The effect of filler concentration on optical property and dielectric behavior of the composites was also analyzed.

9434-20, Session 5

Novel design of honeycombs using a seamless combination of auxetic and conventional cores toward phononic band gap engineering (*Invited Paper*)

Sushovan Mukherjee, Indian Institute of Science (India); Fabrizio Scarpa, Univ. of Bristol (United Kingdom); Srinivasan Gopalakrishnan, Indian Institute of Science (India)

A novel design for the geometric configuration of honeycombs using a seamless combination of auxetic and conventional cores- elements with negative and positive Poisson ratios respectively, has been presented. The proposed design has been shown to generate a superior band gap property while retaining all the advantages of a purely conventional or purely auxetic honeycomb structure. Seamless combination ensures that joint cardinality is also retained. Several configurations involving different degree of auxeticity and different proportions auxetic and conventional elements have been analyzed. It has been shown that the preferred configurations open up wide and clean band gap at a significantly lower frequency ranges compared to their pure counterparts. In view of existence of band gaps being desired feature for the phononic applications, reported results might be appealing. Use of such design may enable superior vibration control as well. Proposed configurations can be made iso-volumic and iso-weight giving designers a fairer ground of applying such configurations without significantly changing size and weight criteria.

9434-21, Session 5

Dynamics of plasmon in graphene oxide (*Invited Paper*)

Brahmanandam Javvaji, D. Roy Mahapatra, Indian Institute of Science (India)

Graphene-oxide is a promising nanostructured material for electronic, opto-electronic, biological and many other applications due to its intrinsic energy bandgap, tenability of optical and electronic properties and high yield with easy synthesis. A mixture of SP2 and SP3 hybridized carbon atoms are

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most common in the Graphene-oxide. The SP₃ hybridization is due to the bonding between the valence pi electrons and the electrons in the oxidizing group or functional group attached to the carbon atoms present in the Graphene. Such complex hybridization is useful in applications like DNA binding, novel water purification systems etc.. The SP₃ bonded pi electrons alters the energy band structure of Graphene, which can be observed in the excitation of pi-plasmons during the optical transition between the bands. This transition requires an amount of 5 eV energy in Graphene where as in Graphene-oxide it is about 2 to 3 eV, which is likely to enable several opto-electronic and photo luminescence applications. One of important dynamical effects of plasmons is its relaxation due to scattering with boundaries or impurities or with other quasi particles such as phonons. We developed a variational formulation involving the energies arising due to first-principal interaction of atoms, vibrational degrees of freedom the atoms and the electromagnetic field necessary to excite the plasmons. Large scale simulations are carried out. Plasmon dispersion characteristics, mode conversion due to scattering are analyzed. Results obtained from this study give insight toward understanding the applicability of Graphene-oxide in various electronic devices.

9434-22, Session 6

A novel intraocular pressure microsensor based on a resonant nanocavity (*Invited Paper*)

Tianlong Li, Longqiu Li, Jiaxin Li, Harbin Institute of Technology (China); Xinrong Zhou, The Second Affiliated Hospital of Harbin Medical Univ. (China); Guangyu Zhang, Harbin Institute of Technology (China)

Glaucoma is a heterogeneous disease characterized by pathological retinal ganglion cell loss resulting in loss of visual field and ultimately blindness. The glaucoma diagnosis and prevention of the disease progression depend heavily on the accuracy of intraocular pressure (IOP) measurement. Continuous monitoring of intraocular pressure would make it possible to detect the disease progression early so as to prevent to lose the vision of patient. With the advantages of ultracompact size, high contrast and easy integration, photonic crystal can be widely used in the field of mechanical microsensors. The performances of these sensors are mainly determined by the resonant nanocavities. The output wavelength of these sensors using photonic crystal varies as functions of force and strain.

In this work, a novel fully implantable, electronic-free, continuous monitoring, photonic crystal microsensor, in which the resonant nanocavity is embedded in an elastic bod, is developed and studied numerically. The relationship between the intraocular pressure and the output wavelength is obtained using finite element method and finite difference time-domain method, respectively. The effect of the resonator nanocavity geometry, elastic body geometry and materials of photonic crystal are investigated. In addition, a comparison between the numerical and theoretical results is provided.

9434-23, Session 6

Non-invasive glucose determination by saliva

Rogério F. Andrade, Iron Bit (Brazil) and CEPAM (Brazil); Helber Holland, Instituto de Pesquisas Energéticas e Nucleares (Brazil); Flavia D. Motta, Iron Bit (Brazil); Maria J. De Oliveira, Instituto de Pesquisas Energéticas e Nucleares (Brazil)

Diabetes mellitus is an endocrine disease characterized by a deficit in insulin production with consequent alteration of blood glucose concentration. This disease is one of the leading causes of death and disability in the world. The blood general test leads to pain and inconvenience caused by finger

pricking, leading to fewer tests and inadequate blood glucose control. One recent non-invasive way to measure glucose levels is by saliva once glucose particles moves rapidly and easily through blood vessels membranes to the gingival fluid. Our propose is a reliable system for glucose monitoring using saliva as substrate for glucose oxidase reaction by a biological catalyst system coupled horseradish peroxidase (HRP) for determination of hydrogen peroxide (H₂O₂). A sensitive H₂O₂ biosensor was idealized based on a conduct surface as an electron transfer mediator to capture electrochemical signals. Cyclic voltammetry background studies showed this is a feasible approach. This system has a stick-like design where one end is used to place saliva sample while on the other lies a sensor that transcript glucose oxidase electrochemical signal to glucose concentration, which is send to colored led that indicates three pre-determined glucose levels, indicating a glucose correspondent concentration. This system enables diabetes monitoring and avoid any kind of pain or the need for finger pricks.

9434-24, Session 6

AC magnetic field-assisted method to develop porous carbon nanotube/ conducting polymer composites for application in thermoelectric materials

Chun-Yu Chuang, Shu-Chian Yang, Su-Hua Chang, Ta-I Yang, Chung Yuan Christian Univ. (Taiwan)

Thermoelectric materials are very effective in converting waste heat sources into useful electricity. Researchers are continuing to develop new polymeric thermoelectric materials. The segregated-network carbon nanotube(CNT)-polymer composites are most promising. Thus, the goal of this study is to develop novel porous CNT -polymer composites with improved thermoelectric properties.

The research efforts focused on modifying the surface of the CNT with magnetic nanoparticles so that heat was released when subjecting to an AC magnetic field. Subsequently, polymers covered on the surface of the CNT were crosslinked. The porous CNT -polymer composites can be obtained by removing the un-crosslinked polymers. The polymers utilized in this study include polydimethylsiloxane, electroactive polymers, and conducting polymers to investigate the effect of their porosity and electrical conductivity on the thermoelectric properties of the composites.

This AC magnetic field-assisted method to develop porous carbon nanotube/conducting polymer composites for application in thermoelectric materials is introduced for the first time. The advantage of this method is that the electrical conductivity of the composites was high since we can easily to manipulate the CNT to form a conducting path. Another advantage is that the high porosity significantly reduced the thermal conductivity of the composites. These two advantages enable us to realize the polymer composites for thermoelectric applications. We are confident that this research will open a new avenue for developing polymer thermoelectric materials.

9434-25, Session 6

Wideband, thin, and flexible graphene-nanotube-iron nanostructure filled PEDOT:PSS film for EMI shielding

Sihwa Lee, Kiwoo Jun, Ilkwon Oh, KAIST (Korea, Republic of)

As the knowledge and technology progressed, the use of various types of electrical and electronic equipment in commercial, military, and scientific applications increased rapidly. These equipment are a source of electromagnetic radiation (EMR), Thus the problem of protection against electromagnetic radiation has a very important technical aspect concerning a reduction in the level of electromagnetic interference (EMI) that occurs between electronic instruments. Furthermore, an even more

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important aspect of protection against electromagnetic radiation is the health protection of persons present in the vicinity of equipment emitting electromagnetic radiation and exposed to its prolonged effects.

This has increased the interest in developing effective materials for EMI shielding

We have developed a fast and facile microwave synthesis method to synthesize a novel G-CNT-Fe 3D functional nanostructure composed of carbon nanotubes grown on graphene sheets and iron nanoparticle decorated on both the carbon nanotubes and on the graphene sheets.

Furthermore, iron nanoparticles are embedded in the network creating a novel 3D ensemble of OD iron nanoparticles distributed on 1D carbon nanotubes and 2D graphene nanosheets.

In G-CNT-Fe nanostructure, all three phases have been combined into a single architecture, which generates strong synergy between the graphene, CNT, and iron nanoparticles. As a result, more reflections and absorption have been obtained on the surface of nanostructure. Moreover, in high frequency area, higher SE is observed. As a whole, G-CNT-Fe nanostructure film demonstrates wideband high performance EMI shielding performance.

Furthermore, the G-CNT-Fe filled PEDOT:PSS film is found to be thinner and generates broader effective bandwidth as compared to previous reports.

9434-26, Session 6

Vibration response of magnetic field affected double single-walled carbon nanotube systems using modified couple stress theory (*Invited Paper*)

Vijay Kumar Gupta, Swati Agrawal Jaiswal, Pavan Kumar Kankar, PDPM IITDM Jabalpur (India)

The application of carbon nanotubes (CNTs) in the field of bio-sensing is increasing enormously because of their physical, mechanical, optical, electronic and magnetic properties. A biosensor may use different arrangement of CNTs to form nanostructures which can detect very small mass and mechanical behavior effectively. Single walled, double walled and multi-walled nano-structures are being explored by various researchers as bio sensor.

The nanostructure considered in this paper is a double single-walled nanotube system (DSWNTS) as used by Murmu, et al, 2012.

The DSWNTS, different from a double walled nanotube, has two single walled CNTs which are coupled by some elastic medium. This can be used as bio sensor based on the principle that with the addition of mass, shift in the frequency of the system occurs, which can be used to detect the mass of bio molecule.

Various researchers have used Classical continuum theories derive the dynamic equations for the system. The classical continuum theories do not interpret the size effect at nanoscale whereas non-classical continuum theories can interpret the size effect at nanoscale. In this paper it is proposed to use Modified couple stress theory for modeling the equations for natural frequencies of the DSWNTS. It is proposed to use Modified couple stress theory in accordance with Maxwell's relation to study the strength of magnetic field on synchronous and asynchronous vibration of given nanostructure. The results obtained so will be compared with results obtained by consideration of nonlocal effect. This study can be useful for modeling and improving nanotube systems for vibration isolation and bio-sensing device both.

Reference:

1. Murmu T., McCarthy M. A. and Adhikari S., 2012, "Nonlocal elasticity based magnetic field affected vibration response of double single-walled carbon nanotube systems", Journal of Applied Physics, Vol: 111, 113511 (2012); doi: 10.1063/1.4720084

9434-39, Session PTues

Study on dynamic characteristics of smart composite laminates with partially debonded piezoelectric actuator

Bin Huang, Heung Soo Kim, Dongguk Univ. (Korea, Republic of); Gil Ho Yoon, Hanyang Univ. (Korea, Republic of)

The dynamic characteristics of smart composite laminates with partially debonded piezoelectric actuator are investigated in this work. The proposed work introduces an improved layerwise theory based mathematical modeling with the Heaviside unit step functions to allow the possible sliding of the in-plane displacements and jump of the out-of-plane displacements for the debonded area. The finite element implementation is conducted using the four-node plate element to derive the governing equation. The dynamic characteristics are investigated by the frequency domain and time domain. The influence of actuator debonding to the natural frequencies is subtler for such kind of smart composite structures. The debonding of piezoelectric actuator also decreases its actuation ability that is reflected in the magnitudes of the system response. The proposed method can well predict the responses of the smart composite laminates with actuator debonding failures and it could be applied to the further damage detection methods.

9434-40, Session PTues

Synthesis of polydiphenylamine nanoparticles: effect of surfactant type and concentration

Tharaporn Permpool, Anuvat Sirivat, The Petroleum and Petrochemical College (Thailand); Darunee Aussawasathien, National Metal and Materials Technology Ctr. (Thailand) and National Science and Technology Development Agency (Thailand)

The emulsion polymerization process was used in the synthesis of polydiphenylamine (PDPA) to obtain the new morphologies and the effects of surfactant types—anionic, cationic, non-ionic, and surfactant concentrations were investigated with the roles of a template and a dopant. Scanning electron microscopic images indicated different polydiphenylamine morphologies depending on the surfactant type. The new morphological structures of the PDPA obtained were: leaf-like, coral reef-like, and red blood cell-like, which have not been synthesized or seen before. The agglomeration of each nanoparticle was in the range of 50 nm to 500 nm depending on the surfactant type. The structure characterizations carried out by Fourier transform infrared spectroscopy, X-ray diffractometry, and UV-visible spectroscopy confirmed the incorporation of surfactant in PDPA. The electrical conductivity values of the PDPA with surfactants were higher than that without a surfactant by four orders of magnitude, and were consistent with the resultant smaller particle sizes and narrower optical band gap as calculated from UV-visible data. To induce higher electrical conductivity of PDPA, various dopants were used. However, the thermal stability of the PDPA was lower than the microscopic PDPA (cPDPA) due to the larger surface area of PDPA which can decompose more easily.

9434-41, Session PTues

Enhanced the interaction of dPPV/Zeolite Y composites towards Ketone vapors: effect of transition metals

Jirarat Kamonsawas, Anuvat Sirivat, The Petroleum and

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Doped poly(p-phenylene vinylene) or DPPV was mixed with modified zeolite Y to improve the selective and sensitive response properties of zeolite Y toward 3 different types of ketone vapors (acetone, MEK and MIBK) known as the toxic components and harmful to the human health. Zeolite Y (Si/Al 5.1, Na+) or NaY was ion exchanged with 3 types of transition cations: Cu²⁺, Ni²⁺ and Fe²⁺ at 80% cation exchanged to prepare 80CuNaY, 80NiNaY and 80FeNaY. In this work, the effect of transition cations, ketone vapor type, ketone vapor concentration, and the content of DPPV are systematically investigated. For the effect of cation types, the highest electrical conductivity response and sensitivity towards acetone vapor at the vapor concentration of 30000 ppm was obtained with 80CuNaY, whereas 80FeNaY showed the lowest values due to the electrostatic interaction between the zeolite framework and the cation. DPPV was mixed with 80CuNaY to study the effect of conductive polymer and exposed to the three different types of ketone vapors (acetone, MEK, and MIBK) at the vapor concentration of 30000 ppm. The electrical conductivity response and sensitivity of the composites towards acetone vapor exhibited the highest values whereas in MIBK exposure showed the lowest value. When mixing 80CuNaY with dPPV at the dPPV concentration of 10%v/v, the minimum vapor concentration which 80CuNaY could respond towards acetone vapor decreased from 9 ppm to 5 ppm. The electrical conductivity response of the dPPV, zeolite Y, and composite is irreversible as evidenced by FTIR and AFM techniques.

9434-42, Session PTues

Thin film of sol-gel deposited in photonic crystal fiber for cholesterol detection

Daniel A. Razo Medina, Edgar Alvarado-Méndez, Mónica Trejo-Durán, Univ. de Guanajuato (Mexico)

In this work, the fabrication of thin films mixed with cholesterol enzyme as recognition component is shown. Using Sol-Gel technique is used. The film was deposited at one end of photonic crystal fiber (optrode), which was used as carrier medium of Sol-Gel matrix process. The concentration of cholesterol in the test sample was determined by the use of absorbance. Measuring device consists of a power source (laser diode), optrode and a light detector. The laser beam is transmitted through the optrode and the variations of intensity, depending on cholesterol concentration, are emitted to be detected by a photoresistor.

9434-43, Session PTues

Simulation and experimental verification of flexible cellulose acetate haptic array actuator

Asma Akther, Md Mohiuddin, Seung-Ki Min, Inha Univ. (Korea, Republic of); Sang-Youn Kim, Korea Univ. of Technology and Education (Korea, Republic of); Jaehwan Kim, Inha Univ. (Korea, Republic of)

This paper refers the experiment and finite element model (FEM) simulation of an array type film haptic actuator. This haptic actuator is made of cellulose acetate with adhesive pillar, array 3x3 to insert in haptic devices. The purpose of an actuator is to feel the vibration of touch. Therefore, cellulose acetate based film is suitable for haptic devices because of its high dielectric constant, flexibility and transparency. The focus of this paper is to use a finite element software ANSYS to simulate, analysis of a haptic actuator and verify that result with practical experiment. This simulation employing result include with array geometry, electrostatic actuators, displacement, Natural frequency and point mass. The reason of preferring electrostatic actuator is its numerous advantages including fast response time ease of integration and fabrication.

9434-44, Session PTues

Electrospinning biodegradable shape memory Chitosan/polyethylene oxide nanofibrous membranes

Hongqiu Wei, Fenghua Zhang, Yanjiu Liu, Jingsong Leng, Harbin Institute of Technology (China)

Shape memory polymers (SMPs) as kinds of smart materials acquire their name from the unique performance to recover the initial shape after going through a shape deformation. In the past decades, researches on SMPs have aroused growing interests, especially in biomedical field. In the present study, chitosan (CS) was blended with polyethylene oxide(PEO) to fabricate a type of biodegradable shape memory composite nanofibrous membrane via electrospinning technology. Fourier transform infrared spectrophotometer(FTIR) confirmed that both of the two components existed in the electrospun films. The fibers presented uniform distribution and the diameters of them were influenced by different compositions of CS and PEO, which were investigated by scanning electron microscopy (SEM). Results of thermal gravimetric analysis (TGA) indicated that the CS/PEO composites exhibited excellent thermal stabilities. Differential Scanning Calorimetry (DSC) was adopted to obtain glass transition temperatures (T_g). The bending-recovery experiment demonstrated the materials could recover their original shape only in 45 seconds with the shape recovery ratio at 95%, suggesting such CS/PEO fibrous films possessed good shape memory effect. Based on the intelligence, the electrospun shape memory CS/PEO nanofibrous composite may have potential applications in cell culture, tissue engineering as well as enzyme immobilization.

9434-27, Session Key

RF to millimeter wave integration and module technologies (*Keynote Presentation*)

Tauno Vaha-Heikkila, VTT Technical Research Ctr. of Finland (Finland)

Aim to higher level of integration is one of the key focuses in modern radio front-end module development from RF (radio frequency) to millimeter waves. Especially this trend is driven by consumer electronics products. Silicon and laminate based technologies are driving development efforts in RF applications below 6 GHz and the same trend can be seen also to millimeter wave applications up to 110 GHz. In addition to these, Low Temperature Co-fired Ceramics (LTCC) is used especially in microwave and millimeter wave integration.

VTT Technical Research Centre of Finland has developed silicon and quartz based integration platform for radio frequency high quality factor passive components and module integration. Newest results will be presented in the conference covering integrated silicon based RF passive components and resonators with quality factors above 100 around 3 GHz. Also, millimeter wave silicon and quartz based resonators and filters are presented. Results on LTCC based modules are also presented as an other integration platform.

9434-28, Session Key

Review of radio wave for power transmission with safety (*Invited Paper*)

Kyo D. Song, John Day, Demetris L. Geddis, Hargsoon Yoon, Norfolk State Univ. (United States); Jaehwan Kim, Inha Univ. (Korea, Republic of); Sang H. Choi, NASA Langley Research Ctr. (United States)

The integration of biosensors with wireless power transmission devices in radio wave frequency is a new type of challenges for implantable devices

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for medical applications. Integration and at the same time miniaturization of medical devices in all are not trivial. The research reported herein, seeks to review possible effects of RF signals with frequencies ranging from 900 MHz to 10 GHz on the human tissues and environment. The preliminary evaluation shows that radio waves selected for test because substantial influence on human tissues based on their dielectric properties. With the rapid development of RF based biosensors, it imperative to have guidelines that specify how to use RF power safely. In this paper, the dielectric properties of various human tissues will be used for estimation of influence within the selected frequency ranges.

9434-29, Session 7

Enhanced electromechanical behaviors of cellulose ZnO hybrid nanocomposite

Seongcheol Mun, Seung-Ki Min, Hyunchan Kim, Jongbeom Im, Inha Univ. (Korea, Republic of); Demetris L Geddis, Norfolk State University (United States); Jaehwan Kim, Inha Univ. (Korea, Republic of)

Inorganic-organic hybrid composite has attracted as its combined synergistic properties. Cellulose based inorganic-organic hybrid composite was fabricated with semiconductive nanomaterials which has functionality of nanomaterial and biocompatibility piezoelectricity, high transparency and flexibility of cellulose electro active paper namely EAPap. ZnO is providing semiconductive functionality to EAPap for hybrid nanocomposite by simple chemical reaction. Cellulose-ZnO hybrid nanocomposite (CEZOHN) demonstrates novel electrical, photoelectrical and electromechanical behaviors. This paper deals with methods to improve electromechanical property of CEZOHN. The fabrication process is introduced briefly, charging mechanism and evaluation is studied with measured piezoelectric constant. And its candidate application will be discussed such as artificial muscle, energy harvester, strain sensor, flexible electrical device.

9434-30, Session 7

3D gel printing for soft-matter systems innovation

Hidemitsu Furukawa, Masaru Kawakami, Jin Gong, Masato Makino, Md. H. Kabir, Azusa Saito, Yamagata Univ. (Japan)

In the past decade, several high-strength gels have been developed, especially from Japan. 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. We consider if various gel materials including such high-strength gels are 3D-printable, many new soft and wet systems will be developed since the most intricate shape gels can be printed regardless of the quite softness and brittleness of gels. Recently we have tried to develop an optical 3D gel printer to realize the free-form formation of gel materials. We named this apparatus Easy Realizer of Soft and Wet Industrial Materials (SWIM-ER). The SWIM-ER will be applied to print bespoke artificial organs, including artificial blood vessels, which will be possibly used for both surgery trainings and actual surgery. The SWIM-ER can print one of the world strongest gels, called Double-Network (DN) gels, by using UV irradiation through an optical fiber. Now we also are developing another type of 3D gel printer for foods, named E-Chef. We believe these new 3D gel printers will broaden the applications of soft-matter gels.

9434-31, Session 7

The effects of width reduction on cantilever type piezoelectric energy harvesters

Jongbeom Im, Lindong Zhai, Inha Univ. (Korea, Republic of); Jedol Dayou, Univ. Malaysia Sabah (Malaysia); Jeongwoong Kim, Jaehwan Kim, Inha Univ. (Korea, Republic of)

In this paper, energy harvesting capability is examined by changing the width of cantilever beam and piezoelectric cellulose. The hypothesis is that if cantilever piezoelectric energy harvester with given width are split, it would increase power output due to the fact that the divided pieces have smaller damping ratio than the original single piece, in turn, they are supposed to vibrate with high amplitude at resonance frequency.

In the experiment, the cantilever piezoelectric energy harvester was used. The harvester was made from regenerated cellulose coated with aluminum that attached to aluminum beam as host structure. The total width of the beam is 5cm, and sets of Piezo Papers with different width and number of beams are made as, 5cm x 1, 2.5cm x 2, 1.66cm x 3, 1.25cm x 4, 1cm x 5 and 0.83cm x 6 beams. The cantilever beams are vibrated on a shaker at its resonance frequency and examined their electrical characteristics in terms of output voltage and current. The results are compared with the original beam of 5 cm wide.

9434-32, Session 7

Effect of microneedle shape on pumping phenomenon in micropumps

Vijay Kumar Gupta, Rakesh Kumar Haldkar, Tanuja Sheorey, PDPM IITDM Jabalpur (India)

In the recent years, micropumps have been investigated by researchers for drug delivery and diagnosis of diseases. Piezoelectric and silicon based micro pumps are more popular as compared to other materials being explored for micro pump. Main aim for the development of micro pump is to painlessly insert microneedle in the body and collect blood sample for investigations.

Microneedle provides an interface between the drug reservoir and the patient's body for extracting the blood for investigation. Blood collected in the pump chamber pass through the biosensor and gives required investigation report.

Shape of the microneedle may affect the pain, insertion force and flow of blood. In this paper we focus on the various shapes of the needles like circular, pentagonal, hexagonal, octagonal, etc. and its effect on the flow properties of the blood. Variation of the velocity and pressure due to change in the shape will be investigated. For the purpose of investigation, piezoelectric based micropump as developed by Tsuchiya, et al. in 2005 is considered. 3-D finite element Simulation will be carried out in Ansys 14.0®.

Pumping action will be carried out by using piezo based bimorph actuator. This study will help in the development of microneedle for the micropump.

Reference:

1. Kazuyoshi Tsuchiya, Naoyuki nakanishi and Eiji nakamachi, 2005, "Development of Blood Extraction System for Health Monitoring System", Biomedical Microdevices, Vol 7(4), pp 347-353.

9434-33, Session 7

Array vibrotactile actuator made with cellulose acetate for flight simulator

Hyun-U Ko, Hyunchan Kim, Abdullahil Kafy, Inha Univ. (Korea, Republic of); Sang-Youn Kim, Korea Univ. of

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Technology and Education (Korea, Republic of); Jaehwan Kim, Inha Univ. (Korea, Republic of)

An array vibrotactile actuator to realize texture of button for virtual flight simulator is fabricated by using cellulose acetate (CA) film. The haptic actuator has independent 3 × 3 cells for identical vibration. To fit within a constrained size, 15 × 15 mm², a microfabrication process is adopted along with micro molding. Each cell consists of a top side CA layer and a bottom side CA layer supported with two pillars. An electrode is deposited on the top with silver nanowire spray-coating and the bottom side is attached to a flexible printed circuit board on which an electrode is specified. By applying electric fields across two electrodes, the top side CA layer vibrates and can produce vibrotactile motion. The vibrotactile motion will be investigated in terms of actuation frequency and acceleration with and without added mass on the top side CA layer. The acceleration performance will also be verified with the known vibrotactile threshold on a wide frequency band from 100 Hz to 400 Hz.

9434-34, Session 8

Mechanoluminescent torque transducer integrated with cost-effective luminescent sensor and UV LEDs

Gi-Woo Kim, Ji-Sik Kim, Jong-Hwan Jun, Min-Young Cho, Kyungpook National Univ. (Korea, Republic of)

This paper presents a preliminary study investigating the development of a new type of non-contacting torque sensor based on the mechanoluminescence (ML) of microparticles, such as SrAl₂O₄:Eu²⁺, Dy³⁺ (SAO), and ZnS:Cu. Typically, applications of ML microparticles have been used in a stress sensor applications successfully, in which these particles are applied to real-time visualization of the stress distribution of cracks, impacts, and ML light source generation. Kim et al. expanded their potentials of ML microparticles by successfully measuring the sinusoidal torque applied to a rotational shaft through the measurement of the ML intensity signature using a photomultiplier tube (PMT) sensor, which can be widely used in various industrial areas such as automobiles, robotics, rotors, and turbines. To enhance their potential, a cost-effective luminescent sensor and UV diode are integrated, and used for detecting the variation of ML intensity in this study. In addition, precision sinusoidal torque waveform with high frequency up to 20 Hz is used to investigate the hysteresis phenomenon.

9434-35, Session 8

Synthesis of hybrid cellulose nanocomposite bonded with dopamine-SiO₂/TiO₂ and its antimicrobial activity

Siva Ramesh, Jaehwan Kim, Joo-Hyung Kim, Inha Univ. (Korea, Republic of)

Organic-inorganic hybrid nanoparticles were synthesized by the sol-gel approach has rapidly become a fascinating new area of research in the materials science. The explosion of activity in this area in the past decade has made tremendous progress in industry and academic both fundamental understanding of sol-gel process and applications of new functionalized hybrid materials. In this present research work focused on cellulose-dopamine functionalized SiO₂/TiO₂ hybrid nanocomposites by sol-gel process. The cellulose-dopamine hybrid nanocomposites were synthesized via γ-aminopropyl triethoxy silane (γ-APTES) coupling agents by in situ sol-gel process. The chemical structure of cellulose-amine functionalized dopamine bonding and covalent crosslinking hybrids were confirmed by FTIR spectral analysis. The cellulose-dopamine nano SiO₂/TiO₂ hybrid nanocomposites materials were characterized by FTIR, XRD, UV-visible, SEM and TEM morphological analysis. From this different analysis results indicate that optical transparency, thermal stability, control morphology of cellulose-dopamine-SiO₂/TiO₂ hybrid nanocomposites. Therefore, the

cellulose-dopamine-SiO₂/TiO₂ hybrid nanocomposites were tested against pathogenic bacteria's for antimicrobial properties.

9434-36, Session 8

Synthesis and characterization of iron oxide-cellulose nanocomposite and its anti-microbial test

Seongcheol Mun, Mithilesh Yadav, Joo-Hyung Kim, Jaehwan Kim, Inha Univ. (Korea, Republic of)

Iron oxide/cellulose high-performance nanocomposite film is successfully synthesized by impregnation of iron oxide nanoparticles into a regenerated cellulose film. The structure, thermal stability and mechanical properties of the nanocomposite films are investigated by the wide-angle X-ray diffraction, Fourier transform infrared spectroscopy, scanning electron microscopy, thermogravimetric analysis, and mechanical pull test. The investigation results reveal that the iron oxide is bound to hydroxyl groups of the regenerated cellulose film by hydrogen bonding. Compared with the regenerated cellulose, the tensile strength, and elastic modulus of iron oxide/cellulose high-performance films are significantly improved by about 39% and 57%, respectively.

9434-37, Session 8

Towards rhombohedral SiGe epitaxy on 150mm c-plane sapphire substrates

Adam J. Duzik, National Institute of Aerospace (United States); Sang H. Choi, NASA Langley Research Ctr. (United States); Yeonjoon Park, National Institute of Aerospace (United States); Glen C. King, NASA Langley Research Ctr. (United States)

Previous work demonstrated for the first time the ability to epitaxially grow uniform single crystal diamond cubic SiGe (111) films on trigonal sapphire (0001) substrates. While SiGe (111) forms two possible crystallographic twins on sapphire (0001), films consisting primarily of one twin were produced up to 99.95% of the total wafer area. This permits new bandgap engineering possibilities and improved group IV based devices, primarily to exploit the higher carrier mobility in Ge over Si. Models are proposed on the epitaxy of such dissimilar crystal structures based on the energetic favorability of crystallographic twins and surface reconstructions.

This new method permits Ge (111) on sapphire (0001) epitaxy, rendering Ge an economically feasible replacement for Si in some applications, including higher efficiency Si/Ge/Si quantum well solar cells. Epitaxial SiGe films on sapphire showed a 280% increase in electron mobility and a 500% increase in hole mobility over single crystal Si. Moreover, Ge possesses a wider bandgap for solar spectrum conversion than Si, while the transparent sapphire substrate permits an inverted device structure, increasing the total efficiency to an estimated 30-40%, much higher than traditional Si solar cells. Hall Effect mobility measurements of the Ge layer in the Si/Ge/Si quantum well structure are performed to demonstrate the advantage in carrier mobility over a pure Si solar cell. Another application comes in the use of MEMs technology, where high-resistivity Si is currently used as a substrate. Sapphire is a more resistive substrate and offers better performance over the current Si-based technology.

9434-38, Session 8

Bismuth-induced surface structure and morphology in III-V semiconductors

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Bi is the largest group V element and has a number of advantages in III-V semiconductor properties, such as bandgap reduction, spin-orbit coupling, a preserved electron mobility over III-V-N materials, and nearly ideal surfactant properties resulting in a surface smoothing effect on GaAs. However, the

mechanism for this behavior is not well understood. Insight on the mechanism is obtained through study of the Bi-terminated GaAs surface morphology and atomic reconstructions produced via molecular beam epitaxy (MBE). Experimental scanning tunneling microscopy (STM) characterization of the Bi/GaAs surface reveal disordered (1x3), (2x3), and (4x3) reconstructions, often sharing the same reflective high-energy electron diffraction (RHEED) patterns. Roughness on the micron length scale decreases as the step widens, attributed to the concurrent increase of opposite direction step edges on the nanometer length scale. Corresponding cluster expansion, density functional theory (DFT), and Monte Carlo simulations all point to the stability of the disordered (4x3) reconstruction at finite temperature as observed in experimental STM.

The effects of incorporated Bi are determined through epitaxial GaSbBi growth on GaSb with various Ga:Sb:Bi flux ratios. Biphasic surface droplets are observed with sub-droplets, facets, and substrate etching. Despite the rough growth front, X-ray diffraction (XRD) and Rutherford backscatter (RBS) measurements show significant Bi incorporation of up to 12% into GaSb, along with a concurrent increase of background As concentration. This is attributed to a strain auto-compensation effect. Bi incorporation of up to 10% is observed for the highest Bi fluxes while maintaining low surface droplet density.

Conference 9435: Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems

Monday - Thursday 9 -12 March 2015

Part of Proceedings of SPIE Vol. 9435 Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2015

9435-1, Session Key

New trends in non-destructive assessment of aerospace structures (*Keynote Presentation*)

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The scope of the paper includes non-destructive assessment of the structure's material condition, for the aerospace structures during its useful lifetime. The paper presents multidisciplinary technologies devoted to development and implementation of methods and systems that realize inspection and damage detection by non-destructive methods.

The paper covers several disciplines which are based on topics such as piezoelectric transducers, elastic waves propagation phenomenon, structural vibrations analysis, phased array techniques, electro-mechanical impedance method, terahertz technique, laser induced fluorescence and 3D laser vibrometry applications.

Among various techniques available the paper presents selected numerical simulations and experimental validations of considered structures. Authors address also the problem of adhesive bonding in the case of CFRP. Techniques for detection of weak bonds are presented together with signal processing approaches. The reported investigations concern weak adhesive bonds caused by both manufacturing (e.g. release agent, poor curing) and in-service contaminations (e.g. moisture). Also the paper provides helpful information about dispersion, mode conversion, thermo-mechanical processes and wave scattering from stiffeners and boundaries. It addresses the problem of optimisation of excitation signal parameters and sensor placement, as well as analysis of signals reflected from damage. It also includes a variety of techniques being related to diagnostics (damage size estimation and damage type recognition) and prognostics.

9435-2, Session Key

Computational service infrastructure for structural health monitoring (*Keynote Presentation*)

Kincho H. Law, Stanford Univ. (United States)

No Abstract Available

9435-3, Session 1

New insights into vibration-based energy harvesting

Hui Zhang, Univ. of Hawai'i at Manoa (United States); David T. Ma, Univ. of Hawai'i (United States); Ning-shou Xu, Univ of Hawai'i at Manoa (United States)

Because of the relatively narrow bandwidth of the linear approaches, using nonlinear oscillators to harvest energy from ambient vibrations has been

a primary trend in this field. Frequency response, which has been used extensively in evaluating linear approaches, has been used as the primary metrics for nonlinear harvesters. Existing results have demonstrated that nonlinear devices may offer "broadband" performance. However, such "broadband" performance can only be obtained from a single-frequency excitation. It does not represent satisfactory performance of such devices under multi-frequency excitations due to the inapplicability of the principle of superposition. Conversely, existing nonlinear devices may perform even worse than their linear counterparts for excitations with multiple dominant frequencies. This paper provides some new insights into the potential of using nonlinear systems to harvest energy from vibrations with multiple frequencies. A previous study has shown that a nonlinear harvester can achieve its maximum performance only at the so-called global resonance condition under which the excitation matches the response. Through the global resonance mechanism, the energy can be dissipated and compensated in multiple frequencies with the maximum efficiency. Moreover, the response is the same as an undisturbed response determined by the potential well. The undisturbed response of a nonlinear system contains not only the fundamental harmonics but also higher-order harmonics. Results suggest that due to theoretical limitations on the frequencies of a potential well, the commonly adopted concept of nonlinear design based on bandwidth is unlikely to be successful. A new device design concept, based on the matching between the potential well of the device and the characteristics of the excitation, is proposed in this study. Numerical results are included to demonstrate the effectiveness of the proposed method. In this study, focus is placed on periodic response; chaos and response under random excitations are not considered.

9435-4, Session 1

A frequency study of a clamped-clamped pipe immersed in a viscous fluid conveying internal steady flow for use in energy harvester development as applied to hydrocarbon production wells

Eric J. Kjolsing, Michael D. Todd, Univ. of California, San Diego (United States)

Hydrocarbon extraction companies are seeking novel methods to generate and store power in down hole applications. Specifically, a robust energy harvesting system, capable of withstanding the harsh environmental and operational demands at the bottom of production wells, is desired to power commercially available well monitoring devices. The wide variety of well configurations makes this a challenging problem. Although some variables relating to the production tube are well defined by American Petroleum Institute standards, other variables may vary widely and be time dependent, such as annulus fluid properties. A first order task, then, is to characterize and understand the dynamics of a well through a study of changes in natural frequency over the broad range of inputs possessing moderate to high uncertainty.

This paper presents the results of an analytical frequency study which illustrates the effect of a select set of variables on the dynamics of a producing well. Specifically, axial force effects, fluid flow effects, and hydrodynamic effects, by means of a hydrodynamic function, are investigated. Due to the nature of the hydrodynamic function, the model is derived in the frequency domain and solved using the spectral element method. A method for calculating the displacement time-history of the structural system under an external forcing is also given.

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9435-5, Session 1
Design, modelling, and road rest of speed bump energy harvester

Lei Zuo, Virginia Polytechnic Institute and State Univ. (United States); Lirong Wang, Stony Brook Univ. (United States); Prakhar Todaria, Virginia Polytechnic Institute and State Univ. (United States); Abhishek Pandey, Stony Brook Univ. (United States)

This paper presents a new energy harvester structure to generate energy from vibration of on-road speed bumps. This energy harvester comprises of transmission mechanism, including a rack & pinion arrangement with a shaft engaged through a roller clutch to provide a unidirectional motion. The harvester is mounted on a base plate and is attached to a speed bump cover by springs and linear bearing. Whenever a vehicle passes through the speed bump and the bump cover creates a stroke, which in turn rotates the shaft connected to the generator and generates output electrical power. Electrical generation takes place twice when a vehicle passes by the speed bump. First when the front wheel crosses the bump, and the second time is when the rear wheel of the vehicle passes by the bump after the speed bump cover regains its position from the first shock of the front wheel. This design has much more electrical output power efficiency and less mechanical transmission dissipation. The designed on-road test revealed that this kind of harvester can generate electricity up to 500 Watts, which is expected to provide sufficient electricity for remote facilities on the road. The proposed harvester is compact in size and can conveniently be installed under the speed bump cover without affecting the basic function of speed bump. The prototyped harvester is supposed to be installed at the entrance of the administration building parking lot at the State University of New York at Stony Brook. More on real-road test will be conducted to bring to light much more promising application of the proposed energy harvester.

9435-6, Session 1
Fluid flow nozzle energy harvesters

Stewart Sherrit, Hyeong Jae Lee, Phil E. Walkemeyer, Jet Propulsion Lab. (United States); Luis Phillipe Tosi, Tim Colonius, California Institute of Technology (United States)

Power generation schemes that could be used downhole in an oil well to produce about 1 Watt average power with long-life (decades) are actively being developed. A variety of proposed energy harvesting schemes could be used to extract energy from this environment but each of these has their own limitations that limit their practical use. Since vibrating piezoelectric structures are solid state and can be driven below their fatigue limit, harvesters based on these structures are capable of operating for very long lifetimes (decades); thereby, possibly overcoming a principle limitation of existing technology based on rotating turbo-machinery. An initial survey [1] identified that spline nozzle configurations can be used to excite a vibrating piezoelectric structure in such a way as to convert the abundant flow energy into useful amounts of electrical power. This paper presents current flow energy harvesting designs and experimental results of specific spline nozzle/ bimorph design configurations which have generated suitable power per nozzle at or above well production analogous flow rates. Theoretical models for non-dimensional analysis and constitutive electromechanical model are also presented in this paper to optimize the flow harvesting system.

9435-7, Session 1
Energy harvesting of two cantilever beams structure: interfacing circuit discussion

Yu-Yin Chen, National Taiwan Univ. (Taiwan) and Ecole Normale Supérieure de Cachan (France); Dejan Vasic,

Ecole Normale Supérieure de Cachan (France)

Energy harvesting from ambient to provide the low power consumption device is highly focused and by using a cantilever beam to be the host structure converted the vibration energy is the most popular topics. In the past researches, the theoretical analysis and interfacing circuit design of single cantilever beam structure is highly developed. In this study, the electrical interfacing circuit of the piezoelectric two cantilever beams energy harvester is proposed and discussed. The nonlinear synchronized switching technique SSHI (synchronized switching harvesting in Inductor) is examined to increase the power efficiency effectively in the piezoelectric energy harvester. In the two, multiple cantilever beam or flag structure application, the structure may be composed of many piezoelectric patches with different voltages (amplitude and phase) and the interfacing circuit becomes more complicated and important. From the theoretical analysis and the governing equation, the equivalent circuit of the two cantilever beam will be proposed and simulated with the multi-SSHI nonlinear technique to optimal the interfacing circuit, decrease the number of components and increase the power efficiency by using the Matlab and PSIM software. The experiments will also show the good agreement with the theoretical analysis. The interfacing circuit design concept in the two cantilever beams structure can be further used in the multi-piezoelectric patches energy harvesting system such as piezoelectric flag to optimize the circuit and increase the power efficiency.

9435-8, Session 2
Mitigating the effects of variable speed on drive-by infrastructure monitoring

Andrew Thorsen, George H. Lederman, Carnegie Mellon Univ. (United States); Yoshinobu Oshima, Kyoto Univ. (Japan); Jacobo Bielak, Hae Young Noh, Carnegie Mellon Univ. (United States)

Drive-by inspection of infrastructure has the potential to be an efficient approach to monitor roads, rails and bridges, by indirectly collecting dynamic data from accelerometers mounted on the vehicle. Numerous studies have shown the potential of the "indirect" method using simulations, laboratory tests, and controlled field experiments. However, the vast majority of this work has assumed the vehicle travels at a constant speed or that the speed profile is identical each pass over the asset of interest. Ultimately, this technique will be most practical if data can be collected from vehicles as they perform their normal travel (e.g., buses or trains in revenue service, police vehicles on patrol, crowd sourcing from regular cars). However, the speed profile of these vehicles at a given location is rarely the same at different passes in time. To detect changes in the infrastructure, signals of interest from different crossings must be normalized before comparison, and then features independent of speed must be selected. To study this problem we have conducted a series of laboratory tests where a vehicle crosses over a bridge structure on a set of rails with a random speed profile varying between 0.4 m/s and 1m/s. We show that to detect changes in a bridge structure, frequency-based features are best, whereas to detect changes in the rails, time-based features are best.

9435-9, Session 2
Intelligent tires for identifying coefficient of friction of tire/road contact surfaces

Ryosuke Matsuzaki, Kazuto Kamai, Tokyo Univ. of Science (Japan); Akira Todoroki, Tokyo Institute of Technology (Japan)

Intelligent tires equipped with sensors as well as the monitoring of the tire/road contact conditions are in demand for improving vehicle control and safety. With the aim of identifying the coefficient of friction of tire/road contact surfaces during driving, including during cornering, we develop an identification scheme for the coefficient of friction that involves estimation

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of the slip angle and applied force by using a single lightweight three-axis accelerometer attached on the inner surface of the tire. To validate the developed scheme, we conduct tire-rolling tests using an accelerometer-equipped tire with various slip angles on various types of road surfaces, including dry and wet surfaces. The results of these tests confirm that the estimated slip angle and applied force are reasonable. Furthermore, the identified coefficient of friction by the developed scheme agreed with that measured by standardized tests.

9435-10, Session 2

Recovering bridge deflections from collocated acceleration and strain measurements

Michael S. Bell, Univ. of Hawaii at Manoa (United States);
David T. Ma, Univ. of Hawai'i (United States)

In this research, an internal model based method is proposed to estimate the displacement profile of a bridge subjected to a moving traffic load using a combination of acceleration and strain measurements. Coupling these two measurements together bypasses the issue of time lapse convergence that is encountered when only using acceleration measurements in real-time bridge applications. The deflection profile is assumed to be dominated by the fundamental mode of the bridge, therefore only requiring knowledge of the first mode. The structural response is assumed to be within the linear range for the duration of the loading process. Using the structural modal parameters and partial knowledge of the moving vehicle load, the internal models of the structure and the moving load can be respectively established, which can be used to form an autonomous state-space representation of the system. The structural displacements, velocities, and accelerations are the states of such a system, and it is fully observable when the measured output contains structural accelerations and strains. Reliable estimates of structural displacements are obtained using the standard Kalman filtering technique on the individual autonomous systems. The effectiveness and robustness of the proposed method has been demonstrated and evaluated via numerical simulation of a simply supported single span concrete bridge subjected to a moving traffic load.

9435-11, Session 2

Analysis of traffic-induced vibration and damage detection by blind source separation with application to bridge monitoring

Sheng-Fu Chen, National Taiwan Univ. (Taiwan); Tzu-Yun Hung, National Taiwan Univ (Taiwan); Chin-Hsiung Loh, National Taiwan Univ. (Taiwan)

Signal-based techniques have shown sufficient promise in extracting damage information from measured structural response data. However, reliable damage identification algorithm remains a challenge when response measurement influenced by noise, which is induced by the harsh operating environment of structures. Recently, blind source separation (BSS) has emerged as a new unsupervised signal processing tool, and has been studied in output-only modal identification. In this study, two particular BSS techniques called Second-Order Blind Identification (SOBI) and Blind Modal Identification (BMID) are considered for the purpose of damage detection in a structural system. Two examples are used to verify the effectiveness of the proposed BSS for system identification and damage detection: one is the monitoring of a traffic-induced vibration of bridge and the other is the damage of a 6-story steel frame. For illustration, first, the SOBI algorithm is used to separate bridge vibration induced by traffic from the vibration induced by other sources. Second, the SOBI is applied to study the change in the dynamic behavior of the bridge structural system. For damage detection of frame structure, experimental studies are conducted, where damage is modeled by the abrupt stiffness change in the structural member.

The BMID technique has also been proven to be a robust and suitable with damage detection.

9435-12, Session 2

A multiresolution signal processing method for extracting frequencies of interest from the interaction of a vehicle-bridge system

Zihao Wang, Jacobo Bielak, Hae Young Noh, Carnegie Mellon Univ. (United States)

Frequencies of interest of the vehicle-bridge system, which can be considered as dominant indicators of bridge conditions, are crucial to detecting damages for bridge indirect Structural Health Monitoring (SHM). As a coupled system, the frequency spectrum of the vibration responses is significantly affected by the interactions between the vehicle and the bridge. A multiresolution signal processing method is used in this paper for extracting frequencies of interest for the indirect SHM approach. The multiresolution method can analyze the constitutions of a signal in both time and frequency domains simultaneously. The signal obtained is decomposed into a number of subsignals with automated time and frequency boundaries. This process focuses on locating frequencies of interest under each time frame by searching for the frequencies whose magnitudes are above a threshold. The threshold values are selected by cross-validations. To verify the feasibility of this method, it is tested on a set of synthetic signals to compare the extracted frequencies with the dominant frequencies artificially defined. It is then tested on laboratory data for binary classifications under different "damage" conditions simulated by adding different mass levels on a laboratory bridge model. The signals are acquired from sensors installed on a vehicle passing the bridge, of which a mass is put on the mid-span, to record the dynamic response of the system. The result shows that the extracted frequencies are very close to the dominant frequencies of synthetic data, and the classification accuracy is high for the laboratory data. These results illustrate that the method provides a valid procedure for extracting frequencies of interest for the vehicle-bridge system for indirect SHM.

9435-13, Session 3

Real-time spatial sensing using a portable electrical impedance tomography data acquisition system

Shieh-Kung Huang, National Taiwan Univ. (Taiwan);
Kenneth J. Loh, Univ. of California, Davis (United States)

The main goal of this study was to develop and validate the performance of a miniature, portable, data acquisition (DAQ) system designed for interrogating carbon nanotube (CNT)-based sensing skins for real-time spatial structural sensing and damage detection. Previous research demonstrated that CNT-based sensing skins coupled with an electrical impedance tomography (EIT) algorithm enabled the detection and localization of damage occurring in an area covered by the artificial sensing skin. The sensing skin's electrical properties were pre-calibrated to different levels of damage; for instance, its resistance was linearly correlated with strain. Instead of manually probing every location of the skin, multiple sets of current injections and corresponding voltage measurements at the skin's boundaries were used for solving EIT and to back-calculate the skin's spatial resistivity (or strain) distribution. It was shown that damage such as deformation, impact, cracks, and drilled holes could be detected. However, one of the main limitations was the large amount of time required for data acquisition, which was largely limited by the existing hardware used. In order to facilitate the adoption of this technology and for field implementation purposes, a miniature DAQ that could interrogate these CNT-based sensing skins was designed and fabricated. The prototype DAQ featured a Howland current source that could generate stable and controlled

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direct current. Measurement of boundary electrode voltages and the switching of the input, output, and measurement channels were achieved using multiplexer units. The entire DAQ was fabricated on a two-layer printed circuit board, and it was designed for integration with a prototype wireless sensing system, which is the next phase of this research.

9435-130, Session 3

Structural damage detection via impediographic tomography

Liuxian Zhao, Jie Yang, Univ. of Notre Dame (United States); Kon-Well Wang, Univ. of Michigan (United States); Fabio Semperlotti, Univ. of Notre Dame (United States)

We investigate the use of impediographic tomographic to achieve high sensitivity and high resolution damage identification in metallic structures. The impediographic approach exploits the coupled piezo-resistive and electrostatic response of the host structure to generate high sensitivity and high resolution maps of its internal electrical conductivity. Focused acoustic waves are used to generate localized electrical conductivity perturbations that allow drastic improvement in the conditioning of the inverse problem by enriching the dataset of input data used for the inverse reconstruction problem. The localized acoustic perturbation is obtained by exploiting the concept of Frequency Selective Structures (FSS) in which intentional mistuning of periodically distributed structural features (e.g. thin notches) enables self-focusing and vibration localization by using a single ultrasonic transducer.

In this paper, we present a numerical study investigating the performance of impediography as damage identification approach for metallic structures. After briefly reviewing the concept of FSS, the impediographic approach is presented together with two possible approaches for the solution of the inverse problem: the 0-Laplacian and the Levenberg-Marquardt methods. The methodologies are compared both in terms of accuracy of the reconstructed electrical conductivity maps and of their ability to deal with important practical issues such as "limited view" and "limited perturbation" data. Numerical results show that, although both approaches perform well in terms of damage identification, localization, and sizing, the LM technique is more flexible and able to handle imperfect data. Results support the conclusion that the FSS-based impediography provides a viable and effective way for high resolution damage identification.

9435-15, Session 4

Sensing sheets based on large area electronics for fatigue crack detection

Yao Yao, Branko Glisic, Princeton Univ. (United States)

Reliable early-stage damage detection requires continuous structural health monitoring (SHM) over large areas of structure, and with high spatial resolution of sensors. This paper presents a stage in development of a prototype of strain sensing sheets based on Large Area Electronics (LAE), in which foil strain gauges are integrated on the flexible substrate that can cover large areas. These sensing sheets were applied for fatigue crack detection on small-scale steel plates. Two types of sensing-sheet interconnections were designed and manufactured, and dense arrays of strain sensors were assembled onto the interconnections. In total, four strain sensing sheets were created and tested, two for each design type. The sensing sheets were bonded to small-scale steel plates, which had a notch on the boundary so that fatigue cracks could be generated under cyclic loading. The fatigue tests were carried out at the Carleton Laboratory in Columbia University, and the steel plates were attached through a fixture to the loading machine that applied cyclic fatigue load. Fatigue cracks then occurred and propagated across the steel plates. The strain sensors that were close to the notch successfully detected the initialization of fatigue crack and localized the damage on the plate. The strain sensors that was away from the crack successfully detected the propagation of fatigue crack based on the time history of measured strain. The sensing

sheets successfully detected and localized the cracks, and the results of the tests validated the general principles of the strain sensing sheets for crack detection.

9435-16, Session 4

Characterization of patterned nanoengineered sensing skins for applications in structural sensing

Andrew R. Burton, Jerome P. Lynch, Univ. of Michigan (United States)

America's infrastructure is in need of greater structural performance characterization. The characterization of structural systems has become increasingly important as greater expectations in longevity and material performance are levied on America's infrastructure across various disciplines. Simultaneously, a number of technologies are emerging in material science and sensor fabrication that could potentially equip future engineers with the information necessary to ensure structural safety and functionality. Among these technologies are the ability to nanoengineer sensing materials and fabricate thin film sensors utilizing processes common to microelectromechanical systems (MEMS). Such technologies have shown considerable promise in expanding sensing capabilities past the current state of point sensing, allowing for spatial damage detection that is of critical value in numerous structural systems where failure occurs at the component-level. However, challenges in instrumentation and signal processing remain as barriers to wide-spread use of such technologies. Here we couple the functionalities of carbon-nanotube thin film composites with MEMS patterning fabrication technologies to present a component-level spatial strain sensor that can be tailored to specific structural geometries. These sensors are fabricated on a thin, flexible polyimide substrate through a layer-by-layer deposition process and patterned with optical lithography. The sensors are then instrumented with electroplated copper electrodes and on-film reference resistors to complete the thin film sensing system. We investigate the impedance properties and strain sensitivities of these thin films as patterned with a variety of pattern widths, lengths, and film thicknesses. Example spatial strain sensors are then fabricated and instrumented on structural components to complete the illustration of such technologies in structural performance monitoring applications. The results are discussed in relation to the potential for such patterned films as circuit components and the utilization of these technologies in structural sensing.

9435-17, Session 4

Peridynamics for wave propagation modelling in graphene nanoribbons

Adam Martowicz, Wieslaw J. Staszewski, AGH Univ. of Science and Technology (Poland); Massimo Ruzzene, Georgia Institute of Technology (United States); Tadeusz Uhl, AGH Univ. of Science and Technology (Poland)

The work is devoted to the study on elastic wave propagation in graphene nanoribbons, performed with peridynamics. Graphene nanoribbons have recently gained dramatic increase of interest in the fields of nanoelectronics and nanoelectromechanical systems. They can play a key role as either modern metallic or semiconductor materials, depending on the edge structure, with zigzag or armchair layout, respectively. Moreover, graphene opens new perspectives for the millimeter wave-based measurements systems.

The authors present a peridynamic model used to analyze the dynamic behavior of a graphene nanoribbon. The model is considered as a periodic structure, i.e. an assembly of fundamental structural elements undergoing propagation of acoustic wave. The auxiliary atomistic-continuum models are used to find equivalent elastic properties, finally applied for the peridynamic model. It is assumed, that the solutions for molecular dynamics, as well as the physical nature of the reactions at the atomic scale, may be effectively

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recovered by peridynamics, as already reported in the literature.

The peridynamic model of the graphene nanoribbon results from upscaling process carried for a small-scale atomic model. The material properties are homogenized over studied domain and the dispersion curves are analyzed. Nonlocality in peridynamics allows to preserve the lengthscale effect, local small-scale inhomogeneity and wave dispersion. The effect of spatial discretization at nano scale, arising from the distribution of atoms of carbon in the structure of graphene, may be represented with a coarse nonlocal macro model. Moreover, an integral-based formulation of the equation of motion in peridynamics eliminates assumptions on smoothness regarding the displacement field.

9435-18, Session 4

Design and fabrication of mechanochromic photonic crystals as strain sensor

Andrea Chiappini, Consiglio Nazionale Delle Ricerche (Italy) and Univ. degli Studi di Trento (Italy); Anna K. Piotrowska, Univ. degli Studi di Trento (Italy) and Univ. degli Studi di Trento (Italy); Marian Marciniak, National Institute of Telecommunications (Poland); Maurizio Ferrari, CNR-Istituto di Fotonica e Nanotecnologie (Italy) and Univ. degli Studi di Trento (Italy); Daniele Zonta, Univ. degli Studi di Trento (Italy) and Univ. degli Studi di Trento (Italy)

Colorimetric sensing, which transduces environmental changes into visible color changes, provides a simple yet powerful detection mechanism that is well-suited to the development of low-cost and low-power sensors. A new approach in colorimetric sensing exploits the structural color of photonic crystals (PCs) to create external stimuli sensitive materials. PCs are artificially created periodic structures, usually produced in the form of thin film, where optical properties are tailored by a periodicity in the refractive index. The idea of using the crystal as sensor is based on the observation that a distortion in the photonic crystal structure produces a change in the reflected wavelength. This feature makes photonic crystals suitable for permanent monitoring of structural elements, as any critical change in the strain field can be promptly and easily detected by visual inspection. In this contribution we report in detail the approach used for the realization of PCs, composed of closely packed colloidal particles embedded in a PDMS elastomer, and their optical and structural characterization. Finally we discuss their integration in form of strain sensor, presenting the results of a laboratory validation test. This type of PC can have potential applications for simple and convenient detection of mechanical strain.

9435-19, Session 5

Design of embedded acoustic lenses in plate-like structures based on periodic acoustic black holes

Hongfei Zhu, Fabio Semperlotti, Univ. of Notre Dame (United States)

Resonant acoustic metamaterials allows manipulating acoustic waves in ways not achievable with conventional materials. Focusing, collimation, and negative refraction are just an example of characteristics achievable via carefully engineered materials. Despite the many interesting properties, the practical application of these materials has been largely limited by their fabrication complexity. In this paper, we present a class of two-dimensional fully isotropic acoustic metamaterials that can be easily embedded in thin-walled structural elements. The new design can achieve the integration of acoustic lenses with largely reduced fabrication complexity. This class of metamaterials is based on the concept of Acoustic Black Hole (ABH) that is an element able to bend and, eventually, trap acoustic waves. Periodic lattices of ABHs enable wave propagation characteristics comparable with resonant metamaterials but without the need and the fabrication

complexities associated with the multi-material or locally resonant inclusions. Our study on the dispersion characteristics of the ABH-based material show the existence of strong mode coupling, low frequency zero group velocity points, and Dirac points at the center of the Brillouin zone. Numerical simulations conducted on a thin metal plate with an embedded slab of ABH material show the existence of a variety of wave propagation effects (such as collimation and bi-refraction) in an extended operating range that goes from the metamaterial to the short wavelength limit. An experimental investigation is also conducted to verify the numerical results. Such an engineered material can pave the way to the design of thin-walled smart-structures with advanced fully passive wave management characteristics.

9435-20, Session 5

Granular chains for the assessment of thermal stress in slender structures

Abdollah Bagheri, Emma La Malfa Ribolla, Piervincenzo Rizzo, Univ. of Pittsburgh (United States)

Slender beams subjected to compressive stress are common in civil engineering. The rapid in-situ measurement of this stress may be of interest to prevent structural anomalies. In this article, we describe the coupling mechanism between highly nonlinear solitary waves (HNSWs) propagating along an L-shaped granular system and a beam in contact with the granular medium. We evaluate the use of HNSWs as a tool to measure stress in thermally loaded structures and to estimate the neutral temperature, i.e. the temperature at which this stress is null. We investigated numerically and experimentally one and two curved chains of spherical particles in contact with a prismatic beam subjected to heat. We found that certain features of the solitary waves are affected by the beam's stress. In the future these findings may be used to develop a novel sensing system for the nondestructive prediction of neutral temperature and thermal buckling.

9435-21, Session 5

Frequency-wavenumber design of spiral micro fiber composite directional actuators

Matteo Carrara, Massimo Ruzzene, Georgia Institute of Technology (United States)

This paper reports on the design and testing of a novel class of transducers for Structural Health Monitoring (SHM), which is able to perform directional interrogation of plate-like structures. The transducer leverages guided waves (GWs), and in particular Lamb waves, that in recent years have emerged as a very prominent option for assessing the state of a structure during operation. GW-SHM approaches greatly benefit from the use of transducers with controllable directional characteristics, so that selective scanning of a surface can be performed to locate damage, impacts, or cracks. In the concepts that we propose, continuous beam steering and directional actuation are achieved through proper selection of the excitation frequency. The design procedure takes advantage of the wavenumber representation of the device, and formulates the problem using a Fourier-based approach. The active layer of the transducer is made of piezoelectric fibers embedded into an epoxy matrix, allowing the device to be flexible, and thus suitable for application on non-flat surfaces. Proper shaping of the electrodes pattern through a compensation function allows taking into account the anisotropy level introduced by the active layer. The resulting spiral frequency steerable acoustic actuator is a configuration that allows for smart patterning of the transducer inner shape, resulting in (i) enhanced performance, (ii) reduced complexity, and (iii) reduced hardware requirements of such devices.

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9435-22, Session 5

Modulation scheme of nonlinear waves for effective crack detection

Sang Eon Lee, Jung-Wuk Hong, KAIST (Korea, Republic of)

This study presents nonlinear ultrasonic wave modulations that can be effectively used for crack detection in thin structural components. Fatigue cracks occur when structure is exposed to repeated load although the load causes the smaller stress than the yield stress. The existence of cracks deteriorates the integrity of structures and reduces the safety. To detect these cracks, several kinds of nonlinear ultrasonic wave modulation techniques have been proposed for many years. However, the fundamental reason of the nonlinearity has not been well explained theoretically yet. Mostly, the phenomenon has been investigated experimentally. In order to find the reasons of the observed modulation, numerical studies are performed considering a variety of sizes of crack widths and depths using a commercial FEA program.

9435-23, Session 5

Thermal effect on E/M impedance spectroscopy (EMIS) of piezoelectric wafer active sensors

Tuncay Kamas, Erik L. Frankforter, Lucy (Lingyu) Yu, Bin Lin, Victor Giurgiutiu, Univ. of South Carolina (United States)

This paper presents a study with respect to theoretical predictive modeling and experimental evaluation of the structural health monitoring capability of piezoelectric wafer active sensors (PWAS) at elevated temperatures. Electro-mechanical impedance spectroscopy (EMIS) method is first qualified using circular PWAS resonators under traction-free boundary condition and in an ambience with increasing temperature. The theoretical study is conducted regarding temperature dependence of the electrical parameters, the capacitance C_0 , d_{31} and g_{31} ; and the elastic parameters, the in-plane compliance s_{11} and Young's modulus c_{11} , of piezoelectric materials. The Curie transition temperature must be well above the operating temperature; otherwise, the piezoelectric material may depolarize under combined temperature and pressure conditions. The material degradation is investigated by introducing the temperature effects on the material parameters that are obtained from experimental observations as well as from related work in literature. The preliminary results from the analytical 2-D circular PWAS-EMIS simulations are presented and validated by the experimental PWAS-EMIS measurements at elevated temperatures. . Temperature variation may produce pyro-electric charges, which may interfere with the piezoelectric effect. Therefore, another explicit analytical model is also carried out by implying the pyro-electric charge term into the piezoelectric constitutive equations to simulate again the temperature effects on a free circular PWAS-EMIS in in-plane mode. For the experimental validation, PWAS transducers are placed in a fixture that provides the traction-free boundary condition. The fixture is then located in an oven integrated with PID temperature controller. The EMIS measurement is conducted during the temperature increase and the first resonance frequency peak in admittance and impedance spectra was acquired.

9435-24, Session 6

A cloud based data management infrastructure for bridge monitoring

Seongwoon Jeong, Stanford Univ. (United States); Jaewook Byun, Daeyoung Kim, Hoon Sohn, KAIST (Korea, Republic of); Kincho Henry Law, Stanford Univ. (United States)

This paper describes the development of a cloud-based data management infrastructure framework for bridge monitoring applications. Given the unstructured data representing the information about bridge structures and the sensor time series data type, traditional structured database systems, such as relational databases, themselves are not sufficient nor appropriate for data storage. In this study, we review current research and development efforts in bridge information modelling (BrIM) and sensor data management and propose a NOSQL framework. Specifically, our work explores the use of Casandra DB and Mongo DB for prototype implementation, utilizing cloud services as the software infrastructure. The paper will provide a detailed description of the system and the prototype modeling for a bridge structure in Icheon, Korea.

9435-25, Session 6

Uncertainty calculation for modal parameters used with stochastic subspace identification: an application to a bridge structure

Wei-Ting Hsu, Chin-Hsiung Loh, National Taiwan Univ. (Taiwan); Shu-Hsien Chao, National Ctr. for Research on Earthquake Engineering (Taiwan)

Stochastic subspace identification method has proven to be an efficient algorithm for the identification of liner-time-invariant system using multivariate measurements taken from a system. Generally, the estimated modal parameters are afflicted with statistical uncertainty, e.g. undefined measurement noises, non-stationary excitation, finite number of data samples etc. Then the identified results are subjected to variance errors. Accordingly the concept of the stability diagram can help users to identify the correct model (i. e. to remove the spurious modes). Modal parameters are estimated at successive model orders where the physical modes of the system are extracted and separated from spurious modes. Besides, an uncertainty computation scheme was derived for the calculation of uncertainty bounds for modal parameters at some given model order. The uncertainty bounds of damping ratios are particularly interesting, as the estimation of damping ratios are difficult to obtain. In this paper, problems are addressed. First, the identification of modal parameters through covariance- driven stochastic subspace identification from the output-only measurements is used for discussion. A systematic way of investigation the criteria for the stability diagram is discussed. Secondly, the computation of uncertainty bounds for the estimated modes at all model order in the stability diagram is discussed. Demonstration of this study on the system identification of a three-span steel bridge under operation condition is presented. It is shown that the proposed study on new criteria for the stability diagram can enhance the computationally and memory efficient, reducing the computation burden in stochastic subspace identification.

9435-26, Session 6

Substructure location and size effects on decentralized model updating

Xinjun Dong, Dapeng Zhu, Yang Wang, Georgia Institute of Technology (United States)

To improve the simulation accuracy of the finite-element (FE) model of an as-built structure, measurement data from the actual structure can be utilized for updating the model parameters, which is termed as FE model updating. During the past few decades, most efforts on FE model updating intend to update the entire structure model altogether, while using measurement data from the entire structure. When applied on large and complex structural models, the typical approaches may fail due to computational challenges and convergence issues. In order to reduce the computational difficulty, this paper studies a decentralized FE model updating approach that intends to update a substructure at a time. The approach divides the entire structure into a substructure (currently being

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instrumented and updated) and the residual structure. The Craig-Bampton transform is adopted to condense the structural model. The optimization objective is formulated to minimize the modal dynamic residuals from the eigenvalue equations in structural dynamics involving natural frequencies and mode shapes. This paper investigates the effects of different substructure locations and sizes on updating performance. A space frame example, which is based on an actual pedestrian bridge on Georgia Tech campus, is used to study the substructure location and size effects.

9435-27, Session 6

Sequential damage detection and localization based on the continuous wavelet transform: a graphical model approach

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Detecting damages during strong motion events enables early diagnosis of the structure, utilizing a strong excitation signal. Recent work presents the statistical models of the Continuous Wavelet Transform (CWT) of acceleration response measurements before and after damage. In this paper, we present a sequential damage detection algorithm that uses wavelet coefficients as damage sensitive features (DSFs) and detects damages through Bayesian approach.

In the proposed algorithm, damage variables are assigned to potential damage locations of a structure. The acceleration response measurements collected by sensors, which are installed at different locations of the structure, are associated with one or more damage variables. The posterior distribution of the time of damage is computed by the pre- and post-damage DSF distributions and the prior distribution of the time of damage. Given the posterior distribution of the time of damage and the allowable probability of false alarm, our algorithm detects a single damage with optimal detection delay. In addition, our algorithm can be extended to detect multiple damages simultaneously. Therefore, the damage localization is achieved by declaring all damage variables or a subset of them. With the aid of the belief propagation algorithm, the damage detection and localization can be utilized by a graphical model, which reduces the computational complexity significantly and allows the algorithm to scale up linearly.

This paper intends to validate the proposed algorithm by a real experiment data set to evaluate the tradeoff between probability of false alarm and detection delay.

9435-28, Session 6

Stochastic filtering for damage identification through nonlinear structural finite element model updating

Rodrigo Astroza, Hamed Ebrahimian, Joel P. Conte, Univ. of California, San Diego (United States)

This paper describes a novel framework that combines advanced mechanics-based nonlinear (hysteretic) finite element (FE) models and stochastic filtering techniques to estimate unknown time-invariant parameters of nonlinear inelastic material models used in the FE model. Using input-output data recorded during earthquake events, the proposed framework updates the nonlinear FE model of the structure. The updated FE model can be directly used for damage identification and further used for damage prognosis. To update the unknown time-invariant parameters of the FE model, two stochastic filtering methods are used: the extended Kalman filter (EKF) and the unscented Kalman filter (UKF). A two-dimensional, 3-story, 3-bay steel moment frame is used to verify the proposed framework. The steel frame is modeled using fiber-section beam-column elements with distributed plasticity and is subjected to a suite of earthquake

ground motions of varying intensity. The results indicate that the proposed framework accurately estimate the unknown material parameters of the nonlinear FE model, provided that: (i) the loading intensity is sufficient to exercise the branches of the nonlinear hysteretic material models, which are governed by the material parameters to be identified, and (ii) the measured response quantities are sufficiently sensitive to the material parameters to be identified

9435-29, Session 6

Sampling considerations for modal analysis with damping

Jae Young Park, Univ. of Michigan (United States); Michael B. Wakin, Colorado School of Mines (United States); Anna C. Gilbert, Univ. of Michigan (United States)

Structural Health Monitoring (SHM) systems are critical for monitoring aging infrastructure (such as buildings or bridges) in a cost-effective manner. Wireless sensor networks that sample vibration data over time are particularly appealing for SHM applications due to their flexibility and low cost. However, in order to extend the battery life of wireless sensor nodes, it is essential to minimize the amount of vibration data these sensors must collect and transmit. In recent work, we have studied the performance of the Singular Value Decomposition (SVD) applied to the collection of data and provided new finite sample analysis characterizing conditions under which this simple technique—also known as the Proper Orthogonal Decomposition (POD)—can correctly estimate the mode shapes of the structure. Considering both deterministic (uniform) and random (nonuniform) time sampling, we provided theoretical guarantees on the number and duration of samples required in order to estimate a structure's mode shapes to a desired level of accuracy. In that previous work, however, we considered only simplified Multiple-Degree-Of-Freedom (MDOF) systems with no damping. In this paper we consider MDOF systems with proportional damping and show that, with sufficiently light damping, the POD can continue to provide accurate estimates of a structure's mode shapes. We support our discussion with new analytical insight and experimental demonstrations. In particular, we study the tradeoffs between the level of damping, the sampling rate and duration, and the accuracy to which the structure's mode shapes can be estimated.

9435-96, Session PTues

Some aspects of electromechanical impedance application for SHM

Vitalijs Pavelko, Riga Technical Univ. (Latvia)

First of all this paper is focused to the improvement and further development of the model of electromechanical impedance (EMI) based on the modal decomposition of the dynamic response of monitored structure with embedded PZT. It concerns the problem of optimal description of the dynamic response of full-scale structural components. It is shown that an appropriate choice of boundary conditions and the level of attenuation for EMI adequate simulation allows to select for dynamic analyses only a relatively small part of a full-scale structure. Examples of EMI simulation for an infinite strip and a frame of the helicopter tailboom. At the latter case, a comparison with test results is given.

On the other hand, the version of combined SHM system that uses the Lamb waves and EMI technologies as well as PZT using for measurement of mechanical strain. Such SHM system is effective for detecting fatigue cracks by using the effect of the crack opening under load. Continuous measurement of strain allows to control the degree of a fatigue crack opening during variable loading, and a crack detection and evaluation of its size can be implemented by comparison of the frequency and amplitude of the Lamb waves and EMI at various load levels. This eliminates many of the shortcomings of comparison with the baseline. The results of the detection of fatigue crack in the aluminum plate by mentioned method are discussed.

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9435-97, Session PTues

Low frequency seismic characterization of underground sites with tunable mechanical monolithic sensors

Fausto Acernese, Univ. degli Studi di Salerno (Italy);
Rosario De Rosa, Univ. degli Studi di Napoli Federico II (Italy);
Gerardo Giordano, Rocco Romano, Fabrizio Barone, Univ. degli Studi di Salerno (Italy)

In this paper we present the scientific data recorded by tunable mechanical monolithic seismometers located in the Gran Sasso National Laboratory of the INFN (L'Aquila, Italy) and in the former mine of Sos Enattos (Iula, Sardinia, Italy). The main goals of this long term large-band measurements are for the seismic characterization of the sites in the frequency band $10^{-6} \div 10$ Hz and the acquisition of all the relevant information for the optimization of the mechanical sensors. Since the end of 2010 and until the end of 2013 innovative prototypes of tunable monolithic seismometers (UNISA Horizontal Seismometers) were installed in the LNGS, within thermally insulating enclosures onto concrete slabs connected to the bedrock. One year later (2012) tests started on monolithic seismometer prototypes in the Sos Enattos mine, positioned in a specially designed seismic station, tests that are still in course. The main goals of these tests are both to provide preliminary global seismic characterization of the two sites in the frequency band $10^{-6} \div 10$ Hz and to obtain all the technical information on the performances of all the monolithic sensors active in the seismic stations in the very low frequency band ($10^{-6} \div 10^{-1}$ Hz), information necessary to understand how to plan sensors upgrades for more sensitive measurements and tests.

In this paper, after a short reference to the architecture of the UNISA Horizontal and Vertical Seismometer, the underground installations and the architecture of the DAQ system are described. Then, the scientific data acquired are presented and discussed, together with the expected future developments and improvements.

9435-100, Session PTues

nap environment control considering respiration rate and music tempo by using sensor agent robot

Sayaka Nakaso, Akira Mita, Keio Univ. (Japan)

We propose a system that controls a nap environment considering respiration rates and music tempo by using a sensor agent robot. The proposed system consists of two sub-systems. The first sub-system measures respiration rates using optical flow. We conducted preparatory experiments to verify the accuracy of this sub-system. The experimental results showed that this sub-system can measure the respiration rates accurately despite several positional relationships. It was also shown that the accuracy could be affected by clothes, movements and light. The second sub-system we constructed was the music play sub-system that chooses music with the certain tempo corresponding to the respiration rates measured by the first sub-system. We conducted verification experiments to verify the effectiveness of this music play sub-system. The experimental results showed the effectiveness of varying music tempo based on the respiration rates in taking a nap. We also demonstrated this system in a real environment; a subject entered into the room being followed by ebioN?. When the subject was considered sleeping, ebioN? started measuring respiration rates, controlling music based on the respiration rates. As a result, we showed that this system could be realized. As a next step, we would like to improve this system to a nap environment control system to be used in offices. To realize this, we need to update the first sub-system measuring respiration rates by removing disturbances. We also need to upgrade music play sub-system considering the numbers of tunes, the kinds of music and time to change music.

9435-101, Session PTues

Homeostasis Lighting Control based on Relationship between Lighting Environment and Human Behavior

Risa Ueda, Akira Mita, Keio Univ. (Japan)

Recently, owing to the diversification of lifestyles and elderly society, living spaces which can respond to various preferences are needed. Therefore, we propose 'Biofied Building' which is attempting to realize comfortable, safe, and energy-saving living spaces by following the adaptive functions of organisms. Every bit a favorite environment is different in each person, the purpose of Biofied Building is to realize the suitable indoor environment for each resident such as air conditioning, lighting, and sound in order to offer the comfortable living space.

The aim of this research is to propose a new lighting control system in Biofied Building. By utilizing the lighting device 'hue' which is released by Philips and can be controlled in both luminance and color, we proposed the lighting control system reflecting a personal preference in luminance and color. We consider colors including the colors out of black body locus.

As a first step, we conducted tests to derive the relationship between the preferred lighting environment and various behaviors. We set up a small room consisting of aluminum frames.

Then, based on this result, we built the lighting control system which can realize the lighting environment suitable for each resident and behavior. We examined the validity of the proposed system.

9435-102, Session PTues

Software design and implementation of ship heave motion monitoring system based on MBD method

Yan Yu, Yuhan Li, Dalian Univ. of Technology (China);
Chunwei Zhang, Won Hee Kang, The Univ. of Western Sydney (Australia);
Jinping Ou, Dalian Univ of Technology (China)

With the fast development of maritime transportation and ocean resource exploitation, more and more attention will be focused on the posture measuring and monitoring of ship and some floating offshore infrastructure systems, therefore the research on developing ship motion monitoring system has become a hot research topic. Especially, with the rapid development of MEMS based inertia sensor element, the application of Strap-down Inertial Navigation System has been founded. According to the characteristic and working theory of the MEMS based accelerometer sensor, a ship heave motion monitoring system has been preliminarily designed based on the combination of accelerometer sensor and gyroscope. The feasibility of this system has been verified on the test platform through preliminary tests. The developed system features large measuring range, high precision, miniaturization, high integration and capacity of real-time monitoring, which has shown a prospective application potential for this system.

9435-103, Session PTues

Statistical analysis of nature frequencies of hemispherical resonator gyroscope based on probability theory

Yu Xudong, Long Xingwu, Wei Guo, Li Geng, Qu Tianliang, National Univ. of Defense Technology (China)

A finite element model of the hemispherical resonator gyro (HRG) is established and the natural frequencies and vibration modes are

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investigated. The matrix perturbation technology in the random finite element method is first introduced to analyze the statistical characteristics of the natural frequencies of HRG. The influences of random material parameters and dimensional parameters on the natural frequencies are quantitatively described based on the probability theory. The statistics expressions of the random parameters are given and the influences of three key parameters on natural frequency are pointed out. These results are important for design and improvement of high accuracy HRG.

9435-104, Session PTues

Inductive wireless sensor-actuator node for structural health monitoring of fiber reinforced polymers by means of Lamb-waves

Mariugenia Salas, Friedrich Wilhelm Bessel Institute (Germany); Oliver Focke, Faserinstitut Bremen e.V. (Germany); Walter Lang, Univ. Bremen (Germany) and Friedrich Wilhelm Bessel Institut (Germany); Axel S. Herrmann, Faserinstitut Bremen e.V. (Germany) and Univ. Bremen (Germany)

Considering sensor integration this system's simplicity is of great importance. The signal is a one pulse burst generated by coils in resonance. The integration of sensor-actuators and coil antennas within the material was achieved. The Tailored-Fiber-Placement process was used for the integration of coils by sewing wire into textile. These results are considered the next stage developing a wireless SHM sensor network using PWAS and inductive coils. Due to material damping a high voltage burst is required to excite the actuator at frequencies in the range of 0 kHz to 500 kHz, where only the lowest wave modes are generated. Depending on the distance between actuator and sensor the SO and AO signal arrive at different arrival times; thus the modes can be identified. A signal of 35 V is wireless inputted to the actuator PWAS, generating up to 100 mV response from the sensors. The response is damped in the presence of a hole on the surface between sensor and actuator when comparing to the reference signal of a healthy plate. This indicates that these signals can help identify the presence of failure. Other factors like temperature change can be determined as well. In order to complete the system a high-frequency flexible coil antenna was added and tuned to 13.56 MHz while bonded on the CFRP plate by adding a thin layer of high permeability material. The sensor signal was analog carried and demodulated by a diode detector. The data was then sampled and filtered for further analysis.

9435-105, Session PTues

In-situ strain sensing with fiber optic sensors embedded into stainless steel 316

Dirk Havermann, Heriot-Watt Univ. (United Kingdom); Jinesh Mathew, Heriot-Watt Univ (United Kingdom); William N. MacPherson, Robert R. J. Maier, Duncan P. Hand, Heriot-Watt Univ. (United Kingdom)

Additive Manufacturing, which builds components layer by layer, opens up exciting possibilities to integrate sophisticated internal features and functionalities such as fiber optic sensors directly into the heart of a metal component. This can create truly smart structures for deployment in harsh environments. In our innovative and multidisciplinary research, we successfully embed fiber optics sensors with thin, protective nickel coatings (outer diameter ~350 μm) into stainless steel (SS 316) coupons by selective laser melting technology (SLM). We present in-depth studies on the mechanism by which strain changes of the metallic components are transferred into the embedded silica fibers, including issues that arise from the significantly different physical properties of the materials involved.

In our approach we manufacture SS 316 components using SLM,

incorporating U-shaped grooves with dimensions suitable to hold nickel coated optical fibers. Coated optical fibers containing fiber Bragg gratings for strain monitoring and Fabry-Perot based sensors for temperature sensing are placed in the groove. The embedding is completed by melting subsequent powder layers on top of the fibers. Cross sectional microscopy analysis of the fabricated components, together with analysis of the Bragg gratings behaviour during fabrication indicates a strong substance-to-substance bond between coated fiber and added SS 316 material. Embedded sensors follow elastic deformations to stress levels of at least half the SS 316 yield strength, with a resolution of better than 3 μ-strain. Strain monitoring in the plastic deformation regime of SS-316 can similarly be monitored. Such embedded sensors can be used to high temperatures of up to ~400 °C and research is in progress to extend this temperature range up to much higher temperatures.

9435-106, Session PTues

Innovative insulations for spacecraft on-surface monitoring system in harsh environments

Ying Huang, Fardad Azarmi, Mehdi S. Jazi, North Dakota State Univ. (United States)

The success of any space mission demands an accurate spacecraft monitoring with dependence on various sensors if possible on-surface of the spacecraft to provide critical structural health information in space. NASA has long recognized the significance to have performance monitoring for spacecraft. However, characterized by the properties of microgravity, vacuum, presence of radiation, large thermal variations, mechanical vibrations and shock resulting from the launch, space is well-known as one of the most challenging environment for any sensing system. One of the major challenges is to operate sensors in extreme harsh environments with large temperature variance, which significantly influences sensor's accuracy, reliability, and durability. In this study, innovative multilayer insulation coatings are developed to eliminate the environmental effects and ultimately adjust the sensitivity the sensors towards the parameters needed to be sensed. The developed composite insulation configures innovative metal and nonmetal layers in a single insulation. The design is guided through theoretical and numerical modeling analysis of heat transfer and thermal stress progressing. Detail theoretic, numerical, and experimental analysis proved the feasibility of the proposed multilayer structure of the insulation to work up to 700°C without inducing significant deformation on the top of sensor surface from heat. The developed multilayer composite insulation, thus, enables accurate monitoring capability for spacecraft on-surface monitoring system in harsh service environments.

9435-107, Session PTues

Liquid polyimide as a substrate for aeronautical sensor systems

Martin Schwerter, Technische Univ. Braunschweig (Germany); Lars Hecht, Technische Universität Braunschweig (Germany); Eugen Koch, Technische Univ Braunschweig (Germany); Monika Leester-Schädel, Stephanus Büttgenbach, Andreas H. Dietzel, Technische Univ. Braunschweig (Germany)

Using more and more controlled systems in future aircraft the need of flexible sensors to be applied on curved aircraft structures increases. An appropriate substrate for such flexible sensors is polyimide, which is available both as foil and liquid polyimide to be spun-on. Latest results in producing and processing of polyimide layers with a thickness of down to 1 μm including designs for thin foil sensors are presented.

The successful processing of liquid polyimide is outlined first. It includes the spin-on procedure, soft bake and curing for polymerization. Parameters

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for spin-on volume and rotation speed on glass substrates along with a comparison with ordinary polyimide foil are presented. High-precision structuring of the polyimide layer is performed either by etching (O₂ and CH₄ in barrel etcher) or physical removal using a femtosecond laser.

In combination with a layer of silicon nitride as a diffusion barrier reliable water protection can be realized. The fabrication of a protection layer and test results in water with protected sensors are presented.

The design of a hot-film sensor array made on spin-on polyimide is demonstrated. With a thickness of down to 7 μm the sensors can be applied on the surface of wind tunnel models without impacting the flow substantially. Additionally both the concept and recent results of a pressure sensor to be applied on polyimide substrate for aeronautical purpose are illustrated.

9435-108, Session PTues

Damage detection of plane frame structure based on a novel reduced model

Dongyu Zhang, Harbin Institute of Technology (China)

When conducting damage detection for frame buildings, a shear structure model is often employed. However, it was shown by many studies that a shear model does not match the dynamics of the frame structure very well due to the existence of modeling error and, thus, using a shear structure model to perform damage detection of a frame structure often leads to inaccurate damage detection results. In this paper, a structural damage detection method for frame structures is proposed using a novel reduced model for. First, a novel model reduction method for a frame structure is proposed, which converts the frame into a beam-like model with one translational and two rotational degrees-of-freedom (DOFs) for each floor. An important characteristics of the new model is that the story horizontal responses match that of the frame very well, thereby significantly reducing the modeling error. Based on this new model, an inductive substructure identification method is formulated, using the cross power spectral densities between the frame floor horizontal accelerations and a reference response, to identify the equivalent story stiffness and damping parameters of the frame from top to bottom iteratively. An identification error analysis reveals how structural responses affect the identification accuracy. Exploiting this result, a smart reference selection rule is proposed to choose the best reference response and further improve the identification accuracy. Finally, a height-story two-bay frame structure is used to demonstrate the efficacy of the proposed substructure identification, very accurately identifying the structural parameters even under the influence of large measurement noise; based on the estimated parameters, a hypothesis testing method is used to detect and locate structural damage, simulated by stiffness reduction of some columns.

9435-109, Session PTues

Research on slope instability displacement monitoring technique based on laser spot video identification method

Xi Xu, China Univ. of Geosciences (China); Hao Liu, Xuefeng Zhao, Dalian Univ. of Technology (China)

Based on image processing technology, a laser identification method of displacement monitoring with high-efficiency and low-cost has been proposed. Fix the laser on the object and project the laser spot onto a fixed screen. When the object movement occurs, the camera fixed in front of the screen will shoot the entire movement of the laser spot on the screen. In this way, the displacement of the object will be obtained by analyzing the movement state of the spot. Experiments have been conducted, which contain static displacement experiments including cyclic loading test experiments and random loading experiments, as well as dynamic displacement. Results are proved well by comparison with the data that a laser displacement sensor collected. There are good reproducibility of the

displacement monitored. Test results show the displacement resolution less than 0.1 mm can be achieved. tests demonstrated that laser identification method of displacement monitoring with high-accuracy and low-cost is one promising way for displacement monitoring for slope instability.

9435-110, Session PTues

Emotion Identification Method using RGB information of Human Face

Shinya Kita, Akira Mita, Keio Univ. (Japan)

In recent years, more and more people live alone due to our elderly society resulting from low birthrate. We propose "biofied building" to help those people by embedding functions learnt from human adaption mechanisms with the help of small robots. The most important task for this research is to identify motions and emotions to know the health conditions of the residents.

Thus, the aim of this research is to identify human health conditions from human face color using Kinect as a sensor. From the previous research, we know that the increase of blood flow results in the increase of red color in the face.

In this paper, we apply some stimulus on the face and comparing the RGB values, we may know the change by comparing with the normal situation.

Then we estimated how much stress human is feeling by getting the change of the skin color in nose area using facetracking and RGB values with Kinect.

We took account of how much the amount of blood depend on the RGB values of the skin color.

This research showed that we could estimate human conditions under contactless situations using Kinect.

This research contributed to biofied building by controlling living space and alarming the resident when any abnormality of the resident is found, utilizing the robot which recognize of the conditions of human living alone.

9435-111, Session PTues

Bio-inspired symbiotic structural control and structural health monitoring system

Zhaoshuo Jiang, San Francisco State Univ. (United States)

Aging infrastructure is an impending problem here in the United States. In particular, highway bridges as essential links in our nation's transportation network, are critical infrastructure that are subjected to continuous, and ever increasing, traffic loading and potential natural and man-made hazards including earthquakes, flood/storm surge/tsunami waters, vehicle impacts, fire, and even improvised explosive devices (IEDs).

Structural health monitoring is a means to use dynamic responses of bridges to determine their current and post-event structural conditions from both the standard in-service traffic loading as well as extreme hazards. While structural health monitoring can potentially identify damage or the failure of a component, repairing or replacing deficient bridges is extremely time and cost consuming. As such, providing supplemental control forces through structural control to safely, economically, and time efficiently increase the safe life and performance of the bridges and prolong the need for replacement is of great importance to bridge owners and the public as a whole.

Traditionally, structural health monitoring and structural control are independently applied. Leveraging structural health monitoring and structural control systems has great potential to provide a more timely and sophisticated solution to the afore-mentioned problems. Inspired by responsive behaviors of human beings, the proposed symbiotic structural health monitoring and structural control system promises to increase resilience in highway bridges by adapting the structural control system to better accommodate loads when damage is detected and using control forces to better interrogate the location and severity of damage detected by the structural health monitoring system.

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9435-112, Session PTues

Simultaneous shear and pressure sensing based on patch antenna

Hao Jiang, Haiying Huang, The Univ. of Texas at Arlington (United States)

In this paper, we presented a sensor which is capable to measure the shear and normal loadings simultaneously. The design is based on the electromagnetic interference between a microstrip patch antenna and a metallic pattern located at a distance on top of the radiation patch of the patch antenna. When the metallic pattern is placed on top of the patch antenna, the electromagnetic wave radiated by the patch antenna will be reflected by the pattern and interfere with the electromagnetic field of the radiation patch, which results in the changes of the antenna resonant frequencies. The resonant frequency changes are related to the lateral and vertical positions of the metallic pattern. Since a shear force will change the lateral position of the pattern while a normal pressure will reduce the distance h between the metallic pattern and the radiation patch, the applied shear force and normal pressure can be detected by monitoring the antenna resonant frequencies. The experimental results show us the linear relationship between the relative resonant frequency shift and the shear displacement at different levels of h and the different shear sensitivities observed for the two fundamental resonant modes indicate decoupling the shear and pressure effects is feasible. 3-D printing skill is adopted to fabricate the sensor structure consists of two rigid frames and two flexible spacers. Since multiple different plastic can be used as ink, it is very convenient to adjust the modulus of the elastic spacers to control the shear and pressure sensitivity of the sensor.

9435-113, Session PTues

Dielectric and electro-mechanical properties of (Na_{0.5}K_{0.5})NbO₃ based thin films prepared by pulsed laser deposition

Kazuhiko Tonooka, Naoto Kikuchi, National Institute of Advanced Industrial Science and Technology (Japan)

Lead-free piezoelectric materials are drawing attention because they can reduce environmental pollution by replacing PZT-based materials that are potentially toxic in disposal. (Na_{0.5}K_{0.5})NbO₃ (NKN) based materials are considered to be the most promising alternatives for their good piezoelectric properties and high curie temperature.

In this study, dielectric and electro-mechanical properties were investigated on NKN based thin films prepared by pulsed laser deposition (PLD). The epitaxial NKN thin films of about 1.5 micrometer thick were deposited on SrTiO₃ substrates at 700 degree C by PLD from targets of (Na_{0.5}K_{0.5})NbO₃ and (Na_{0.7}K_{0.3})NbO₃ ceramics. Dielectric properties of the samples were measured in the frequency range between 1 kHz and 10 MHz. A plate-type sample of 10mm x 10mm x 0.5mm in shape exhibited a resonance and anti-resonance response at around 220 kHz in the complex admittance curve as a function of frequency. The resonance ($f_r \approx 190$ kHz) and anti-resonance ($f_a \approx 230$ kHz) behavior was considered to be resulted from the electro-mechanical coupling effects of the NKN thin film grown on the SrTiO₃ substrate.

We are working on the NKN thin films to develop piezoelectric devices for structural health monitoring. Applications to the acoustic emission (AE) sensors are focused on, since increasing environmental restrictions will require environmentally-friendly piezoelectric materials like NKN, especially for sensors to monitor infrastructures.

9435-114, Session PTues

Influence of surface processing on the fracture strength of structurally integrated PZT fibers in shaped sheet metal parts

Marek Schmidt, Volker Wittstock, Michael Müller, Technische Univ. Chemnitz (Germany)

In the present state of the art, the function integration into lightweight metal structures is generally based upon adhesive bonding of sensors or actuators to the surface. A new technology enables a direct structural integration of lead-zirconate-titanate (PZT) fibers into local microstructures of metal sheets and subsequent joining by forming. This provides a complete functional integration of the piezoelectric ceramic in the metal for sensors and actuators purposes. In a further process step, the composite is shaped by deep drawing with a cup with a double curvature radius of 100 mm into a complex 3D surface. During the shaping process it is expected that the PZT- fibers get damaged with the result of degradation of the piezoelectric function. This paper describes the application of various surface processing methods to improve the shaping behavior of the piezoceramic fibers.

The production of the interconnected parallel piezoceramic fibers with dimensions of 0.25 x 0.25 x 11.5 mm² is based on piezoceramic plates. The plates are treated by different surface processing. One experimental series is lapped and another series is extra polished by chemical mechanical polishing (CMP). The resulting piezoceramic plates, fibers and piezo-metal composites were examined with regard to the fracture strength and the degradation of the piezoelectric properties during manufacturing and operation. It has been shown, that the lapped and polished fibers have a clearly better persistence with regard to the shaping processes compared to the unprocessed plates. The best results in this process were achieved by the polished piezoceramic fibers. Furthermore, the piezoelectric characteristics were better preserved by the lapped and polished fibers.

9435-115, Session PTues

Dynamic pressure sensor calibration techniques offering expanded bandwidth with increased resolution

David Wisniewski, Meggitt Sensing Systems (United States)

Advancements in the aerospace, defense and energy markets are being made possible by increasingly more sophisticated systems and sub-systems which rely upon critical information to be conveyed from the physical environment being monitored through ever more specialized, extreme environment sensing components.

One sensing parameter of particular interest is dynamic pressure measurement. Crossing the boundary of all three markets (i.e. aerospace, defense and energy) is dynamic pressure sensing which is used in research and development of gas turbine technology, and subsequently embedded into a control loop used for long-term monitoring. Applications include quantifying the effects of aircraft boundary layer ingestion into the engine inlet to provide a reliable and robust design. Another application includes optimization of combustor dynamics by "listening" to the acoustic signature so that fuel-to-air mixture can be adjusted in real-time to provide cost operating efficiencies and reduced NOx emissions.

With the vast majority of pressure sensors supplied today being calibrated either statically or "quasi" statically, the dynamic response characterization of the frequency dependent sensitivity (i.e. transfer function) of the pressure sensor is noticeably absent. The Shock Tube has been shown to be an efficient vehicle to provide frequency response of pressure sensors from extremely high frequencies down to 500 Hz. Recent development activity has lowered this starting frequency; thereby augmenting the calibration bandwidth with increased frequency resolution so that as the pressure sensor is used in an actual test application, more understanding of the physical measurement can be ascertained by the end-user.

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9435-116, Session PTues

**Pressure Sensing Using Low-cost
Microstrip Antenna Sensor**

Jun Yao, The Univ. of Texas at Arlington (United States); cancan xu, University of Texas at Arlington, department of Bioengineering (United States); Austin Mears, Mauricio Jaguan, Univ of Texas Arlington, Department of Mechanical and Aerospace Engineering (United States); Saibun Tjuatja, Haiying Huang, The Univ. of Texas at Arlington (United States)

Due to plantar somatosensory deficits, some diabetes patients may not feel the abnormal stresses experienced by their feet and would not seek treatment until the wound has reached advanced stages. For this case, a foot pressure sensing system which can be fitted in the insole of the shoes is extremely needed. This paper presents a novel foot pressure sensing system by using the low-cost microstrip patch antenna. A rectangular radiation patch was placed beneath the insole as the pressure sensor. The resonant frequency of the patch antenna is sensitive to the dielectric constant of the insole material and this dielectric constant varies with the applied foot pressures. The linear relationship between the antenna resonant frequency and the applied pressure was validated by the HFSS electromagnetic (EM) simulation. Therefore, real-time foot pressure can be calculated from the measured antenna resonant frequency shift once the sensitivity of the sensor is calibrated. For the purpose of validation, the pressure sensor was fabricated and a PCB-based sensor interrogation circuit was designed. In the circuit, a frequency modulated continue wave (FMCW) was generated by a voltage control oscillator (VCO) controlled by a triangular wave and supplied to the antenna sensor through a circulator. The power reflected by the antenna was routed by the circulator to a power detector. The power detector converts the power of its input signal into a DC voltage. By correlating the highest DC voltage in each FMCW period to the control voltage of VCO, the resonant frequency of the antenna sensor can be determined. Pressure experiments were performed and the results will be discussed in the conference.

9435-117, Session PTues

**Damage identification via asymmetric
active magnetic bearing acceleration
feedback control**

Jie Zhao, Schlumberger Ltd. (United States); Hans DeSmidt, The Univ. of Tennessee Knoxville (United States); Wei Yao, The University of Tennessee (United States)

A Floquet-based damage detection methodology for cracked rotor systems is developed and demonstrated on a periodically time-varying shaft-disk system. This approach utilizes measured changes in the system natural frequencies to estimate the severity and location of shaft structural cracks during operation. The damage identification is enhanced through the use of an Active Magnetic Bearing (AMB) with adjustable support acceleration feedback. Here, structural symmetry of the rotor system is broken by introducing AMB during the iterative damage identification process to enrich the data set by removing the Eigen degeneracy of the symmetric shaft structure. The AMB virtual mass is tuned to find its sensitive range with respect to the natural frequency shifts. This approach enables full damage identification from a single sensor and hence without requiring measured modeshape information. The rotor model is built by using assumed modes method and Lagrange Principle while the crack model is based on the strain energy the crack released. The method is synthesized via harmonic balance and numerical examples for a shaft/disk system demonstrate the effectiveness in detecting both location and severity of the structural damage. Finally, the benefit of asymmetric support in damage identification is shown by comparing the waterfall plots of symmetric and asymmetric supports.

9435-118, Session PTues

**The effect of calibration approach on
the predictive performance of a general
two dimensional constitutive model for
magnetic shape memory alloys**

Jason Dikes, Heidi P. Feigenbaum, Constantin Ciocanel, Northern Arizona Univ. (United States)

A general two dimensional constitutive model, capable of predicting the magneto-mechanical response of an MSMA material to any 2D loading combinations, has been previously developed by our group and calibrated using the output of a constant field-variable stress test. The calibration constants generated from this test data facilitates good model predictions of the material response for a wide range of constant field-variable stress loading conditions. However, the same calibration constants yield much less accurate model predictions of the constant stress-variable field material response. Accordingly, this paper focuses on generating model calibrations constants using constant stress-variable field data, and on the analysis of model predictions of both types of loadings, constant field-variable stress and constant stress-variable field, with the new set of calibration constants. In addition, a sensitivity analysis of the model performance relative to the variation in calibration constants is performed.

9435-119, Session PTues

**Structural damage detection for in-service
highway bridge under operational and
environmental variability**

Chenhao Jin, Jingcheng Li, Shinae Jang, Univ. of Connecticut (United States); Xiaorong Sun, University of Connecticut (United States); Richard Christenson, Univ. of Connecticut (United States)

Structural health monitoring has drawn significant attention in the past decades with numerous methodologies and applications for civil structural systems. Although many researchers have developed analytical and experimental damage detection algorithms through modal based methods, these methods are not widely accepted for practical structural systems because of their sensitivity to uncertain environmental and operational conditions. The primary environmental factor that influences the structural modal properties is temperature. The goal of this article is to detect structural damage in the presence of operational and environmental variations using modal-based method. For this purpose, temporal and spatial correlations between identified modal properties and environmental variables are analyzed by using statistical and artificial intelligent methods. A long-term structural health monitoring system was installed on an in-service highway bridge located in Meriden, Connecticut to obtain time-series data from vibration and environment. Natural frequencies of the bridge are estimated with confidence intervals given any temperature derivations. Numerical results show that the variability of measured modal parameters due to temperature should be well understood, and the temperature induced changes in natural frequencies should also be considered prior to the establishment of the threshold in the damage warning system. This would be helpful to determine the state of the structure and add the ability for structural health monitoring system to aid bridge management and maintenance.

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9435-120, Session PTues

Method for generating dynamic fiber optic Bragg grating sensor array in a single sigle-mode fiber

Cui Zhang, Lixin Wang, Yu-Tang Dai, Weibing Gan, Wuhan Univ. of Technology (China)

1550nm wavelength laser light source was modulated, scanning in the range of 2nm. Another broadband source, 1550nm of central wavelength and the laser light source were launched into two end of a single-mode optical fiber separately. While the light source was turned on, 30 dynamic gratings can be observed by demodulator or spectrometer. Wavelength range was from 1500nm to 1590nm and the interval of wavelength was about 3nm. Experiments showed that dynamic Bragg grating in full complied with the fiber optic Bragg grating theory. It responded to strain and temperature with good linearity. Generating dynamic grating had no effect on the optical fiber itself. It can be used in structural monitoring and other fields.

9435-121, Session PTues

Numerical investigations on metal wire based variant of EMI technique for structural health monitoring

Suresh Bhalla, Susmita Naskar, Indian Institute of Technology Delhi (India)

The electro mechanical impedance technique (EMI) is one and half decade's old non-destructive evaluation technique, which is increasingly becoming very popular in the field of structural health monitoring (SHM). Though this technique shows promising results in the area of SHM, the main disadvantage of this technique is the brittleness of the piezo-electric (PZT) material and inability to take measurements from high temperature/ inaccessible/hazardous locations. In addition, bonding PZT patches is hazardous where the surface of the structure is continuously under impact. To overcome this problem, a new variant has recently emerged wherein a metal wire is coupled with the PZT patch and then attached with the host structure. In this study, the metal wire based technique has been further improvised by replacing the wire by a thin foil. Numerical modelling is employed to develop a new algorithm to locate damage in a 2D steel structure with minimum number of PZT patches in the metal wire configuration. Compared to the conventional grid type sensor configuration, the proposed approach saves the number of sensors and the time required for carrying out structural diagnostics.

9435-122, Session PTues

Flexible patch composed of PZT thin-film on stainless steel foil for energy harvesting from low-frequency human motions

Yin-Jie Wang, Chao-Ting Chen, Chun-Liang Kuo, Shou-Peng Yeh, Wen-Jong Wu, National Taiwan Univ. (Taiwan)

To harvest energy from human motion and generate power for the emerging wearable devices, energy harvesters are required to work at very low frequency. There are several studies based on energy harvesting through human gait, which can generate significant power. However, when wearing these kind of devices, additional effort may be required and the user may feel uncomfortable when moving. The energy harvester developed here is composed of a 10µm PZT thin-film deposited on 50µm thick stainless steel foil deposited by the aerosol deposition method. The PZT layer and the stainless steel foil are both very thin, thus the patch is highly flexible. The patch can be attached on the skin to harvest power through human motions such as the expansion of the chest region while breathing. The

energy harvester will first be tested with a moving stage for power output measurements. The energy density can be determined for different deformation ranges and frequencies. The fabrication processes and testing results will all be detailed in this paper.

9435-123, Session PTues

IDENTIFICATION OF SENSOR FAULT FOR THE PERFORMANCE AND STABILITY OF CENTRALIZED CONTROL LOGICS

Gabriele Cazzulani, Simone Cinquemani, Marco Ronchi, Francesco Ripamonti, Politecnico di Milano (Italy)

Centralized control logics are based on a single controller which gets information from a certain number of sensors and generates consequently a certain number of control forces. Typically, when defining the control logic and when calculating the control gains, the effect of possible actuator or sensor faults is not taken into account. Consequently, this effect is unpredictable and it can result in strong reduction of control performance or even in instability of the controlled system.

This paper focuses on the study of the effect of sensor fault when large sensor arrays (for example Fiber Bragg Grating arrays) are considered. Indeed, sensor arrays provide a distributed measurement of the structure vibrations, allowing the design of optimized control logics. Anyway, due to the large number of sensors, the reliability is lower and the malfunctioning of one or more sensors can occur.

The effect of sensor fault on the measurement of structure vibrations and, consequently of the active control will be investigated. Numerical and experimental tests on a beam equipped with a 30-sensors FBG array will be reported.

9435-124, Session PTues

Fault detection in small diameter pipes using ultrasonic guided wave technology

Rahul Shabahnani, Victor Humphrey, Bahareh Zaghari, Mohammed Moshrefi-Torbati, Univ. of Southampton (United Kingdom)

Condition monitoring of small pipes (with diameters less than 50 mm) are considered here as most of the literature focuses on larger pipes. Guided wave theory is explained alongside a numerical simulation of the relevant dispersion curves of the system. This paper investigates the feasibility of using different configurations of piezoelectric transducers to generate torsional guided waves for inspecting defects in buried pipes. Experiments are conducted using two dry coupled piezoelectric transducers, where one of them transmits guided waves along the pipe and the other receives them. The transducers produce tangential displacement, thereby generating the fundamental torsional mode T(0, 1). The experiment was performed by rotating the receiving transducer around the circumference of the pipe. An advantage of this technology compared to a conventional ultrasonics approach is that it allows inspection of the whole pipe by placing the transducers at single convenient locations. Experiments are performed on a buried pipe and a bitumen coated pipe since most underground pipes have external insulation.

On a non-buried bitumen coated pipe, the experiments demonstrated that the guided waves attenuate and dissipate quickly. It is also shown that pipe end echoes are visible with the use of lower frequency waves, which is likely to be due to higher dispersion rate of high-frequency waves over shorter distances. The significant reduction in the examination range to find defects in small size buried pipes can be compensated for by changing the two piezoelectric transducers' configuration and hence avoid using large number of transducers.

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9435-125, Session PTues

**Design and simulation of multi-resonance
sonic transducer using Terfenol-D**

Mohammad Reza Sheykhleslami, Yousef Hojjat, Tarbiat Modares Univ. (Iran, Islamic Republic of); Simone Cinquemani, Politecnico di Milano (Italy); Mojtaba Ghodsi, Sultan Qaboos University (Oman)

Terfenol-D transducer that works in resonance frequency has some advantages that make them suitable for working in wide range of application. High energy density and high vibrational amplitude are some of advantages. Despite these features, operating frequency is fixed. If working frequency is far away from the resonance frequency, efficiency of the transducer can be decrease suddenly. In this paper, an attempt to design and simulation of a multi-resonance sonic transducer is presented. Range of resonance frequency change for this transducer is about 1.25 kHz (from 8500 Hz to 10000 Hz). This work can be done by changing Young modulus in Terfenol-D using delta E effect by changing in operational bias condition of Terfenol-D. Design procedure is validated by ANSYS12 FEM commercial software. Effect of changing resonance frequency in vibrational mode shape of the transducer is also presented. Furthermore, magnetic circuit of the transducer is design and simulated with ANSYS12. Magnetic circuit is design in a way to minimize flux leakage. Results of this paper can help to design the more flexible transducer in operating frequency and mode shape and enhance it for many applications.

9435-126, Session PTues

**Comparative discussion between first and
second modes of Terfenol-D transducer**

Mohammad Reza Sheykhleslami, Yousef Hojjat, Mojtaba Ghodsi, Tarbiat Modares Univ. (Iran, Islamic Republic of); Simone Cinquemani, Politecnico di Milano (Italy)

Terfenol-D resonance transducer has high energy-density and high vibration amplitude. These features make them good selection for using in different applications such as liquid atomizers and sonar transducers. Operating mode of the Terfenol-D transducer plays an important role in efficiency of it. It can also change some parameters of the transducer such as stiffness. In this paper, experimental comparative study between first and second longitudinal modes of vibration in the Terfenol-D transducer is presented. It contains the mechanical quality factor for working in air and water, equivalent stiffness, equivalent mass, mechanical losses, magneto-mechanical coupling factor and efficiency of the transducer. Different efficiency criteria for these two modes are discussed. Also, bandwidth frequencies in these modes are compared. These factors can be obtained from impedance response analysis of the transducer. Study is performed on the Terfenol-D transducer that resonance frequency of it is 3.1 kHz in the first mode and 8.25 kHz in the second mode. Despite some limitations for working in second mode such as length of the transducer, results of this paper show some advantages of second longitudinal mode for application in the Terfenol-D transducer such as a high mechanical quality factor. Results of this paper can give useful guidelines for designing the Terfenol-D transducer.

9435-127, Session PTues

**Characterization of a soft elastomeric
capacitive strain sensor for fatigue crack
monitoring**

Xiangxiong Kong, Jian Li, The Univ. of Kansas (United States); Simon Laflamme, Sari Kharroub, Iowa State Univ. (United States); Caroline R. Bennett, The Univ. of Kansas

(United States); Adolfo B. Matamoros, The Univ. of Texas at San Antonio (United States)

Fatigue cracks have been one of the major factors for the deterioration of steel bridges. In order to maintain structural integrity, monitoring fatigue crack activities such as crack initiation and propagation is critical to prevent catastrophic failure of steel bridges due to the accumulation of fatigue damage. Measuring the strain change under cracking is an effective way of monitoring fatigue cracks. However, traditional strain sensors such as metal foil gauges are not able to capture crack development due to their small size, limited measurement range, and high failure rate under harsh environmental conditions. Recently, a newly developed soft elastomeric capacitive sensor has great promise to overcome these limitations. In this paper, crack detection capability of the capacitive sensor is demonstrated through Finite Element Analysis. A nonlinear FE model of a standard ASTM compact tension specimen is created which is calibrated to experimental data to simulate its response under fatigue loading, with the goal to 1) depict the strain distribution of the specimen under the large area covered by the capacitive sensor due to cracking; 2) characterize the relationship between capacitance change and crack width; (3) quantify the minimum required resolution of data acquisition system for detecting sub-millimeter fatigue cracks, which serves as a basis for the development of a dedicated wireless data acquisition system for the capacitive strain sensor.

9435-128, Session PTues

**Statistical analysis of modal properties of
a cable-stayed bridge through long-term
structural health monitoring with wireless
smart sensor networks**

Jian Li, Parisa Asadollahi, The Univ. of Kansas (United States)

Understanding the dynamic behavior of complex structures such as long-span bridges requires dense deployment of sensors. Traditional wired sensor systems are generally expensive and time-consuming to install due to cabling. With wireless communication and on-board computation capabilities, wireless smart sensor networks have the advantages of being low cost, easy to deploy and maintain and therefore facilitate dense instrumentation for structural health monitoring. A long-term monitoring project was recently carried out for a cable-stayed bridge in South Korea with a dense array of 113 smart sensors, which feature the world's largest wireless smart sensor network for civil structural monitoring. This paper presents a comprehensive statistical analysis of the modal properties (natural frequency, mode shape, and damping ratio) of the monitored cable-stayed bridge. Data analyzed in this paper is composed of structural vibration signals monitored during a 12-month period under ambient excitations. The correlation between environmental temperature and the modal frequencies is also investigated. The results showed the long-term statistical structural behavior of the bridge, which serves as the basis for Bayesian statistical updating for the numerical model.

9435-129, Session PTues

**Regenerative magnetorheological
dampers for vehicle suspensions**

Chao Chen, Li Zou, Wei-Hsin Liao, The Chinese Univ. of Hong Kong (Hong Kong, China)

Magnetorheological (MR) dampers are promising for vehicle suspensions, by virtue of their adaptive properties. During the everyday use of vehicles, a large amount of energy is wasted due to the energy dissipation by dampers under the road irregularities, accelerating, cornering and braking processes. On the other hand, extra batteries are required for the current MR damper systems. To reduce the energy waste and get rid of the dependence on extra batteries, in this paper, regenerative MR dampers are proposed for

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vehicle suspensions, which have self-contained power regeneration and MR damping abilities. The wasted vibration energy can be converted into useful electrical energy and power the MR damper coil. A regenerative MR damper which has compatible size, connection and stroke with an electric car, is designed and fabricated. The prototype of the damper is tested in the lab to obtain the controllable force and power generation characteristics. Modelling of the damper including damping force and power generation are performed and validated by the testing results. Experimental results show that the regenerative MR damper is more energy saving, and has better vibration-isolation performance than the Original Equipment (OE) damper of the car.

9435-131, Session PTues

Fundamental study on the performance of modified microcombustors with porous media inserts

K. J. Chua, W. M. Yang, N. Aqdas, Y. Tong, National Univ. of Singapore (Singapore); Terence K. L. Goh, National Univ. of Singapore (Singapore) and SIM Univ. (Singapore)

In this paper, the performance of micro-thermophotovoltaic power systems with modified microcombustor structures or with porous media inserted are studied using numerical simulations. The main focus is to improve the wall temperature uniformity, increase the average temperature and thus attain higher emitter efficiency by modifying the internal design or incorporating porous media. Physical modifications investigated include the use of additional inlets and recirculation designs incorporated internally within the combustor chamber. Internal recirculation designs have been found to be highly effective in promoting the wall temperature and improving emitter efficiency. In addition, key parameters of porous media which influence the performance of both single and multiple combustion chambers have been identified and studied.

9435-30, Session 7A

Big data extraction with adaptive wavelet analysis

Hongya Qu, Genda Chen, Missouri Univ. of Science and Technology (United States); Yiqing Ni, The Hong Kong Polytechnic Univ. (China)

Nondestructive evaluation and sensing technology have been increasingly applied to characterize material properties and detect local damage in structures. More often than not, they generate images or data strings that are difficult to see any physical features without novel data extraction techniques. In the literature, popular data analysis techniques include Short-time Fourier Transform, Wavelet Transform, and Hilbert Transform for time efficiency and adaptive recognition. In this study, a new data analysis technique is proposed and developed by introducing an adaptive central frequency of the continuous Morlet wavelet transform so that both high frequency and time resolution can be maintained in a time-frequency window of interest. The new analysis technique is referred to as Adaptive Wavelet Analysis (AWA). This paper will be organized in several sections. In the first section, finite time-frequency resolution limitations in the traditional wavelet transform are introduced. Such limitations would greatly distort the transformed signals with a significant frequency variation with time. In the second section, Short Time Wavelet Transform (STWT), similar to Short Time Fourier Transform (STFT), is defined and developed to overcome such shortcoming of the traditional wavelet transform. In the third section, by utilizing the STWT and a time-variant central frequency of the Morlet wavelet, AWA can adapt the time-frequency resolution requirement to the signal variation over time. Finally, the advantage of the proposed AWA is demonstrated in Section 4 with a ground penetrating radar (GPR) image from a bridge deck, an analytical chirp signal with a large range sinusoidal frequency change over time, the train-induced acceleration responses of

the Tsing-Ma Suspension Bridge in Hong Kong, China. The performance of the proposed AWA will be compared with the STFT and traditional wavelet transform.

9435-31, Session 7A

Data Management for Biofied Building

Kohta Matsuura, Akira Mita, Keio Univ. (Japan)

The "Biofied Building" is the building in which small robots monitor body parameters, emotions and activities of a person. However, the person will be in various places such as home, office and school. We may use different robots in different buildings. To have meaningful information on the person, the data obtained by the different robots should be seamless. In this paper, a portable database for Biofied Building is proposed. This database is able to store information of robots, users, and history of service measured via various robots in a portable form. This database is capable of connecting previous studies of Biofied Building each other. In addition, users can enjoy the same service all over the place.

9435-32, Session 7B

Gust alleviation of highly flexible UAVs with artificial hair sensors

Weihua Su, The Univ. of Alabama (United States); Gregory W. Reich, Air Force Research Lab. (United States)

Recently, artificial hair sensors (AHS) have been developed in Air Force Research Laboratory (AFRL). The deformation of CNT in air flow causes voltage and current changes in the circuit, which can be used to quantify the dynamic pressure and aerodynamic loads along the surfaces. AFRL has done a lot of essential works in design, manufacturing, and measurement of AHSs. The proposed paper is to bridge the current AFRL's work on AHSs and their feasible applications in flight dynamics and control (e.g., the gust alleviation) of highly flexible aircraft.

A highly flexible vehicle is modeled with a strain-based geometrically nonlinear beam, coupled with finite-state inflow aerodynamics. A feedback control algorithm for rejection of gust perturbations will be developed. As a starting point, the state-space representation of the linearized system will be used with the aerodynamic states suppressed, while states associated with the full structural model will be retained. All AHS measurements will be used for the control input, i.e., wing sectional aerodynamic loads will be defined as the control output, which is used to design the feedback gain. A simplified Linear Quadratic Regulator (LQR) controller will first be implemented. Once the controller is designed, closed-loop aeroelastic and flight dynamic simulations will be performed to evaluate the performance of different controllers with force feedback and be compared to traditional controller designs with state feedback. From the study, the feasibility of AHSs in flight control will be assessed. The whole study will facilitate in building a fly-by-feel simulation environment for autonomous vehicles.

9435-33, Session 7B

Low frequency motion measurement and control of spacecrafts and satellites

Fausto Acernese, Gerardo Giordano, Rocco Romano, Fabrizio Barone, Univ. degli Studi di Salerno (Italy)

This paper describes a new mechanical application of the Watt-linkage for the development and implementation of mono-axial sensors aimed to low frequency motion measurement and control of spacecrafts and satellites. The basic component of these sensors is the one dimensional UNISA Folded Pendulum mechanical sensor, developed for ground-based applications, whose unique features are due to a very effective optimization of the effects

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of gravitational force on the folded pendulum mechanical components, that allowed the design and implementation of folded pendulum compact (< 10 cm), light (< 200 g), scalable, tunable resonance frequency < 100mHz) sensors, with large band (10⁷ Hz ? 10Hz), high quality factor (Q > 15000 in vacuum at 1Hz), with good immunity to environmental noises and sensitivity, guaranteed by an integrated laser optical readout, and fully adaptable to the specific requirements of the application. In this paper we show how to extend the application of ground-based folded pendulum also to space, in absence of gravity, still keeping all the above interesting features and characteristics that make this class of sensors very effective in terms of large band, especially in the low frequency, sensitivity and long term reliability. Preliminary measurements on a prototype confirm the feasibility, showing also that very good performances can be relatively easily obtained.

9435-34, Session 8A

Sparse feedback structures for wireless control of civil systems

Reuben Verdoljak, Lauren Linderman, Univ. of Minnesota, Twin Cities (United States)

Although originally popularized for structural health monitoring, wireless smart sensors are an attractive alternative to traditional tethered systems for structural control. Their onboard sensing, processing, and wireless communication offer all the components of a feedback control system. However, wireless smart sensors pose unique challenges for the application of centralized control, which is common in most modern control systems. Decentralized control offers several advantages to wireless structural control, including limiting the wireless communication required and the associated slow sampling rate and time delays in the control system. Previous decentralized structural control algorithms, both ad-hoc and heuristic, enforce a spatial sparsity pattern during the design, which is assumed a priori. Therefore, the optimal feedback structure is not considered in the design. This work explores a decentralized optimal LQR design algorithm where the sparsity of the feedback gain is incorporated into the objective function. The algorithm is extended for wireless systems in which the number of connections would impact the sampling rate performance of the control system. The control approach is compared to previous decentralized control techniques on the twenty-story control benchmark structure. Sparsity and control performance are compared to centralized and tethered designs. The optimal sparse feedback design offers the best balance of performance, measurement feedback, sampling rate, and control effort. Additionally, the feedback structure is not easily identifiable a priori; thus, highlighting the significance of particular measurements in this wireless feedback framework.

9435-35, Session 8A

A driven active mass damper by using output of a neural oscillator: effects of position control system changes on vibration mitigation performance

Junichi Hongu, Daiuske Iba, Takayuki Sasaki, Morimasa Nakamura, Ichiro Moriwaki, Kyoto Institute of Technology (Japan)

In recent our study, a new control system for active mass dampers has been proposed. The control system is a feedback system, which combines a single neural oscillator and a position controller. The output of the neural oscillator synchronized with the structure response is a rhythmic command which decides the driving direction of the auxiliary mass, and a special map plotted by limit cycles of the oscillator determines the travel distance of the auxiliary mass in comparison with the current state of the neural oscillator affected by the structure response. In addition, in order to move the auxiliary mass to the desire value, the position control system is used. In this research, we investigate the effect of the position control system changes on the proposed controller's vibration mitigation performance.

9435-36, Session 8A

Low-force magneto-rheological damper design for small-scale structural control experimentation

Benjamin D. Winter, Antonio H. Velazquez, R. Andrew Swartz, Michigan Technological Univ. (United States)

Experimental validation of novel structural control algorithms is a vital step in the development and this technology. Small-scale experimental test-beds fulfill an important role in the validation of multiple-degree-of-freedom (MDOF) and distributed semi-active control systems, allowing researchers to test control algorithms, communication topologies, and timing-critical aspects of structural control systems that do not necessarily require full-scale testing. In addition, small-scale building specimens can be useful in combined structural health monitoring (SHM)/adaptive control studies, where safety is considerably enhanced for excitation and control of damaged structures by using kilogram-scale specimens rather than metric ton-scale specimens. Development of such small-scale test-beds is hampered by difficulties in actuator design. In order to be a useful analog to full-scale structures, small-scale test-beds should exhibit similar features and limitations to their full-scale counterparts. In particular, semi-active devices, such as magneto-rheological (MR) fluid dampers, exhibit limited authority (e.g., vs. active mass dampers) and non-linear behaviors that difficult to mimic over small force scales due to fluid confinement and friction issues. In this study, a small-scale structural control test-bed intended for wireless control validation studies is proposed. The key development enabling its function is a novel extraction-type small-force (0-10 N) MR-fluid damper which exhibits non-linear hysteresis similar to a full-scale, commercial MR-device. To validate this prototype damper, a 3-story scale structure subjected to single-axis seismic excitation is controlled using LQG state feedback control as well as a modified Bouc-Wen lookup table previously employed in full-scale applications. Additionally, the damper dynamic range is characterized using force output magnitude and frequency characteristics.

9435-37, Session 8A

Development and application of a vibration isolation system with adaptive stiffness considering potential energy

Chii-Jen Chen, National Chung Cheng Univ. (Taiwan); Tzu Kang Lin, National Chiao Tung Univ. (Taiwan)

In recent years, a study of semi-active isolation system named Leverage-type Stiffness Controllable Isolation System (LSCIS) was proposed. The main concept of the LSCIS is to adjust the stiffness in the isolator for the fundamental period of the superstructure by a simple leverage mechanism. Although great performance has been achieved with the support of an algorithm considering the least input energy in far-field earthquakes, some result still reveal that the proposed system is not suitable in application for near-fault strong ground motion. To overcome this problem, an upgraded algorithm is proposed by considering the potential energy effect in the semi-active structural control system in this study. Firstly, the new algorithm is developed with the combination of the potential energy (Ep) and the kinetic energy (Ek) as the control objective to reduce the structural displacement responses efficiently. The optimal weightings between the potential and kinetic energy are then determined through a series of near-fault earthquake simulation. In order to demonstrate the performance of the proposed algorithm, a two-degree-of-freedom structure is used as a benchmark in both numerical simulation and experimental verification. Numerical result has shown that the dynamic response of the structure can be effectively alleviated by the proposed algorithm under both far-field and near-fault earthquakes, while the structural responses by the original algorithm may be worse than the pure passive control. The feasibility of implementing the proposed system has also been experimentally verified.

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9435-38, Session 8B

Detection of Fatigue Crack on a Rotating Steel Shaft Using Air-coupled Nonlinear Ultrasonic Modulation

Byeongju Song, Byeongjin Park, Hoon Sohn, KAIST (Korea, Republic of); Cheol-Woo Lim, Jae-Roung Park, KIA Motors Hwasung Plant (Korea, Republic of)

Rotating shafts in drop lifts of manufacturing facilities are susceptible to fatigue cracks as they are under repetitive heavy loading and high speed spins. However, it is challenging to use conventional contact transducers to monitor these shafts as they are continuously spinning with a high speed. In this study, a noncontact crack detection and localization technique for a rotating shaft is proposed using air-coupled transducers (ACTs). (1) Low frequency (LF) sinusoidal and high frequency (HF) toneburst inputs are applied to a shaft using two ACTs, respectively. A fatigue crack can provide a mechanism for nonlinear ultrasonic modulation and create spectral sidebands at the modulation frequencies, which are the sum and difference of the two input frequencies. (2) The corresponding ultrasonic response is measured using another ACT. The damage index (DI) is defined as the energy of the first sideband component, which corresponds to the frequency difference between HF and LF inputs. (3) Steps (1) and (2) are repeated with various combinations of HF and LF inputs. Crack existence is detected through an outlier analysis of the DIs. (4) By analyzing the arrival time of the first sideband component, the crack location is estimated as well. The effectiveness of the proposed technique is investigated using a steel shaft with a real fatigue crack.

9435-39, Session 8B

Volumetric loss quantification using ultrasonic inductively coupled transducers

Peng Gong, Carnegie Mellon Univ. (United States); Thomas R. Hay, TechKnowServ Corp. (United States); David W. Greve, Irving J. Oppenheim, Carnegie Mellon Univ. (United States)

In our earlier work, we developed the inductively coupled transducer, studied its electrical behavior, and used it to generate Lamb waves in plates and longitudinal waves in a steel box girder for damage detection. The inductively coupled transducer has advantages of no exposed electrical wiring, long lifetime, and easy fabrication over wired transducers.

In this paper, we propose a novel method using an inductively coupled transducer to generate bulk waves propagating circumferentially in a thick-walled aluminum tube. In our tests, the bulk waves are shown to bounce off the inner and outer surfaces of the aluminum tube and at the same time propagate circumferentially around the tube. The ultrasonic pulses propagate in both directions and along multiple paths, and some pulses can be directly interpreted. The circumferentially propagating pulses are shown to be sensitive to machined volume loss on the inner diameter. As a comparison, the standard through-thickness pulse echo method does not always work because an inclined and curved loss surface can reflect the pulses away from the transducer and make it difficult to detect an echo.

9435-40, Session 8B

Protection of sandwich composite panels from local buckling phenomena using non-linear wave modulation methodology

Nikos A. Chrysochoidis, Eugenio Gutiérrez, European Commission Joint Research Ctr. (Italy)

Early detection of local buckling phenomena in composite structures

receives high attention, as the volume of composite materials used in primary aerospace, transport and energy structures is rapidly increasing. Application of composite materials in constructions subjected to compressive loading indicates the requirements for protection from local buckling phenomena. Various methodologies have been applied for early detection of the buckling point and some of them focused on the study of modulation characteristics of linear wave propagation. Towards this direction non-linear wave modulation techniques, are newly developed methodologies for which are reported to provide high sensitivity for detection of crack damage via the study of the non linear signatures (ie. sidebands etc) of the damage on the propagated wave response. Objective of the proposed paper is the application of two non linear ultrasonics methodologies for the detection of the structural nonlinearity when the applied compressive force approaches the critical buckling load.

Our experimental study is performed on sandwich foam core composite panels which are manufactured having [0/90]4S skin lamination configuration and 30mm core thickness. The panels are equipped with a set of three piezoceramic wafers attached on the specimen surface, operating as actuation and sensing devices and utilizing the active nonlinear acousto-ultrasonic piezoelectric sensor previously demonstrated [1,2] for composites damage detection. The specimens are subjected under compressive loading in a 50KN testing frame and two non linear ultrasonic methodologies are applied on the tested structures; the first one is based on the single mode non linear resonance acoustic spectroscopy of the first modal frequency and the second to the wave modulation spectroscopy. The slowly increasing non linearity in the structure as the compressive load approaches the critical buckling point manifests itself in two ways; for the 1st methodology with a slight modulation of the peak of the first modal frequency and for the second one with the presence of sideband spectral components at the two sides of the central carrier frequency. The phenomenon is studied till the specimens failure, and all the critical loading stages are discussed. Early detection of the close to critical point compression of a composite structure can prevent from further loading with catastrophic consequences.

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9435-41, Session 8B

Nonlinear ultrasonic fatigue crack detection using a single piezoelectric transducer

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This paper proposes a new nonlinear ultrasonic technique for fatigue crack detection using a single piezoelectric transducer (PZT). The proposed technique identifies a fatigue crack using linear (?) and nonlinear (?) parameters obtained from only a single PZT mounted on a target structure. Based on the different physical characteristics of ? and ?, a fatigue crack-induced feature is able to be effectively isolated from the inherent nonlinearity of a target structure and data acquisition system. The proposed technique requires much simpler test setup and less processing costs than the existing nonlinear ultrasonic techniques, but fast and powerful. To validate the proposed technique, a real fatigue crack is created in an aluminum plate, and then false positive and negative tests are carried out under varying temperature conditions. The experimental results reveal that the fatigue crack is successfully detected, and no positive false alarm is indicated.

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9435-42, Session 9A

FE model updating of a full-scale five-story reinforced concrete building tested on NEES-UCSD shake table

Rodrigo Astroza, Hamed Ebrahimian, Joel P. Conte, Univ. of California, San Diego (United States)

A full-scale five-story reinforced concrete building fully outfitted with a wide range of nonstructural components and systems (NCSs) was built and tested on the NEES-UCSD shake table in 2012. Before performing the seismic tests, the bare structure and the complete building (before and after installation of NCSs, respectively) were subjected to low-amplitude white noise (WN) base excitations and the response of the structure was recorded. In this paper, parameters associated to damping and stiffness properties of the building are estimated based on a linear FE model updating approach, which utilizes the input and output acceleration time histories recorded during low-amplitude WN base excitation tests and a stochastic (Bayesian) nonlinear filtering technique, namely the unscented Kalman filter (UKF). First, a detailed 3D linear finite element (FE) model of the bare structure is developed and updated to estimate the mean values and standard deviations of time-invariant parameters of the FE model (i.e., damping and stiffness parameters). Then, lumped linear springs are added at each story of the building in the updated FE model of the bare structure to account for the effect of NCSs. The FE model of the complete building is then updated to estimate the parameters associated to the damping of the complete building and the stiffness parameters representing the NCSs. The FE model updating procedure is conducted using both parameter-only and joint (state-parameter) estimation approaches.

9435-43, Session 9A

Development of a relationship between external measurements and reinforcement stress

Andre Brault, Neil A. Hoult, Queen's Univ. (Canada); Janet M. Lees, Univ. of Cambridge (United Kingdom)

As many countries around the world face an aging infrastructure crisis, there is an increasing need to develop more accurate monitoring and analysis techniques for reinforced concrete structures. One of the challenges associated with assessing existing infrastructure is correlating externally measured parameters such as crack widths and surface strains with reinforcement stresses as this is dependent on the debonded length of the bar in the vicinity of the crack. To external measurements, an effective reinforcement gauge length is required. However, the bond between the reinforcement is affected by a number of variables including the bar diameter and the stress in the reinforcement. It is also difficult to determine the maximum stress in the reinforcement bar as without a priori knowledge of the crack location consistently locating a strain gage at the critical location is impossible. The current research investigates how the use of distributed fiber optic sensors to measure reinforcement strain combined with digital image correlation to measure crack widths and surface strains can be used to convert external measurements to reinforcement stresses. An initial set of experiments was undertaken involving a series of small-scale beam specimens tested in three-point bending with variable reinforcement properties. Relationships between external measurements and internal reinforcement stresses are observed. The technique was shown to have promise although the error associated with the measurements is not insignificant. The reliability of these results is discussed and suggestions for future research are given.

9435-44, Session 9A

Multifractal analysis of two-dimensional images for damage assessment of reinforced concrete structures

Arvin Ebrahimkhanlou, Alireza Farhidzadeh, Salvatore Salamone, Univ. at Buffalo (United States)

The most common assessment technique for reinforced concrete shear walls (RCSW) is currently Visual Inspection (VI). The current practice suffers from subjective and labor intensive nature as it highly relies on judgment and expertise of the inspectors. In post-earthquake events where urgent and objective decisions are crucial failure of the conventional VI could be catastrophic. Conventional VI is mainly based on width of residual cracks. Given that cracks could close partially (e.g., due to weight of the structure, behavior of adjacent elastic members, earthquake displacement spectrum, etc.), methods based on crack width may lead to underestimating the state of damage and eventually an erroneous decision. This paper proposes a novel method to circumvent the aforementioned limitations by first automating the process, and then utilizing the information hidden in crack patterns. Off-the-shelf image processing techniques are used to extract crack patterns from images of the surface cracks on RCSW, followed by Multifractal Analysis (MFA) of the extracted crack patterns. The method is validated on two large scale low aspect ratio RCSW under quasi-static cyclic loading, and MFA show promising results in quantifying level of the damage as well as detecting tri-linear shear controlled behavior observed in backbone curves of the studied walls.

9435-45, Session 9A

The qualitative identification of void at interface of concrete-filled steel tube by the acceleration sensors monitoring information

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Based on the vibration testing principle, and taking the local vibration of steel tube at the interface separation area as the study object, a real-time monitoring and the damage detection method of the interface separation of concrete-filled steel tube by accelerometer array through quantitative transient self-excitation is proposed. The accelerometers are arranged on the steel tube area with or without void respectively, and the signals of accelerometers are collected at the same time and compared under different transient excitation points. The results show that compared with the signal of compact area, the peak value of accelerometer signal at void area increases and attenuation speed slows down obviously, and the spectrum peaks of the void area are much more and disordered and the amplitude increases obviously. Whether the input point of transient excitation is on void area or not irrelevant with qualitative identification results. So the qualitative identification of the interface separation of concrete-filled steel tube based on the signal of acceleration transducer is feasible and valid.

9435-46, Session 9A

Electromechanical admittance-based damage monitoring of concrete structures using wirelessly connected PZT sensors

Costas P. Provdakis, E. Kampianakis, Maristella Voutetaki, John Tsompanakis, Maria Stavroulaki, John Agadakos, Technical Univ. of Crete (Greece); George Pentas,

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Technological Educational Institute of Crete (Greece);
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In the present paper a structural health monitoring system which integrates an electromechanical admittance-based technique and a wireless sensor network approach is experimentally evaluated. More specifically, the present work investigates an alternative technique, based on the electromechanical admittance principle, which is employed by only acquiring variations in the root mean square voltage of distributed piezoelectric transducers bonded to a concrete structure. The traditionally used equipments for admittance measurements require data acquisition devices with high sampling rate capabilities which make those equipments too expensive. The proposed electromechanical admittance type technique is not limited by the sample rate of the analog-to-digital converter and is responsible for both acquiring sensor measurements and analyzing data which in turn are transferred to a central database server for permanent storage or any further data interpretation. The validation of the integrated approach is achieved by identifying the changes in electrical admittance signatures as measured on the surface electrodes of piezoelectric transducers. Those changes occur when damage alters the mechanical impedance of the examined concrete structure. Experimental models of damages occurring in conventional unreinforced and steel-reinforced concrete beam specimens are investigated. Results illustrate that the proposed integrated technique is an efficient approach for damage identification of concrete structures.

9435-47, Session 9B

Development of Arduino based wireless control system

Zhuoxiong Sun, Shirley J. Dyke, Francisco Pena, Alana Wilbee, Purdue Univ. (United States)

Over the past few decades, considerable attention has been given to structural control systems to mitigate structural vibration under natural hazards such as earthquakes and extreme weather conditions. Traditional wired structural control systems often employ a large amount of cables for communication among sensors, controllers and actuators. In such systems, implementation of wired sensors is usually quite complicated and expensive, especially on large scale structures such as bridges and buildings. To reduce the laborious installation and maintenance cost, wireless control systems are considered as a novel approach for structural vibration control. In this work, a wireless control system (WSC) is developed based on the open source Arduino platform. Low cost, low power wireless sensing and communication components are built on the Arduino platform. Structural control algorithms are embedded within the wireless sensor board for feedback control. The developed WSC is first validated through a series of tests. After that, the WSC is implemented on a 3-story shear building with semi-active control devices. Shaketable tests are conducted using a six-degree-of-freedom hydraulic shaketable. The control performances are evaluated with the impact of modeling uncertainties, measurement noises as well as time delay and data loss induced by the wireless network. The developed wireless control system is shown to be effective in controlling structural vibrations under several historical earthquake ground motions.

9435-48, Session 9B

A wireless magnetorheological elastomer sensor system

Nima Ghafoorianfar, David Mar, Nelson G. Publicover, Faramarz Gordaninejad, Univ. of Nevada, Reno (United States)

A magnetorheological elastomer (MRE)-based wireless sensor is designed, developed, and tested, which is capable of sensing compression and shear forces. The MRE wireless sensor system consists of a disk shaped MRE with two thin steel electrodes attached to both sides, and two wires connected to electrodes. Digital resistant meter sends voltage output corresponding

to the resistance of MRE to an Arduino microcontroller. The voltage signal is stored in the data logger shield and sends out Wi-Fi to a receiver and/or uploads it to a website, worldwide. Various MRE sensor configurations were evaluated for design optimization. The system was designed to send an email to a user, when a predefined force threshold is reached.

9435-49, Session 9B

Wireless ultrasound pitch-catch sensor powered by microwave energy

Farshad Zahedi, Jun Yao, Haiying Huang, The Univ. of Texas at Arlington (United States)

In this paper, a wireless ultrasound pitch-catch system whose wireless sensor node is powered by microwave energy is presented. The system consists of two subsystems; wireless interrogation unit and wireless sensor node, each of which is designed to work in generation and sensing mode but operates at different microwave frequency. Wireless transmission of the ultrasound excitation and sensing signals are achieved by upconverting the ultrasound signal to the microwaves using passive frequency mixers. In this way, wireless sensor nodes can be implemented. After wireless transmission, the microwave signals are demodulated using the same principle to recover the original ultrasound signals. A low power amplifier is required in the sensor node to amplify the structural response prior to the wireless transmission. Therefore, an RF-energy harvester was developed to power the amplifier so that the wireless sensor node can operate without any external power source. The wireless generation and sensing channels are characterized together with the RF-harvester and amplifier, to find the maximum distance available for the wireless pitch-catch system.

9435-50, Session 9B

Packet loss compensation of Wi-Fi-based wireless sensor networks

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Yuequan Bao, Harbin Institute of Technology (China);
Jinping Ou, Dalian Univ of Technology (China)

In wireless data transmissions processes, the problem of packet loss become important factor that affects the robustness of wireless data transmission. In order to solve the problem, the compressive sensing (CS) based wireless data transmission approach is proposed in this paper. The specific steps that use the CS approach to reconstruct lost data are as follows: The first step is to encode the original data in a random sampling matrix. Then the original data and the encoded data are sent to the receiving side through the wireless transmission. After the data is received, if there is packet loss, it can be reconstructed by CS approach. The reconstructed data is able to compensate for the incomplete original data in a certain range. In this paper, a wireless sensor network (WSN) based on Wi-Fi is developed for verifying the effectiveness and feasibility of the CS approach. The WSN consists of small nodes with sensors, base stations, PC client. Experimental results show that the wireless sensor network is working properly and steady. Moreover, the CS approach could compensate for the packet loss effectively, and increase the robustness and the speed of wireless transmission greatly.

9435-51, Session 9B

Cable force monitoring system of cable stayed bridges using accelerometers inside mobile smart phone

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and Harbin Institute of Technology (China)

Cable force is one of the most important parameters in structural health monitoring system integrated on cable stayed bridges for safety evaluation. In this paper, one kind of cable force monitoring system scheme was proposed. Accelerometers inside mobile smart phones were utilized for the acceleration monitoring of cable vibration. Firstly, comparative tests were conducted in the lab. The test results showed that the accelerometers inside smartphones can detect the cable vibration, and then the cable force can be obtained. Furthermore, there is good agreement between the monitoring results of different kinds of accelerometers. Finally, the proposed cable force monitoring system was applied on one cable stayed bridge structure, the monitoring result verified the feasibility of the monitoring system.

9435-52, Session 10A

Characterization of the electrical properties of individual multi-walled carbon nanotubes

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As next-generation materials with complex properties are used in structures and numerous existing structures are nearing their predicted lifetimes, the need for structural health monitoring (SHM) becomes increasingly evident. Numerous methods for performing SHM have been developed, with the addition of electrically-based monitoring. These methods typically involve monitoring for changes of the electrical conductivity of a material, from which a decrease is generally correlated to damage. In some cases, the application of a conductive thin film is required to perform these electrically-based methods. In order to optimize the properties of these sensitive materials, engineers refer to material models for this practice. To properly model the electrical response of a CNT-PVDF thin film to changes in CNT content, applied strain, and other phenomena, we require an accurate understanding of the CNT network geometry, electrical properties of individual CNTs, and the electrical properties of the CNT junctions. This work focuses on obtaining the electrical properties of individual multi-walled CNTs (MWCNTs) using conductive atomic force microscopy (C-AFM) measurements. These measurements are conducted by depositing the MWCNTs on a silicon wafer, applying electrodes to one end of the MWCNTs, grounding the electrode, biasing a conductive AFM probe, and measuring the current as a function of length along each MWCNT. We present the resistance per length of a distribution of MWCNTs with respect to MWCNT diameter and a comparison to other values of MWCNTs in the literature.

9435-53, Session 10A

Nanoscale optimization of ultrasonic dispersion of multi-walled carbon nanotubes in polyelectrolyte aqueous solution

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As structural engineers use next-generation materials that have complex aging and damage modes and legacy structures that are nearing their service lives, in situ monitoring of these structures' health is necessary to keep the public safe from potential structural failures. One of the thrust areas in structural health monitoring is using electrically-based methods for damage detection and structural deterioration. These methods detect for changes in electrical conductivity which have been correlated to certain

damage modes. In order to apply this sensing methodology to large-scale structures, the structure must have appropriate electrical properties, or a conductive material is applied to the surface. One main thrust area of electrical sensing is applying carbon nanotube thin films to structures. For large scale deposition, we have developed a latex-based carbon nanotube (CNT)-poly(vinylidene fluoride) (PVDF) thin film that is able to be spray-deposited for large areal deposition. It is widely known that the amplitude of electrical conductivity of these nanocomposites is directly linked to the CNT weight ratio in the film and the quality of the dispersion. Using ultrasonic energy to separate the CNTs has been shown to de-agglomerate the CNTs but can cleave them into shorter CNTs. This study reports the optimization of ultrasonication time and amplitude of multi-walled carbon nanotubes dispersed and polymer-wrapped into a poly(sodium 4-styrenesulfonate) (PSS) solution. The resulting CNTs are analyzed for length and agglomeration under AFM as well as for conductivity of the resulting CNT-PVDF thin film.

9435-54, Session 10A

A remote-readable graphite oxide (GO) based tamper-evident seal with self-reporting and self-authentication capabilities

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The blossoming of sensing solutions based on the use of graphene-oxide (GO) thin films and the pervasive exploration of compressed sensing (CS) for developing structural health monitoring applications suggest the possibility of combining these two research areas in a novel family of smart structures. Specifically, the authors propose an architecture for security-related applications that leverages the tunable electrical properties of a GO-paper-based tamper-evident seal with a compressed-sensing (CS) encryption/authentication protocol. The electrical properties of GO are sensitive to the traditional methods that are commonly used to remove and replace paper-based tamper-evident seals (mechanical lifting, solvents, heat/cold temperature changes, steam). The sensitivity of the electro-chemical properties of GO to such malicious insults is exploited in this architecture. This is accomplished by using GO paper to physically realize the measurement matrix required to implement a compressive sampling procedure. The proposed architecture allows the seal to characterize its integrity, while simultaneously providing an encrypted/authentication feature making the seal difficult to counterfeit, spoof, or remove/replace. Traditional digital encryption/authentication techniques are often bit sensitive making them difficult to implement as part of a measurement process. CS is not bit sensitive and can tolerate deviation caused by noise and allows the seal to be robust with respect to environmental changes that can affect the electrical properties of the GO paper during normal operation. Further, the reduced amount of samples that need to be stored and transmitted makes the proposed solution highly attractive for power constrained applications where the seal is interrogated by a remote reader.

9435-55, Session 10A

Development and characterization of polyvinylidene fluoride-polyaniline films for supercapacitor applications

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Piezoelectric polymer nanocomposites are prepared to improve the dielectric properties of Polyvinylidene fluoride (PVDF) for supercapacitor applications. Polyaniline (PANI) was chosen as a filler material to prepare the nanocomposites. PVDF-PANI nanocomposite films were prepared using solvent cast method with different volume fractions of PANI varying from 0.04% to 0.048% of PANI content. The films are characterized for structural, mechanical and surface morphological using X-ray diffraction, differential scanning calorimeter, Raman spectra, Infrared spectra, tensile testing, and scanning electron microscopy. The X-ray diffraction analysis shows that, prepared films were in β -phase. The DSC scans indicated that the degree of crystallinity in PVDF-PANI is improved. Raman and Infrared spectrum further confirm the presence of β -phase of PVDF-PANI film. Tensile properties of PVDF-PANI films were in good agreement with those reported in literature. The surface feature shows that PANI is uniformly distributed in PVDF and also results in disappearance of spherulites. The influence of volume fraction of PANI in PVDF on dielectric properties was analyzed. The results showed that the dielectric permittivity of PVDF-PANI (120) was much higher than that of PVDF (12). The sensitivity of these films was studied on application of a pressure and the voltage response of PVDF-PANI film sensor is 12.4V pk-pk which is steady, with the constant application of 1.85kg weight. The PVDF-PANI film sensor shows higher sensitive with longer period of time as compared to the PVDF film sensor. These films were tested for supercapacitors applications.

9435-56, Session 10A

Self-sensing properties of smart composite based on embedded buckypaper layer

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Advanced polymer matrix composites is brittle material, and local fibre, matrix fracture and bonding delamination will cause the catastrophic failure of the composite. So the strain and damage structural health monitoring of the composite material and its structures is very important for its applications. Basing on the piezo-resistivity effect, micro-pore structure, resin infiltration properties of buckypaper (BP), in this study we develop a self-sensing composite based on embedded BP, which only act as a sensing layer to monitor the strain and damage of the composite. The strain, damage of the composite are reflected by the resistance change of the embedded BP. The strain sensing properties of the BP/epoxy film with different BP aspect ratios was studied with voltammetry method, and the results indicated that there were two stages relation between resistance change and strain, under low strain level ($\sim 2000\mu\epsilon$), the strain sensitivity was nonlinear and unstable, but in the high strain level, the strain sensitivity was high with strain factor about 6.2, which was independent to the dimension of BP layer. The self-sensing composite made of glass fibre reinforced composite with embedded BP show the same strain sensing properties as BP/epoxy film, at same time the damage revolution of the composite could be monitored by resistance development. The SEM characterization demonstrated that the resin can penetrate into BP of the composite, and form strong bonding interface. The self-sensing composite can be applied in further large scale advanced polymer composite materials and structures structural health monitoring.

9435-57, Session 10A

Algorithm for decomposition of additive strain from dense network of thin film sensors

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The authors have developed a capacitive-based thin film sensor for monitoring strain on meso-surfaces. Arranged in a network configuration, the sensing system is analogous to a biological skin, where local strain can be monitored over a global area. The measurement principle is based on a measurable change in capacitance provoked by strain. In the case of bi-directional in-plane strain, the sensor output contains the additive measurement of both principal strain components. In this paper, we present an algorithm for retrieving the directional strain from measurements. The algorithm leverages the dense network application of the thin film sensor to reconstruct the surface strain map. A bi-directional shape function is assumed, and it is differentiated to obtain expressions for planar strain. A least square estimator (LSE) is used to reconstruct the planar strain map from the sensors' measurements, after the system's boundary conditions have been enforced in the model. The coefficients obtained by the LSE can be used to reconstruct the estimated strain map or the deflection shape directly. Results from numerical simulations and experimental investigations show good performance of the algorithm, in particular for monitoring surface strain on cantilever plates and wind turbine blades.

9435-58, Session 10B

Non-contact ultrasonic guided wave inspection of rails: field test results and updates

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The University of California at San Diego (UCSD), under a Federal Railroad Administration (FRA) Office of Research and Development (R&D) grant, is developing a system for high-speed and non-contact rail integrity evaluation. A prototype using an ultrasonic air-coupled guided wave signal generation and air-coupled signal detection in pair with a real-time statistical analysis algorithm has been realized. This system requires a specialized filtering approach based on matched filter due to the inherently poor signal-to-noise ratio of the air-coupled ultrasonic measurements in rail steel. For the same reason, impedance matching techniques have been designed and developed. Various aspects of the prototype have been designed with the aid of numerical analyses. In particular, simulations of ultrasonic guided wave propagation in rails and surrounding air have been performed using both a LISA algorithm and a finite element software (LS-DYNA). Many of the system operating parameters were selected based on Receiver Operating Characteristic (ROC) curves, which provide a quantitative manner to evaluate different detection performances based on the trade-off between detection rate and false positive rate. Preliminary experimental tests have been carried out at the UCSD Rail Defect Farm. The laboratory results indicate that the prototype is able to detect internal rail defects with a high reliability. Results from the first field test scheduled for October 2014 will be presented and discussed.

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9435-59, Session 10B

Impact induced delamination detection and quantification with guided wavefield analysis

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Unexpected damage can occur in aerospace composites due to impact events or material stress during off-nominal loading events. In particular, laminated composites are susceptible to delamination damage due to weak transverse tensile and interlaminar shear strengths. Delamination damage can occur internally, where it is not visible to the naked eye. Such hidden delamination damage must be detected and evaluated before it becomes critical. Developments of reliable and quantitative techniques to detect delamination damage in laminated composites are imperative for safe and functional optimally-designed next-generation composite structures.

This paper studies impact induced delamination detection and quantification by using guided wavefield data and wavenumber analysis. Complex geometry impact-like delamination damage is created through a quasi-static indentation test. A scanning laser Doppler vibrometer is used to acquire guided wave wavefield data. Strong wave interaction and trapping are observed at the delamination region. Delamination detection and evaluation methods are developed using wavenumber field analysis where the dominant local wavenumber is determined at each spatial location. The approach was applied to a single Teflon insert simulating a delamination as well as the real, impact induced delamination damage. Analysis results show that the wavenumber field can not only determine the delamination location, but also provide quantitative evaluation regarding the delamination size and shape. The impact induced delamination detection was compared to ultrasonic C-scan data. Good agreement was observed, showing that the wavenumber approach can yield accurate delamination location and size information.

9435-60, Session 10B

Effects of structure thickness on ultrasound generation and sensing using bonded PWASs

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This paper presents an analytical simulation model to study the effects of slender beam/bar thicknesses on ultrasound generation and sensing using bonded piezoelectric wafer active sensors (PWASs). By adopting shear lag model1, the in-plane deformation of the PWAS is coupled with the in-plane deformation of the structure which undergoes both the longitudinal and the flexural deformation2. Based on the parametric simulation, it is found out that there is an optimized thickness of the structure at which the pitch-catch signal is significantly high for both the longitudinal and the flexural mode of the structure. In addition, for the longitudinal mode of the structure, the magnitude of the ultrasound pitch-catch signal reduces with the increase in thickness of the structure, and thus, for higher thickness of the structure, the longitudinal mode won't be excited. In contrast, the pitch-catch signal in the flexural mode of the structure increases with the increase in thickness of the structure. Three specimens having different thicknesses were instrumented with PWASs at a given adhesive thickness in order to validate the simulation predictions. Based on the experiments, it is observed that pure flexural mode of the structure provides greater magnitude of the pitch-catch signals compared with that of the longitudinal mode. Interestingly, by adopting time-frequency analysis of the ultrasound pitch-catch signals acquired from three specimens, we observed that the thicker beam, i.e. equal to or more than 5 mm thicknesses does not have longitudinal mode which validates

the simulation prediction. The simulated pitch-catch signals will be matched with the measurements by tuning the unknown adhesive layer parameters.

9435-61, Session 10B

Structural damage identification using piezoelectric impedance and Bayesian inference

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The impedance information measured by piezoelectric sensor can be used for damage detection. When combined with a credible baseline model, the impedance information may further lead to the identification of location and severity of damage. In practice, however, damage identification is challenging, primarily due to that the problem is usually under-determined and the inverse analysis is sensitive to uncertainty/noise. In this research we formulate a Bayesian inference-based identification framework, in which the direct inversion process is avoided. Moreover, the Bayesian framework conveniently incorporates the probabilistic analysis into the decision making. Correlated numerical and experimental studies are performed to validate the new method proposed.

9435-62, Session 10B

Spira Mirabilis: a shaped piezoelectric sensor for impact localization

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In this work, a novel piezoelectric sensor for guided wave detection on laminate composite and metallic structures is presented. The sensor is composed by two electrodes (E1, E2) on the top surface of the device, plus a common electrode EC on the bottom surface, which is bonded to the structure to be inspected. E1 has a circular shape, while E2 is shaped as a segment of a logarithmic spiral (or spira mirabilis). Because of this asymmetric shaping, the wavefront of a generic acoustic event (e.g. the one generated by an impact) hits the electrodes in two points whose distance "D" varies with the Direction of Arrival (DoA) of the wave itself. With a dedicated processing procedure, the information about the distance D (and the DoA) can be retrieved from the waveforms acquired and digitized at the two electrodes. In particular, the procedure computes the cross-correlation of the dispersion compensated signals, and infers the distance D by extracting the position of the maximum of the cross-correlation envelope. The effectiveness of the proposed technology is assessed with a numerical and experimental validation.

9435-63, Session 10B

Influence of higher and sub harmonics in time reversed Lamb wave generated and sensed using de-bonded piezoelectric wafers

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Time reversed lamb wave based damage detection is very suitable for online Structural Health Monitoring (SHM). Time reversibility is the process in which a response signal recorded at a receiver location is reversed in time and transmitted back through the receiver to the original transmitter location. In the absence of any non-linearity in the path between the transmitter-receiver locations, theoretically the signal received back at the original

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transmitter location (reconstructed signal) is identical to the original input signal. Therefore, differences in the transmitted and reconstructed signals are indications of the possibility of defects. Non linear higher harmonics are generated in the Lamb waves which are generated and sensed using piezoelectric wafer transducers (PWT) which are partially de-bonded from the host plate. Experimental and numerical studies of the influence of higher harmonics in time reversed reconstruction of Lamb waves in aluminium plate are presented in this work. Root mean square deviation (RMSD) and percentage correlation are used to quantify the extend of time reversed reconstruction. Experiments are carried out using de-bonded actuator and receiver separately and the influence of actuator de-bonding is found to have more influence. Generation of higher harmonics at the sensor location is further studied by comparing signals sensed by PWT and Laser Doppler vibrometer. It is also observed that the amplitude of the input signal plays a major role in the generation of higher harmonics. 2D finite element simulations are done for transducer de-bonding and cracks. Influence of different crack orientations and sizes on change in reconstruction is also studied.

9435-64, Session 11A

Recognition of human activities using depth images of Kinect for biofied building

Ami Ogawa, Akira Mita, Keio Univ. (Japan)

These days, people need various functions in their living spaces because of an aging society, promotion of energy conservation, and diversification of lifestyles. To meet this requirement we propose "Biofied Building". "Biofied Building" is the system learnt from living beings. As a key function of this system, accumulates the various information in database using small sensor agent robots, and control the living spaces. However, there are various kinds of information about the living spaces, for example human activities can be triggers for lighting or air conditioning control. By doing so, customized space is possible. Human activities are divided into two groups, the activities consisting of single behavior and the activities consisting of multiple behaviors. For example, "standing up" or "sitting down" consists of a single behavior. These activities are accompanied by large motions. On the other hand "eating" consists of several behaviors, holding the chopsticks, catching the food, putting them in mouth, and so on. These are continuous motions. Considering the characteristics of two types of human activities, we individually use two methods, R transformation and variance. In this paper, we focus on the two different type of human activities, and purpose the two methods of human activity recognition methods for construction of the database of living space for "Biofied Building". Finally, we compare the results of both methods.

9435-65, Session 11A

The smart Peano fluidic muscle: a low profile flexible orthosis actuator that feels pain

Allan J. Veale, The Univ. of Auckland (New Zealand) and Auckland Bioengineering Institute (New Zealand); Iain A. Anderson, Auckland Bioengineering Institute (New Zealand) and The Univ. of Auckland (New Zealand) and StretchSense (New Zealand); Sheng Quan Xie, The Univ. of Auckland (New Zealand)

Robotic orthoses have the potential to provide effective rehabilitation while overcoming the availability and cost constraints of therapists. However, current orthoses use actuation components designed for industrial applications, not interacting with humans. The result is heavy, rigid, and bulky actuators whereas an effective orthosis must be light, compliant, and portable.

Pneumatic muscle actuators (PMAs) are a popular orthosis actuator because of their inherent compliance, high force, and muscle-like load-displacement characteristics. However, the circular cross-section of PMA gives them a large dead volume to surface area. This increases PMA's profile and reduces their flexibility. PMA are also notoriously unreliable, but their soft nature makes monitoring their physical state to improve their robustness a challenge.

Here the Peano fluidic muscle, a new low profile yet high surface area to dead volume PMA geometry is introduced. This PMA is smart, featuring bioinspired embedded pressure and flexible magnetic encoder sensors. Given this pressure and displacement sensor data, experimental validation shows that a parameterised analytical model can be used to predict the muscle's force for quasi-static motion with a resolution comparable to biological muscles. The result is a high-force compliant actuator less than 15mm thick that can be discreetly worn under an orthosis user's clothing. This smart PMA sets a precedent for flexible orthosis actuation that uses embedded sensors to prevent damage to the actuator and its environment.

9435-66, Session 11B

A wind turbine hybrid simulation framework considering aeroelastic effects

Wei Song, Weihua Su, The Univ. of Alabama (United States)

Wind energy is one of the most promising renewable energy resources in US. Over the past 40 years, wind energy manufacturers have successfully pushed the design of wind turbine towards more economical and efficient power generation. The wind turbine sizes have been dramatically changed. The rotor diameter has been increased from 15m, 50kW in 1980 to today's 250m, 6-8MW power generation. However, with the additional wind loading demand brought by the larger size, researchers have become more and more concerned with structural safety of wind turbines.

In performing an effective structural analysis for wind turbine, the simulation of turbine aerodynamic loads is of great importance. The interaction between the wake flow and the blades may impact turbine blades loading condition, energy yield and operational behavior. Ideally, direct experimental measurement of wind flow field and wind profiles around wind turbines is very helpful to the turbine structural analysis. However, with the growth of the size of wind turbines for higher energy output, it is not feasible to obtain all the desired data in wind-tunnel and field tests.

In this study, a hybrid simulation experimental framework is proposed to resolve this issue. In the proposed framework, the aerodynamic-dominant components, such as the turbine blades and rotor, are simulated in computer, whereas the turbine tower, where the collapse or failure may occur with highly nonlinear behavior, is tested physically in a structures laboratory. By applying advance algorithms and high-performance actuators to interface the numerical and physical components, the dynamic behavior of the original wind turbine can be captured. This experimental framework can provide a promising platform to investigate large-scale wind turbine dynamic behavior under realistic loading conditions.

9435-67, Session 11B

Adaptive pitch control of wind turbines to mitigate loads

Yuan Yuan, Jiong Tang, Univ. of Connecticut (United States)

In this paper, an application of Model Reference Adaptive Control of pitch controlled wind turbines is presented to make a trade-off between the maximum energy captured and long term maintenance cost. A wind turbine may suffer from extreme loads and fatigue when operated in a high speed, which leads to a shorter lifetime. In the reference model, the optimal rotor speed is updated by the sampling interval, thus the main control objective is to track the optimal rotor speed under the time varying wind speed and

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other uncertainties. The Lyapunov stability is used to design the adaptive pitch algorithm. The proposed algorithm is tested with a simplified nonlinear model of a wind turbine, and then compared with the performance of gain scheduled PI controller. The results show adaptive pitch algorithm has better characteristics.

9435-68, Session 12A

Seven-year-long crack detection monitoring by Brillouin-based fiber optic strain sensor

Michio Imai, Kajima Technical Research Institute (Japan)

Brillouin-based sensor can provide us distributed strain information along the whole length of the sensing optical fiber. The sensor has been used in a wide range of civil engineering applications, because no other tool can satisfactorily detect the location of the unpredictable event such as a crack. Detailed strain information can identify even a fine crack as a local strain change, thus Brillouin optical correlation domain analysis (BOCDA), which offers high spatial resolution by using stimulated Brillouin scattering, is especially expected as one of the best candidates for crack detection on concrete structures. The author installed the surface-mounted optical fiber on a fiber reinforced concrete deck, and has periodically monitored strain distribution for seven years. In this paper, it is demonstrated how a BOCDA-based strain sensor can be employed to monitor cracks in concrete for years.

9435-69, Session 12A

Pipeline corrosion assessment using embedded Fiber Bragg grating sensors

Liang Xiao, Ying Huang, Sahar A. Galedari, Fardad Azarmi, North Dakota State Univ. (United States)

Corrosion is a leading cause of failure in metallic transmission pipelines. It significantly impacts the reliability and safety of metallic pipelines. An accurate assessment of corrosion status of the pipelines would contribute to timely pipeline maintenance and repair and extend the service life of the associated pipelines. To assess pipeline corrosion, various technologies have been investigated and the pipe-to-soil voltage potential measurement was commonly applied. However, remote and real-time corrosion assessment approaches are in urgent needs but yet achieved. Fiber optic sensors, especially, fiber Bragg gating (FBG) sensors, with unique advantages of real-time sensing, compactness, immune to EMI and moisture, capability of quasi-distributed sensing, and long life cycle, will be a perfect candidate for long-term pipeline corrosion assessment. In this study, FBG sensors are embedded inside pipeline external coating for corrosion monitoring of on-shore buried metallic transmission pipelines. Detail sensing principle, sensor calibration and embedment are introduced in this paper together with experimental corrosion evaluation testing. Upon validation, the developed sensing system could serve the purpose of corrosion monitoring to the numerous metallic pipelines across nation and would possibly reduce the pipeline corrosion induced tragedies.

9435-70, Session 12A

Damage monitoring of CFRP retrofits using triboluminescent optical fiber sensors

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Okenwa O. Okoli, Florida State Univ. (United States); Tarik J. Dickens, Florida State Univ. (United States) and High Performance Materials Institute (United States)

With nearly 25% of bridge infrastructure deemed deficient, repair of concrete structures is the need of the hour. Fiber reinforced polymer (FRP) laminate materials offer an ideal alternative to traditional repair technology, because of their high strength- & stiffness-to -weight ratios. In addition, FRP materials offer significant potential for lightweight, cost-effective and durable retrofit. One drawback of using CFRP retrofitting is its brittle-type failure; caused by its nearly linear elastic nature of the stress-strain behavior. This causes a strength reduction of the retrofitted member, thus the health of the retrofit applied on the structure becomes equally important to sustain the serviceability of the structure. This paper provides a system to monitor damage on the CFRP retrofit through integrated triboluminescent optical fiber sensors to provide damage sensing functionality. Ten reinforced concrete beams were precracked and retrofitted using CFRP laminates, using principle of 'Additive Manufacturing' (AM). Net shaped molds are fabricated for application of fiber-reinforced polymer composites, which will offer precise manufacturing and installation of the CFRP retrofit on a structural member. These beams will be tested under constant stress to allow the retrofitting to fail while evaluating the performance of the sensing system. Finite element analysis will be conducted to validate the results. The retrofit damage-monitoring scheme aims at providing a tool to reduce the response time and decision making involved in maintenance of a structure.

9435-71, Session 12A

Evaluation of the use of fiber optic sensors in identification of fresco fracturing patterns

Branko Glisic, Dorotea H. Sigurdardottir, David Dobkin, Princeton Univ. (United States)

Ageing of materials and extreme events tend to damage structures, and ancient historical monuments are particularly vulnerable due to their age and long-term exposure to adverse events and influences. As an example, the wall paintings (frescoes) from the seventeenth century BCE found at the archaeological site of Akrotiri (Santorini, Greece) were recovered from volcanic ash in fragments with dimensions ranging from a few centimeters to a few decimeters. Identification of the fracturing patterns is necessary to piece together the fragments of frescos. The current identification technique involves experimental study of fracture development on plaster specimens using a high-speed camera combined with sophisticated algorithms for shape recognition. However, the use of high-speed camera is challenging due to very demanding data processing and analysis, and features some inaccuracies in identification of fracture initialization. This paper aims to evaluate whether or not short-gauge fiber optic sensors (FOS) based on Fiber Bragg-Gratings (FBG), can be used to help identify the fracturing patterns of falling frescoes as an alternative to high-speed cameras. In total four tests were performed using surface and embedded sensors on various plaster specimens. The data taken by sensors installed on the surface of the specimen were more complex to analyze and interpret than the data taken by embedded sensors, since the former reflected combined influence from fracture and bending. While their practicality is challenged by cost, moderately dense arrays of embedded FOS are found to be a plausible alternative to high speed-camera in the experiments.

9435-72, Session 12B

Hyperspectral imaging utility for transportation systems

Raj Bridgelall, J. Bruce Rafert, Denver Tolliver, North Dakota State Univ. (United States)

The transportation system is massive, open, and dynamic. Regular

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performance and condition assessments of the complex interacting networks of roadways, bridges, railroads, pipelines, waterways, airways, and intermodal ports are expensive. Hyperspectral imaging is an emerging remote sensing technique for the non-destructive evaluation of multimodal transportation infrastructure. Unlike panchromatic, color, and infrared imaging, each layer of a hyperspectral image pixel records reflectance intensity from one of dozens of relatively narrow wavelength bands that span a broad range of the electromagnetic spectrum. Hence, every pixel of a hyperspectral scene provides a unique spectral signature that offers new opportunities for informed decision-making in transportation systems development, operations, and maintenance. Spaceborne systems capture images of vast areas in a short period but provide lower spatial resolution than airborne systems. Practitioners use manned aircraft to achieve higher spatial and spectral resolution, but at the price of longer data acquisition time and less uniformity. The rapid size and cost reduction of unmanned aircraft systems promise a third, and potentially more affordable alternative. This research formulates a theoretical framework for a pushbroom type of hyperspectral imaging system on each type of data acquisition platform. The study then applies the framework to assess the relative potential utility of hyperspectral imaging for previously proposed remote sensing applications in transportation. The authors also introduce and suggest new potential applications of hyperspectral imaging in transportation asset management, network performance evaluation, and risk assessments to enable effective and objective decision- and policy-making.

9435-73, Session 12B

A digital sampling moiré method for two-dimensional displacement measurement

Xinxing Chen, Chih-Chen Chang, Hong Kong Univ. of Science and Technology (Hong Kong, China)

Measuring static and dynamic displacement of in-service structures is an important issue for the purpose of design validation, performance monitoring or safety assessment. Currently available techniques can be classified into indirect measurement and direct measurement. Indirect measurement techniques include double integration of recorded accelerations and inferring from mathematical models using measured strains. Applicable direct measurement techniques include the global position system (GPS) and the laser Doppler vibrometers. These direct and indirect measurement methods however have their problems and limitations.

Recently, vision-based techniques have been developed for structural displacement measurement. Most of these techniques follow the classical pinhole model and rely on the geometrical relationship between the camera and the target attached on the structure for displacement measurement. In this paper, a technique based on digital sampling moiré is investigated for the displacement measurement of civil engineering structures. As the moiré fringes can magnify the pattern's movement, this technique is expected to provide more accurate displacement measurement than the other vision based approaches. This digital sampling moiré technique uses one camera to capture digital images containing a grating pattern. The images are down sampled and interpolated to generate moiré fringes which phase information can be then used to calculate displacements of the grating pattern. Also, depending on the grating pattern, this technique can be used to measure one dimensional or two dimensional displacements. A series of laboratory tests are conducted to verify the accuracy of this technique. Potential of this technique for civil engineering applications will also be discussed.

9435-74, Session 12B

Strain characterization of embedded aerospace smart materials using shearography

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Groves, Technische Univ. Delft (Netherlands)

The development of smart materials for embedding in aerospace composites provides enhanced functionality for future aircraft structures. Embedded heater elements in the leading edge of fibre metal laminate (FML) wing structures provide anti-icing and de-icing capabilities. However when the embedded heater is switched on it can act as an active aerodynamic element, modifying the leading edge of the wing. Therefore, full-field defect detection, strain and shape measurement are important to characterize this behaviour of the structure during thermal cycling.

In this research, a shearography (speckle shearing interferometry) instrument is used for measuring surface displacement gradient giving a quantitative estimate of in- and out-of-plane surface strain. The specimen under test was illuminated by expanded laser beam; speckle patterns were recorded by pre-calibrated system of four spatially-distributed shearing cameras, with Michelson interferometers acting as the shearing device.

For the experimental part, flat FML specimens of 500x500 mm were manufactured with different thicknesses, mesh patterns of embedded copper heaters (linear, angled, and serpentine) and delamination. Surface strain maps were obtained at different temperatures according to the flight conditions and the effect of the heater pattern on total surface strain was explored in detail.

Results of the experiments are analysed with respect to the optimization of heating regime and the heater element pattern and location. Furthermore, the possibility of FML defect detection with thermal loading by embedded heater elements and shearography is also investigated.

9435-75, Session 12B

A stereovision-based method for the whole process of collapse measurement of a three-floor frame model under earthquake excitation

Baohua Shan, Wenting Yuan, Xiaoyang Huo, Shuang Li, Harbin Institute of Technology (China)

Traditional contact sensors usually break with the failure of structures or model in lab or actual engineering, and whole dynamic response process of structures couldn't be finally obtained. To solve this problem, a stereovision-based 3D deformation measurement method is proposed to detect the whole process of structure deformations in this paper. The parallel binocular stereovision model is employed to calculate 3D coordinates of measured point on structures or models. And stereo matching of corresponding measured points on the left and right image at the same time is accomplished by the feature guided Bayesian estimation algorithm, which can generate dense disparity map quickly. Moreover, An ROI-based search strategy algorithm is presented to improve sequence matching of DIC method. Based on above principle, MATLAB is selected to compile the stereovision-based 3D deformation measurement software. A three-floor frame model subjected to earthquake excitation is tested with the proposed method in lab. The experiment results show good agreement with LVDT data during small deformation stage, it is verified that the presented approach is reliable. At large deformation stage, LVDT sensors are destroyed, the whole dynamic response process curves of three-floor frame models are only obtained by the stereovision-based method. Experimental results fully prove that the proposed approach is feasible and useful for monitoring whole-process deformations of structures even at collapse stage.

9435-14, Session 13A

Application of computed tomography techniques to heat transfer physics for use in damage detection

Nephi R. Johnson, Jerome P. Lynch, Ann E. Jeffers, Univ. of Michigan (United States)

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The detection of damage in structures at its earliest stages has many economical and safety benefits. Permanent monitoring systems using various forms of sensor networks and analysis methods are often employed to increase the frequency and diagnostic capabilities of inspections. Some of these techniques provide spatial/volumetric information about a given area/volume of a structure. Many current spatial sensing techniques can be costly and aren't permanently deployable (e.g., IR camera thermography). For this reason intricate analysis methods using permanently deployable sensors are being developed (e.g., ultrasonic piezoelectrics, sensing skins). One approach is to leverage the low cost of heaters and temperature sensors to develop an economical, permanently installable heat transfer based method of spatial damage detection. This paper presents a method similar to that of X-ray computed tomography (CT). However, the theories for X-ray CT must be adapted to properly represent heat transfer as well as account for the relatively large and immobile sensors spacing used on a structure (i.e., there is a finite number of heaters/sensors permanently installed around the perimeter of the area of interest). The derivation of heat transfer computed tomography is discussed in this paper. A high fidelity finite element method (FEM) model is used to verify the analytical derivation of individual steps within the method as well as simulate the complete damage detection technique. An experimental setup using damaged and undamaged aluminum plate specimens is used to validate this new technique. The simulation and experimental results are discussed along with possible improvements and modifications to the technique.

9435-76, Session 13A

Investigation into phosphors for corrosion detection in aerospace and naval applications

Vishnu Baba Sundaesan, Srivatsava Krishnan, The Ohio State Univ. (United States)

Corrosion protection coatings are applied to metallic surfaces of aircrafts, ships, submarines, etc., to prevent corrosion and increase performance lifetime. Continuous monitoring and early detection of damage to the corrosion protection coatings is of utmost importance to protect base metal. In this context, a novel approach to detect corrosion of coatings using phosphors as paint primer additives is being developed in our group and will be presented in this talk. Phosphors are used for damage detection of corrosion protection coatings for the first time and we propose this approach as an efficient alternative to contemporary inspection methods. The phosphor investigated as corrosion sensor is a long persistent blue-green phosphor - Strontium Aluminate (SAO) doped with Europium and Dysprosium (SrAl₂O₄:Eu²⁺,Dy³⁺). SAO-Eu/Dy has an absorption peak centered at around 320nm and an intense emission peak at around 525nm, and is selected for its long afterglow (9500 minutes) and very high quantum efficiency (32%). In our approach, SAO-Eu/Dy is added to the primer layer underneath the corrosion protection layer for use as corrosion sensing coating. Damage to the corrosion protection layer would expose the SAO-Eu/Dy layer underneath and enable the detection of damage. Detection of the damage will utilize the phosphorescence of the SAO-Eu/Dy layer through in-service imaging and detection methodologies. It is anticipated that the phosphor-based approach to detect damage to a corrosion protective coating would be simple, quick, non-destructive and would not require use of expensive technology for detection or post-processing.

9435-77, Session 13A

Thermal analysis of brazing seal and sterilizing technique to break contamination path for Mars sample return

Xiaoqi Bao, Mircea Badescu, Yoseph Bar-Cohen, Jet Propulsion Lab. (United States)

Returning Martian samples to Earth for extensive analysis is in great interest

of the planetary science community. It is important to make sure the mission does not bring any living microbes that may possibly exist on Mars back to Earth's environment. A brazing sealing and sterilizing technique was proposed to break the Mars-to-Earth contamination path. Thermal analysis of the brazing procedure was conducted for several container configurations. The temperature profiles of the Martian samples being sealed in the container were predicted. The results show that the sealing and sterilizing process can be controlled such that the samples temperature is maintained below the required level and the brazing technique is a feasible approach to break the contamination path.

9435-78, Session 13A

Spiral passive electromagnetic sensor (SPES) for smart sensing and de-icing

Michele Meo, Univ. of Bath (United Kingdom)

A wireless Spiral Passive Electromagnetic Sensor (SPES) was developed to monitor the complex permittivity of a surrounding medium. The sensor is a self-resonating planar pattern of electrically conductive material. This paper presents studies for using the SPES-for smart-sensing showing its ability to monitor humidity and temperature gradient, and acting as an ice protection tool. An oscillating signal is used to interrogate remotely the sensor with a single loop antenna or wiring it directly to a spectrum analyzer and monitoring the backscattering signal. The excited sensor responds with its own resonant frequency, amplitude and bandwidth that can be correlated to physical quantities to be monitored. Our studies showed the capability of the sensor to monitor temperature and humidity changes in composite materials and uniformly produce induction heating when the conductive path is activated by an external electric power supply that can be used for deicing of aircraft structures.

9435-79, Session 13A

Testing of tactile sensors for space applications

Lisa Kogan, Timothy L. Weadon, Thomas Evans, David B. DeVallance, Edward M. Sabolsky, West Virginia Univ. (United States)

There is a need to integrate tactile sensing into robotic manipulators performing tasks in space environments, including those used to repair satellites. Integration can be achieved by embedding specialized tactile sensors. Reliable and consistent signal interpretation can be obtained by ensuring that sensors with a suitable sensing mechanism are selected based on operational demands, and that materials used within the sensors do not change structurally under vacuum and expected applied pressures, and between temperatures of -80°C to +120°C. The sensors must be able to withstand space environmental conditions and remain adequately sensitive throughout their operating life. Additionally, it is necessary to integrate the sensors into the target system with minimum disturbance while remaining responsive to applied loads. Previous work has been completed to characterize sensors within the selected temperature and pressure ranges. The current work builds on this investigation by embedding these sensors in different geometries and testing the response measured among varying configurations. Embedding material selection was aided by using a dynamic mechanical analyzer (DMA) to determine stress/strain behavior for adhesives and compliant layers used to keep the sensors in place and distribute stresses evenly. Electromechanical characterization of the embedded sensor packages was conducted by using the DMA in tandem with an inductance-capacitance-resistance (LCR) meter. Methods for embedding the sensor packages were developed with the aid of finite element analysis and physical testing to account for specific geometrical constraints. Embedded sensor prototypes were tested within representative models of potential embedding locations to compare final embedded sensor performance.

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9435-80, Session 13B

The design, characterization, and comparison of MEMS comb-drive acoustic emission transducers with the principles of area-change and gap-change

Minoo Kabir, Hossain Saboonchi, Didem Ozevin, Univ. of Illinois at Chicago (United States)

Comb-drive transducers are made of interdigitized fingers formed by the stationary part known as stator and the moving part known as rotor, and based on the transduction principle of capacitance change. They can be designed as area-change or gap-change mechanism to convert the mechanical signal at in-plane direction into electrical output. The comb-drive transducers can be utilized to differentiate the wave motion in orthogonal directions when they are utilized with the out-of-plane transducers. However, their sensitivity is weak to detect the wave motion released by newly formed damage surfaces. In this study, Micro-Electro-Mechanical System (MEMS) comb-drive Acoustic Emission (AE) transducer designs with two different mechanisms are designed, characterized and compared for sensing high frequency wave propagation. The MEMS AE transducers are manufactured using MetalMUMPs (Metal Multi-User MEMS Processes), which use electroplating technique for highly elevated microstructure geometries. Each type of the transducers is numerically modeled using COMSOL Multiphysics program in order to determine the sensitivity based on the applied load. The transducers are experimentally characterized and compared to the numerical models. The experiments include laser excitation to control the direction of the wave generation, and actual crack growth monitoring of aluminum 7075 specimens loaded under fatigue. Behavior and responses of the transducers are compared based on the parameters such as waveform signature, peak frequency, damping, sensitivity, and signal to noise ratio. The comparisons between the measured parameters are scaled according to the respective capacitance of each sensor in order to determine the most sensitive design geometry.

9435-81, Session 13B

Developing a dual-beam gyroscope to measure rotation rate

S. Amir Mousavi Lajimi, Simon Fraser Univ. (Canada)

We are modeling a Coriolis vibratory gyroscope, based on a composite beam structure, used as a sensor. The composite beam includes a primary clamped-clamped beam excited by an electrostatic force and a cantilever beam mounted on the primary structure used as a sense element. The sensor is used to detect out-of-plane rotation rate coupling the secondary and primary motions. Variations of the design are introduced used to measure in-plane rotation rate vector. We model the system and perform an analysis of the static and dynamic responses of the structure.

In this work, we propose a model of a gyroscope based on a dual beam structure including a clamped-clamped (drive) beam and a (sense) cantilever beam. To measure out-of-plane rotation rate, while the drive beam is excited in x-direction, the vibration of the sense beam is measured in the y-direction. Various configuration of the same structure can be used to measure other components of the rotation rate vector. 1. To this end, the drive and sense electrodes must be positioned such that the drive and sense directions are properly coupled through the Coriolis term. To measure a rotation rate about the longitudinal axis of the clamped-clamped beam, the sense electrode is placed under the sense beam, and to measure a rotation rate about the longitudinal axis of the cantilever beam, the drive electrode is placed under the fixed-fixed beam.

The drive electrode is actuated by a combination of DC and AC signals while the sense electrode is actuated by a constant bias DC voltage. The electrostatic force introduces strong nonlinearity into the system which further complicates the behaviour of the system. By using the DC voltage, the drive and sense frequencies are tuned at the desired values to obtain different response behaviour.

9435-82, Session 13B

A coin size, 40mW, 20 grams sensor node for guided waves detection

Nicola Testoni, Luca De Marchi, Univ. degli Studi di Bologna (Italy); Alberto Ferraro, University of Bologna (Italy); Alessandro Marzani, Univ. degli Studi di Bologna (Italy)

In this work, a small footprint, low power, and light weight sensor node for guided wave detection on laminate composite and metallic structures is presented. This device is meant as a basic building block for smart structure passive sensor networks development. It draws power from a two-wires data-over-power (DoP) network communication interface, which is also used for half-duplex data handling at 200kbps. Each node is roughly 20x24mm, consumes less than 40mW, and weights less than 20 grams, making it attractive for aerospace systems where size, power and weight reduction are crucial. Elastic waves generated from impacts and propagating on the structure are recorded by an innovative, patent-pending, dual-element piezoelectric transducer and processed by an embedded low-voltage 8-bit PIC. A 1Mbit SPI serial SRAM is used for data storage while program instruction are stored in the PIC embedded 7 KB flash. A low-voltage, high-speed, half-duplex RS485 transceiver with an internal, programmable termination resistance is used to interface the PIC to the bus through a filtering mesh of passive components. This mesh also connects to a low-dropout voltage regulator, allowing it to draw power from the DoP bus without interfering with data transmission. A separate gateway device has also been developed: it is capable to simultaneously interface and feed the DoP bus by drawing power either from the USB or from an external power supply. A network counting up to 256 nodes can be implemented and interfaced to a PC for real-time impact detection applications.

9435-83, Session 13B

Quantification of seismic damage in steel beam-column connection using PVDF strain sensors and model-updating technique

Akiko Suzuki, Masahiro Kurata, Kyoto Univ. (Japan); Xiaohua Li, Kyoto University (Japan); Kaede Minegishi, Kyoto Univ. (Japan); Zenyung Tang, Beijing Univ. of Technology (China); Andrew Burton, University of Michigan (United States)

Recent earthquakes such as 2011 Christchurch and Tohoku illustrated that a lack of quantitative information on the conditions of the affected structures potentially paralyzed society by delaying decision-making for evacuation and re-occupation significantly. In steel frames, even severe damage such as fracture at connections are difficult to be identified by visual inspection since almost all steel members are covered by fire-proofing and architectural finishing.

This paper presents the concept and experimental study of an autonomous condition assessment technique quantifies the amount of fracture occurred in steel beam-column connections and evaluates their residual strength. The developed system utilizes a few PolyVinylidene DiFluoride (PVDF) strain sensors to evaluate the moment distribution in a connection under ambient vibrations at the building's first mode. A simple analysis model of the connection is updated as the distribution changes with seismic damage, and the residual moment of inertia at damaged sections and the lateral strength of the connection are estimated. For verifying the technique, a novel testing environment was design to simulate seismic damage of beam-column connections incrementally by quasi-static cyclic loading and, as damage progress, to vibrate the connections at the first mode of buildings. Two quarter-scaled connections were tested. The proposed technique succeeded to estimate the amount of fracture and the residual strength with the difference of 15% or smaller to experimental observations.

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9435-84, Session 13B

Experimental feasibility analysis of self-powered magnetic shape memory alloy based sensors

Constantin Ciocanel, Jason Dikes, Edward Smaglik, Niranjana Venkatraman, Northern Arizona Univ. (United States)

Magnetic shape memory alloys (MSMAs) are a class of smart materials that exhibits high strain (up to 10%), fast magneto-mechanical time response (milliseconds level), and a change in magnetization during deformation. Due to these characteristics, the material is commonly used for actuation, sensing and power harvesting. In this paper, we investigate the feasibility of development of a self-powered MSMA based sensor. A self-powered MSMA based sensor takes advantage of the change in material magnetization, which can be harnessed for sensing and power harvesting purposes. In particular, we evaluated the power output achievable with two MSMA elements, which deform simultaneously, and which had the pick-up coils connected either in series or in parallel. The results show that the highest output is obtained when the two MSMA specimens are deformed simultaneously and their corresponding pick-up coils are connected in series. The power output levels appear to be large enough to support the development of a self-powered sensor.

9435-85, Session 14A

Relation between repeatability and speed of robot-based systems for composite aircraft production through multilateration sensor system

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Fiber composites are becoming increasingly important in different fields of lightweight application. To guarantee the estimated demand of components made of carbon fiber reinforced plastics the use of industrial robots is suggested in production. High velocity of the layup process is addressed to significantly increase the production rate. Today, the layup of the fiber material is performed by gantry systems. They are heavy weight, slow and the variety of possible part shapes is limited. Articulated robots offer a huge operational area in relation to their construction size. Moreover, they are flexible enough to layup fiber material into different shaped molds. Thus, standard articulated robots are less accurate and more susceptible to vibration than gantry systems.

Therefore, this paper illustrates an approach to classify volumetric errors to obtain a relation between the achievable speed in production and precision. The prediction of an achievable precision at a defined speed is the result. Based on the measurement results the repeatability of the robotic unit within the workspace is calculated and presented. At the minimum speed that is applicable in production the mean repeatability is less than 30 μm . Subsequently, an online strategy for path error compensation is presented. The approach uses a multilateration system that consists of four laser tracer units and it measures the current absolute position of a reflector mounted at the endeffector of the robot. By calculating the deviation between the planned and the actual position a compensation motion is applied. The paper concludes with a discussion for further investigations.

9435-86, Session 14A

Soliton-based detection of delaminations and weak bonds in laminated composites

Eunho Kim, Taru Singhal, Brian Chang, Jinkyu Yang, Univ. of Washington (United States)

In this presentation, we report a new diagnostic method based on stress wave solitons to identify delaminations and potentially, weak bonds in carbon fiber reinforced polymer (CFRP) composites. As composite materials are widely employed in commercial aircrafts, adhesive bonding gains more importance due to their unique advantages, such as light weight, simplified fabrication process, and reduced stress concentration compared to mechanical fastener joints. However, their applications to key structural elements in aircrafts are substantially restricted because of the possibility of delaminations and weak bonds (including kissing bonds) resulting from imperfection at bonding interfaces, e.g., pores, disbond, and contaminants. Undetected delaminations and/or weak bonds in composites can cause abrupt rupture of structures during operations, potentially leading to catastrophic failure in aircraft structures. In this study, we design, fabricate, and test a new type of sensor device that uses stress wave solitons to detect the areas of delaminations and weak adhesive bonds in CFRP. Stress wave solitons are tsunami-like nonlinear waves, which can be efficiently formed in nonlinear phononic crystal sensors. By using these sensors, we inject high energy solitons to a specific inspection area and then measure reflected waves simultaneously to identify delaminations and characterize the quality of adhesive bonding interfaces in a fast and efficient manner. We also simulate the interaction between solitons and delaminations/weak bonds by using cohesive zone modeling. The proposed sensor technology can open a new way in conducting composite structures inspection, contributing to enhancing maintenance and inspection accuracy and efficiency.

9435-88, Session 14A

Self sensing composites with emi shielding and self repair

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Emi shielding provided by metal coating on repair fibers and conductive repair chemical maintained overall emi resistance of structural panels as well as provided the basis for eddy current and ultrasonic sensing/monitoring of structural panels. The sensing/repair system was easily inserted into composite processing and survived the heat and pressure of VARTM, resin infusion /pressing and pultrusion processing. The panels were tested with a commercial emi test lab, a commercial non destructive testing lab, and a structural testing lab, The results were positive and will be presented in the paper .

9435-89, Session 14A

Modelling of shear lag effect for piezo-elstodynamic structure for electro-mechanical impedance technique

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The impedance based structural health monitoring (SHM) techniques have utilized the electro-mechanical coupling property of piezoelectric materials (piezo-impedance transducers), due to their self-sensing nature (ability to act both as actuators and sensors), and its diminutive in shape and size, cost effectiveness and ease of installation. The adhesive bond acts as an elastic medium which facilitates the transfer of stresses and strains developed due to piezo displacement and also couples the impedance of PZT patch with that of the host structure. The sensitivity of the electro-mechanical impedance (EMI) technique can be enhanced by understanding

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shear mechanism phenomena of the adhesive layer. This paper reviews the existing shear lag models and discuss the recent advances in impedance based coupled piezo-structural model duly considering the shear lag effect with all responsible piezo-mechanical parameters. The paper also includes the parametric study on the influence of various sensor parameters and piezo-mechanical properties on the EMI signatures.

9435-90, Session 14B

Structural damage detection using extended Kalman filter combined with statistical process control

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In recent years, structural health monitoring has become increasingly important for the assessment of damage and maintenance of civil infrastructure. The goal of structural health monitoring system is to determine the status of the structure and to detect the damage when it occurs. Modal-based methods, which identify damage based upon changes in the vibration characteristics of the structure on a global basis, have received considerable attention in the past decades. However, the effectiveness of the modal-based methods is dependent on the type of damage and the accuracy of the structural model, and these methods may also have difficulties when applied to complex structures. In this paper, a Statistical Process Control (SPC) based method for damage detection is presented to overcome the above shortcomings. Based on historical measurements of damage-sensitive features involved in the state-space dynamic models, Extended Kalman Filter (EKF) algorithm is used to produce real-time estimations of these features as well as standard derivations (sigma), which can then be used to form control ranges for SPC to detect any abnormality of selected features. Moreover, confidence levels of the detection can be adjusted by choosing different times of sigma and number of adjacent out-of-range points. Numerical results from a series of experimental tests using a laboratory-scale building structure demonstrate high damage detection accuracy and light computation of this presented method.

9435-91, Session 14B

Variation of modal properties induced by combined effects of temperature and boundary condition

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Changes in environmental conditions (such as temperature and humidity) and boundary conditions have been observed to have significant impact on structure's dynamic properties [1,3,4,5]. Various studies show that natural frequencies have a strong correlation with temperature and humidity [1,4,6]. For example, researchers from Los Alamos National Laboratory [3] found that the first natural frequency of the Alamosa Canyon Bridge varied about 4.7% during a 24-hour period as the temperature of the bridge deck changed by approximately 40° [4]. In Europe, Peeters and De Roeck [5] monitored the Z24 Bridge during one-year period and reported that the environmental changes caused 14-18% variation of the first 4 natural frequencies.

In general, environmental factors affect structures in such a complicated manner that it may result in support movement and thus strengthen or weaken the constraints [6]. Changes of boundary conditions also can lead to significant variation of structure's modal properties, although many researchers assume the boundary conditions to be unchanged when evaluating the environmental influence. Xia et al. [6] made such

assumptions when investigating the dynamic responses of a RC slab, since the slab rests on supports and can move freely except friction. However, few studies have considered both temperature and boundary condition as the combined contributing factors in changing structure's dynamic properties.

This paper proposes a numerical study to analyze structure's dynamic properties under combined influence of temperature and boundary condition. A beam finite element model that can consider the changes in both temperature and boundary condition is established. Numerical study is conducted to reveal the relationship between the variation of the beam's dynamic properties and the changes of its boundary condition as well as temperature. The obtained conclusion will provide insights of the influence of those two factors on future dynamic based structural health monitoring studies.

9435-92, Session 14B

On predicting monitoring system effectiveness

Carlo Cappello, Univ. degli Studi di Trento (Italy); Dorotea Sigurdardottir, Princeton University (United States); Branko Glisic, Princeton Univ. (United States); Daniele Zonta, Univ. degli Studi di Trento (Italy); Matteo Pozzi, Carnegie Mellon Univ. (United States)

When designing a structure, a civil engineer follows a well-established, rational procedure, whereby the performance of the design concept is predicted through structural analysis and quantitatively assessed with respect to the target performance. On the contrary when an engineer designs a monitoring system, the approach is often heuristic with performance evaluation based on common sense or experience. Herein we describe a rational procedure for the design of monitoring systems, keeping in mind an analogy between structural and monitoring design. The structural design process includes: definition of design loads; calculation of stresses; choice of a technological solution that offers the required capacity. The design is satisfactory if the capacity is greater than given load. The monitoring design process includes: definition of the target performance of monitoring; calculation of the required accuracy of instrumental data, using a model; choice of sensor technology. The design is satisfactory if knowledge accuracy is equal or better than the demand. Whereas the structural design objective is to achieve stability with an appropriate level of safety, the object of monitoring is to acquire knowledge with an appropriate level of confidence. In logical terms, structural health monitoring is formally identical to the metrology problem of indirect measurement, where the measurand is indirectly estimated based on observation of other physical quantities linked to the measurand. In this contribution we use Bayesian logic to judge a priori the effectiveness of a monitoring method. We also demonstrate the approach proposed using actual data coming from a case study.

9435-93, Session 14B

Optimal Design of Force Magnification Frame of a Piezoelectric Stack Energy Harvester

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Long lasting and reliable portable energy source has been in increasing demand for various applications, for example military and outdoor camping. In this project, the optimal design of a force magnification frame is conducted for piezoelectric multilayer stack energy harvester, which can

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be arranged in series and put under, for example, a soldier's backpack to harvesting energy from walking. Rhombic or elliptical shape frame with flexure hinge (compliant mechanism) is proposed, through which the force along the short axis (input) is magnified and transmitted to the long axis (output) and acts on the piezoelectric stack. Larger frame of similar design can be exerted on the existing frame to form multiple stages mechanism. Design of Experiment method is used to explore the relationship between the frame geometries and the mechanical performance along with Finite Element Method in ANSYS for shape optimization. The goal of the optimization is to reduce the mechanical stress, have higher force output and increase the efficiency of energy transmitting to the stack. The frame is going to be fabricated with Electric Discharge Machine with spring steel and titanium, and tested with vibration shaker. The overall size of single stage harvester is 38mmX17mmX8mm. As a result, the current frame magnifies the force by 6 times in single stage design and 25 times total with dual-stage. The energy transmission efficiency is about 20%. The voltage output is estimated to be 53V voltage with 50N input for a dual-stage energy harvester.

9435-94, Session 14B

Experimental investigation of concrete hydration and fracture using embedded piezo sensor

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In the modern world, structural health monitoring (SHM) of engineering structures is gaining importance because of automated nature of the sensing system and continuous performance assessment. Smart piezoelectric ceramic material (PZT) has emerged as a potential sensing tool for the implementation of a built-in diagnostic system for an efficient SHM system. Concrete is the most important material component of modern civil infrastructure systems. Hydration is the necessary step in concrete hardening and strength gain, so continuous monitoring of hydration process during this period is very important. Interim crack development and localization is again a constitutive part of hydration which further leads to fracture in concrete structure while its subjected to structural load. This paper aims to monitor the concrete strength gain during hydration process using self-impedance approach and embedded piezoelectric sensor. In this paper an effective approach is proposed to detect the initiation and progression of structural damage under fracture load using the global dynamic vibration technique. The embedded piezo concrete vibration sensors (CVS) were employed to determine the natural frequencies and the strain mode shapes of the structure for an improved damage assessment. Finally Occurrence and location of the damage are determined using the global dynamic technique.

9435-95, Session 14B

Non-contact sensing through image-based 3D scene reconstruction in the presence of mismatched features

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Image-based 3D scene reconstruction has numerous applications, including construction progress evaluation, operational efficiency assessment, situational awareness, environmental monitoring and remote sensing. Image-based 3D scene reconstruction involves accurate feature detection and matching between multiple views. In practice, there are often misassociations between matched features in different views and it is impossible to eliminate them. Misassociated features significantly degrade the accuracy and the robustness of the 3D scene reconstruction algorithms. We introduce a relaxation-based bundle adjustment approach that, as opposed to the regular bundle adjustment, refines the 3D points and camera poses separately. Furthermore, the proposed approach adaptively identifies the potential misassociated features at each iteration where these potential outliers, contrary to previous studies, are preserved and reexamined at later iterations. In this way, if a feature is mistakenly labeled as a potential outlier in the early iterations, it can be included as an inlier in future iterations as the structure and motion parameters refine. The results from several simulation experiments as well as real data sets are presented and it is shown that the proposed approach outperforms the existing Sparse Bundle Adjustment (SBA) approaches in the presence of misassociated features.

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Part of Proceedings of SPIE Vol. 9436 Smart Sensor Phenomena, Technology, Networks, and Systems Integration 2015

9436-1, Session 1

Ultra-thin sensor array for 3D curvature sensing

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Flexible systems-in-foil are very attractive since they allow easy attachment to bodies with non-planar shapes and new forms of sensing dynamic shape changes. They may find applications in structural health monitoring or in the medical field. This paper describes the design and fabrication of a novel flexible curvature sensor-array on a plastic foil substrate. Each sensor element consists of four strain gages in a Wheatstone bridge configuration. To increase sensitivity the strain gages are located on opposite foil surfaces. Two resistors of the Wheatstone bridge are placed on the top and the two others, which are orthogonal to the top side resistors, on the bottom of the foil substrate. Thereby, an output signal can be achieved, which is four times higher when compared with a one-sided sensor design. To characterize the sensor, bending experiments have been performed of both the double-sided and one-sided sensor designs. As the carrier foil material, we used a dry film photoresist encapsulated in spin-on polyimide from both sides to protect the sensing elements. The resistors are made of chromium and are fabricated by a sputter process with subsequent photolithography. The advantage of our process sequence is that the complete double sided sensor with a thickness below 70 μm can be fabricated without the need to flip over the substrate in between. A key challenge in the fabrication process is the interconnection between the top and the bottom resistors. The interconnect vias are filled by electroplating and can withstand the bending experiments without disruption.

9436-3, Session 1

Delamination monitoring in composite materials using dedicated microstructured optical fiber Bragg grating sensors

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We present shear strain sensing and delamination detection inside a laminated composite material using a Bragg grating-based sensor that is fabricated in a highly birefringent 'Butterfly' microstructured optical fiber (MOF). This sensor has been specifically designed for transverse strain sensing in composite materials. We now demonstrate with experimental and numerical results that this sensor can also be used to detect shear strain in a carbon fiber reinforced (CFRP) material with a resolution on the order of 20 $\mu\text{?}$. This is the first time, to the best of our knowledge, that a non-intrusive sensor technique is presented that can quantitatively evaluate the shear strain inside a composite material.

When a delamination initiates and propagates in a composite material, its internal stress distribution will change. By embedding the Butterfly MOF sensor in this material, we can exploit its multi-axial strain sensing capacities to detect these stress redistributions. We have fabricated several CFRP test coupons in which Butterfly MOF sensors have been embedded. These coupons have been subjected to four-point bending tests to induce

high levels of shear strain that will cause delamination. The response of the sensors has been recorded throughout these tests, and we show that their specific response can be linked to the initiation and propagation of the delamination. Moreover, these results have been verified using finite element analyses.

Our results demonstrate the added value of Butterfly MOF sensors for multi-axial strain sensing in composite materials and emphasize their potential for delamination monitoring.

9436-4, Session 1

Correction factors for cross-correlation processing of FBG sensor network data

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The nature of FBG sensors allows them to be multiplexed to form large sensor networks with only a few measurement channels. The benefits of high density multiplexing are particularly strong when FBG sensor networks are applied to monitor large structural systems such as aircraft, wind turbines or civil infrastructure systems. The challenge associated with multiplexing is to be able to identify and track each separate FBG sensor. The difficulty of this task is increased whenever a large number of FBG sensors must be tracked at high sampling rates. In this paper, we increase the number of FBG sensors that can be identified within a given wavelength window, applying the concept of shape division multiplexing (SDM), combined with WDM. The SDM is based on each FBG sensor having a distinct reflected spectral shape in the wavelength domain. To address the issue of data processing speed, we apply a cross-correlation algorithm to identify the wavelength location of each individual spectra. While the cross-correlation algorithm produces rapid processing benefits, the approach also produces uncertainties when a significant number of sensors are present. The sources of this uncertainty are due to the small differences in spectral shape, as compared to the noise level, and distortion to the combined output reflected spectra from multiple FBG sensors overlap in the wavelength domain. Correction factors, based on previous time steps, are added to the cross-correlation algorithm to reduce these uncertainties and their effects on sensor tracking accuracy are investigated.

9436-31, Session 1

Monitoring the fracture behaviour of metal matrix composites by combined NDE methodologies

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Current work deals with the nondestructive evaluation (NDE) of the fracture behavior of metal matrix composites (MMCs) materials using Infrared Thermography (IRT) and Acoustic Emission (AE). AE monitoring was employed to record a wide spectrum of cracking events enabling the characterization of the severity of fracture in relation to the applied load. IR thermography as a non-destructive, real-time and non-contact

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technique, allows the detection of heat waves generated by the thermo-mechanical coupling during mechanical loading of the sample. In this study different thermographic methodologies, based on the monitoring of the surface temperature and the intrinsically dissipated energy were applied. The thermographic assessment is in total agreement with the AE results enabling the reliable monitoring of the MMC's fracture behavior.

9436-5, Session 2

Effective combination of DIC, AE, and UPV nondestructive techniques on a scaled model of the Belgian nuclear waste container

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Protecting the environment and future generations against the potential hazards arising from high-level and heat emitting radioactive waste is a worldwide concern. Following this direction, the Belgian Agency for Radioactive Waste and Enriched Fissile Materials has come up with the reference design which considers the geological disposal of the waste in purely indurated clay. In this design the wastes are first post-conditioned in massive concrete structures called Supercontainers before being transported to the underground repositories. The Supercontainers are cylindrical structures which consist of four engineering barriers that from the inner to the outer surface are namely: the overpack, the filler, the concrete buffer and the envelope. The overpack, which is made of carbon steel, is the place where the vitrified wastes and spent fuel are stored. The buffer, which is made of concrete, creates a highly alkaline environment ensuring slow and uniform overpack corrosion as well as radiological shielding. In order to evaluate the feasibility to construct such Supercontainers two scaled models have so far been designed and tested. The first scaled model indicated crack formation on the surface of the concrete buffer but the absence of a crack detection and monitoring system precluded defining the exact time of crack initiation, as well as the origin, the penetration depth, the crack path and the propagation history. For this reason, the second scaled model test was performed to obtain further insight by answering to the aforementioned questions using the Digital Image Correlation, Acoustic Emission and Ultrasonic Pulse Velocity nondestructive testing techniques.

9436-6, Session 2

Implementation and validation of a multi-modal mobile sensor system for surface and subsurface assessment of roadways

Ming Wang, Ralf Birken, Salar Shahini Shamsabadi, Northeastern Univ. (United States)

There are more than 4 million miles of roads and 600,000 bridges in the United States alone. On-going investments are required to maintain the physical and operational quality of these assets to ensure public's safety and prosperity of the economy. Planning cost-effective maintenance and repair (M&R) operations must be armed with a meticulous pavement inspection method that is non-disruptive, is affordable and requires minimum manual effort.

The Versatile Onboard Traffic Embedded Roaming Sensors (VOTERS) project developed a technology able to cost-effectively monitor the condition of roadway systems to plan for the right repairs, in the right place, at the right time. VOTERS technology consists of an affordable,

lightweight package of multi-modal sensor systems including acoustic, optical, electromagnetic, and GPS sensors. Vehicles that are outfitted with this technology would be capable of collecting information on a variety of pavement-related characteristics at both surface and subsurface levels while roaming through daily traffic. By correlating the sensors' outputs with the positioning data collected in tight time synchronization, a GIS-based control center attaches a spatial component to all the sensors' measurements and delivers multiple ratings of the pavement every meter. These spatially indexed ratings are then leveraged by VOTERS decision making modules to plan the optimum M&R operations and predict the future budget needs. In 2014, VOTERS inspection results were validated by comparing them to the outputs of recent professionally done condition surveys of a local engineering firm for 300 miles of Massachusetts roads. Success of the VOTERS project portrays rapid, intelligent, and comprehensive evaluation of tomorrow's transportation infrastructure to increase public's safety, boost the nation's economy, and deter catastrophic failures.

9436-7, Session 2

A Bayesian optimization approach for wind farm power maximization

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The objective of this study is to develop a robust method to derive the operational conditions of wind turbines in a wind farm that improves the total wind farm energy production. Conventionally, for a given wind condition, an individual wind turbine is controlled to maximize its own energy production without considering other wind turbines. Under this greedy control strategy, due to the reduced wind speed and the increased turbulence intensity inside the wake, the downstream wind turbines produce only a fraction of energy by the upstream wind turbines. To minimize the wake interference among wind turbines and thus to maximize the overall wind farm energy production, in this study, we formulate a wind farm power maximization problem in a cooperative game framework where coordinated control actions, namely the induction factors and the yaw angles, of all wind turbines can be derived. We determine the optimal, coordinated control actions by applying Bayesian optimization (BO) algorithm, a probabilistic model-free optimization algorithm. In BO framework, at each iteration, the wind farm power function is modeled as Gaussian Process (GP) using the historical input (control actions) and the output (total wind farm energy production) data, and the constructed GP is used to determine the next trial control actions. Numerical simulations using the analytically derived wind farm power function show that BO is able to find a near optimal set of yaw offset angles and induction factors for 80 wind turbines by sampling (evaluating) a small number of the wind farm power function.

9436-8, Session 2

Environmental barrier coating (EBC) durability test validation using combined digital image correlation and NDE

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Ceramic Matrix Composites (CMC) is gaining attractive interests from engine manufacturers and aerospace industry due to its characteristics of being low maintenance, sustain high temperature (200 °C higher than metal), good dependability and cost efficiency. However, these materials experience structural durability issues during in service operating environment. These conditions are confined to moisture, oxidation, thermo-mechanical loads, creep and fatigue. Such circumstances lead to degradation which includes coating oxidation. To help ease the impact of these harsh environmental and in service induced damage and failure, a high temperature protective system, Environmental Barrier Coating (EBC) that can operate a high temperature greater than 1100 °C [1, 3] is being considered. This is to alleviate and help controlling these environmentally induced impairments.

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In spite of the protective environment the EBC coating provide for the CMC, there are structural concerns that these coatings endure during typical engine operation such as cracking, spalling and delamination which can reduce and limit the life of the component. Therefore, it is very pertinent to develop an understating of the issues that control cracking along the interfaces of coated layered ceramics to allow maximum energy dissipation capabilities.

In this paper, an overview of an experimental work up to evaluate the failure mechanism and characterize the crack initiation, durability and life of the EBC is being presented. The work includes presenting results obtained from defined tensile test experiments using three layered EBC coated CMC dogbone specimen. The tests are conducted at different load levels to validate the overall failure sequence of the EBC and CMC with an earlier analytical modeling prediction [1, 4]. Experimental data collected from the test and compared with nondestructive evaluation (NDE) and digital image correlation [4] are being presented and discussed.

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9436-9, Session 2

Engine rotor health monitoring: an experimental approach to fault detection and durability assessment

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Efforts to update and improve turbine engine components in meeting flights safety and durability requirements are commitments that engine manufacturers try to continuously fulfill. Most of their concerns and developments energies focus on the rotating components as rotor disks. These components typically undergo rigorous operating conditions and are subject to high centrifugal loadings which subject them to various failure mechanisms. Therefore, to alleviate these design issues, health monitoring is a must. However, taking on such attribute is somewhat challenging to undertake. The reason is mainly due to the fact that there are various issues such as the presence of scattered loading conditions, flaw sizes, and component geometry and materials properties that hamper the simplicity of implementing such applications. Thus, developing highly advanced health monitoring technology to screen their efficacy and performance is very essential to their prolonged service life and operational success. Nondestructive evaluation techniques are among the many screening methods that presently are being used to pre-detect hidden flaws and mini cracks prior to any appalling events occurrence. Most of these methods or procedures are confided to evaluating material's discontinuities and other defects that have mature to a point where failure is eminent.

Therefore, a more practical approach to monitoring such durability and failure events in the turbine engine rotating components is the ultimate goal. As a result, this paper is focused on presenting research activities concerning the ongoing efforts at NASA Glenn Research Center rotor

dynamics laboratory supporting the development of a fault detection system for the turbine engine system. Data obtained from spin test experiments of a rotor disk that relates to investigating blade tip clearance, tip timing and shaft displacement sensors devices based on frequency measurement are presented. Additional results correlating test data with finite element modeling to characterize the structural durability of a cracked rotor as it relates to the experimental findings is also presented.

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9436-10, Session 3

Modeling, optimization, and experimental validation of a resonant piezo-optical ring sensor for enhanced active and passive structural health monitoring

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This paper presents a mechanical resonant piezo-optical ring sensor designed to enhance the response of piezoelectric wafer active sensors (PWAS) and fiber Bragg grating (FBG) sensors. Modeling of the ring sensor characteristics and guided wave response were used to optimize the ring by improved grounding, FBG placement, and PWAS installation. FEM modeling of the ring sensor under a pitch-catch model was also performed to elucidate the principles behind the ring sensor operation.

Then, the ring sensor was compared to PWAS and FBG bonded directly to a plate during pitch-catch, acoustic emission (AE), and impact detection experiments. The characteristics of the ring sensor such as resonance amplification, mode selectivity, mechanical filtering, and omnidirectionality were investigated. These characteristics were related to the experiments for an analysis of how the ring sensor performs for both passive and active SHM compared to FBG and PWAS. To investigate the resonance amplification, the counts were varied for a PWAS-excited Hanning windowed tone burst, which showed a large asymptotic increase in response amplitude towards that of a sine wave. The filtering characteristics of the ring sensor were able to isolate guided waves at a single desired frequency, with a quiescent response on either side. This same effect gave the ring sensor a sharper and more distinct initial response for impact and AE detection. The ring sensor was used to detect guided waves, impact, and AE signals from various directions with little attenuation in response; this effect was investigated and quantified through modeling and experiment.

9436-11, Session 3

New non-local lattice models for the description of wave dispersion in concrete

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The propagation of longitudinal waves through concrete materials is strongly affected by dispersion. This is clearly indicated experimentally from the increase of phase velocity at low frequencies whereas many attempts have been made to explain this behavior analytically. Since the classical elastic theory for bulk media are by default non-dispersive, enhanced theories have been developed. The most commonly used higher order theory is the dipolar gradient elastic theory which takes into account the microstructural effects in heterogeneous media like concrete. The microstructural effects are described by two internal length scale parameters (g and h) which correspond to the micro-stiffness and micro-inertia respectively. In the current paper, this simplest possible version of the general gradient elastic theory proposed by Mindlin is reproduced through non-local lattice models consisting of discrete springs and masses. The masses simulate the aggregates of the concrete specimen whereas the springs are the mechanical similitude of the concrete matrix. The springs in these models are connecting the closest masses between them as well as the second or third closest to each other masses creating a non-local system of links. These non-neighboring interactions are represented by massless springs of constant stiffness while on the other hand one cannot neglect the significant mass of the springs connecting neighboring masses as this is responsible for the micro-inertia term. The major advantage of the presented lattice models is the fact that the considered microstructural effects can be accurately expressed as a function of the size and the mechanical properties of the microstructure.

9436-12, Session 3
Alternate solution for the cylindrical Helmholtz vector equation applied to elastic helical guided waves in pipes

Haraprasad Kannajosyula, Giovanni F. Nino, Qi2 (United States)

Elastic helical guided wave propagation in pipes that has recently gained importance in applications related to tomography and structural health monitoring is analyzed using an alternate formalism. Closed form exponential function based solutions for the Helmholtz vector equation in cylindrical polar coordinates are derived. Relationship of these alternate solutions for the Helmholtz vector equation with the traditional integer order Bessel function based formulation – that has been established for the corresponding solutions of Helmholtz scalar equation in prior literature – is presented. The solutions are single valued at every point in the physical space, and therefore, unlike traditional non-integer order Bessel function based methods the formulation presented herein preserves the physical uniqueness of the field quantities involved in the wave propagation. The alternate solutions, when applied to the boundary value problem of an isotropic elastic pipe with stress free boundaries, yield a formulation for helical guided wave propagation. A class of helical guided wave modes that have a constant helix angle across the wall thickness of the pipe is predicted. Dispersion characteristics for guided wave propagation such as phase velocity curves; displacement profiles for some points of interest on the phase velocity curves, for select helical angles are presented. The results are compared against traditional notions about helical guided wave propagation.

9436-13, Session 3
The effect of CNTs reinforcement, on thermal and electrical properties, of cement-based materials

Dimitrios A. Exarchos, Panagiota T. Dalla, Theodore E. Matikas, Univ. of Ioannina (Greece)

This research aims to investigate the influence of the nano-reinforcement on the thermal properties of cement mortar. Nano-modified cement mortar with carbon nanotubes (CNTs) leading to the development of innovative materials possessing multi-functionality and smartness. Such multifunctional properties include enhanced mechanical behavior, electrical and thermal conductivity, and piezo-electric characteristics. The thermal behavior of cement-based nanocomposites was assessed using infrared thermography. Two different thermographic techniques were used to monitor the influence of the nano-reinforcement in the structure. To eliminate any extrinsic effects (e.g. humidity) the specimens were dried in an oven before testing. The electrical resistivity was measured with a contact test method using a custom made apparatus and applying a known D.C. voltage. It was found that the CNT nano-reinforcements can enhance the thermal and electrical properties of the materials and delineated their potential use as sensors for a wide variety of applications.

9436-15, Session 3
Acoustic emission activity during fracture of human femur bone

Dimitrios G. Aggelis, Maria Strantza, Vrije Univ. Brussel (Belgium); Olivia Louis, Univ. Ziekenhuis Brussel (Belgium); Frans Boulpaep, Vrije Univ. Brussel (Belgium); Demosthenes Polyzos, Univ. of Patras (Greece); Danny Van Hemelrijck, Vrije Univ. Brussel (Belgium)

This study presents the acoustic emission (AE) behaviour of human femur bone during fracture. The specimens are fixed as cantilevers and AE broadband sensors are placed in two points, one near the fix point and the other near the head, where the load is applied. The objective is to investigate whether AE procedures and parameters established for usual engineering materials monitoring may also offer insight to the fracture of the specific biological material which has a far more complicated structure. Preliminary analysis indicates that the number and rate of the received AE signals are strongly connected to the load history. The brittle nature of bone tissue does not allow any visible signs of cracking until the final rupture. However, AE can detect the onset of fracture of human tissue from the early micro-cracks that occur at loads less than 20% of the maximum, and enables the monitoring of the entire process. Specific parameters like the rise time and frequency content exhibit fluctuations during or earlier than fracture moments. Despite the inherent difficulties due to anisotropy, AE source location is used to identify the zones of fracture earlier than the visual signs appear. Effort is also put in correlating AE parameters to the failure pattern, i.e. simple detachment of the head or deflection of the crack into the femoral shaft. It is concluded that AE can improve the understanding of the fracture behavior providing information that is difficult to obtain with any other monitoring technique.

9436-16, Session 3
An intelligent algorithm of impact source localization with embedded sensors array in the CFRP plate

Tao Fu, Yanju Liu, Jinsong Leng, Harbin Institute of Technology (China)

An intelligent algorithm of acoustic emission (AE) source localization is proposed based on BP artificial neural network (ANN). The BP ANN is trained with theoretical time difference of arrival (TDOA) and the relative point of intersection. The intelligent algorithm is applied for locating the impact source in the carbon fiber reinforced polymer (CFRP) plate. Four sensors distributed as a sensor diamond array were integrated into the CFRP plate to detect the TDOA of Lamb waves propagating in the anisotropic structures. The embedded four sensors are developed from the optical fiber coupler, which are only 1.0mm in diameter and not harm for the matrix CFRP plate. The response characteristic of the embedded sensor

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is calibrated with the commercial PZT acoustic emission sensor, which provided that it is better suited to detect the low frequency of stress wave. Experiment results provided that the maximum error was only 6.3mm in the diamond measurement area with the dimension of 200mm²200mm by using the intelligent algorithm, which reduced the non-linear errors and improved the accuracy.

9436-28, Session 3
Nondestructive evaluation of the mechanical behavior of cement based nanocomposites under bending

Ilias K. Tragazikis, Dimitrios A. Exarchos, Konstantinos G. Dassios, Theodore E. Matikas, Univ. of Ioannina (Greece)

This research aims in investigating the crack growth behavior of modified cement mortar with multi-wall carbon nanotubes (MWCNTs) under flexural testing using acoustic emission (AE). MWCNTs were used in various concentrations and act as nano-reinforcement in the matrix. During 3-point bending tests, acoustic emission monitoring allows real-time identification of the damage process in the specimens. In order to determine the fracture toughness property, single-edge notch specimens were used. It was found that the inclusion of MWCNTs in the cement-based matrix improves the mechanical properties of the material, such as flexural strength (σ_s), fracture toughness (K_{Ic}) and the critical crack mouth opening displacement (δ_c) of the nano-composites. Furthermore, the ultrasonic speed measured in nanocomposites with various MWCNTs concentrations lead to the determination of their elastic properties.

9436-17, Session 4
Rapid chloride permeability test for durability study of carbon nanoreinforced mortar

Panagiota T. Dalla, Panagiota Alafogianni, Ilias K. Tragazikis, Nektaria-M. Barkoula, Theodore E. Matikas, Univ. of Ioannina (Greece)

The addition of a conductive admixture in a cement-based material could lead to innovative products with multi-functional features. These materials are designed to possess enhanced properties, such as improved mechanical properties, electrical and thermal conductivity, and piezo-electric characteristics. Carbon nanotubes (CNTs) can be used as nano-reinforcement in cement-based materials because of their huge aspect ratio as well as their extremely large specific surface area. For cement-based composites, one of the major types of environmental attack is the chloride ingress, which leads to corrosion of the material and, subsequently, to the reduction of strength and serviceability of the structure. A common method of preventing such deterioration is to avert chlorides from penetrating the structure. The penetration of the concrete by chloride ions is a slow process. It cannot be determined directly in a time frame that would be useful as a quality control measure. Therefore, in order to assess chloride penetration, a test method that accelerates the process is needed, to allow the determination of diffusion values in a reasonable time. In the present research, nano-modified mortars with various concentrations of multi-wall carbon nanotubes (0.2% wt. cement CNTs - 0.8% wt. cement CNTs) were used. The chloride penetration in these materials was monitored according to ASTM C1202 standard. This is known as the Coulomb test or Rapid Chloride Permeability Test (RCPT).

9436-18, Session 4
A novel downhole fiber optical flowmeter using Fabry-Perot sensor

Hongtao Zhang, Harbin Institute of Technology (China)

Real-time downhole flow data is very important for reservoir evaluation and optimizing well exploration, particularly for the wells with high cost and low production. However, traditional electronic flowmeters are not available and reliable to install in wells permanently, especially for deep and ultra-deep wells with high temperature beyond 150°. With development of fiber optical technology in the past years, downhole fiber optical flowmeters become possible for monitoring production of each producing zone in wells. This should thank to the various advantages of optical fibers, such as small size, capability of anti-electromagnetic interference, high reliability and high temperature resistant.

In this study, a novel downhole optical fiber flowmeter using fiber Bragg grating (FBG)-based Fabry-Perot (F-P) sensor is proposed and studied. Flow rate measurement is based on cross-correlation analysis of dynamic pressure induced by turbulent eddies during flowing. An F-P sensor array is used to measure the dynamic pressure to determine the flow rate. The sensor array structure is described. The relationship between the dynamic pressure and length of the F-P cavity is analyzed, and the method for length measurement of the F-P cavity is introduced.

9436-19, Session 5
Target-free dynamic displacement measurement using computer vision

Hyungchul Yoon, Hazem Elanwar, Hajin Choi, Billie F. Spencer Jr., Univ. of Illinois at Urbana-Champaign (United States)

Computer Vision techniques are being used to measure the displacements of the structure with cameras. These methods do not require any sensor installment, however still have some limitations such as "target marker". In this study, we introduce a Computer Vision based dynamic displacement measurement that doesn't require any target marker. Also, the proposed system is for using commercial camera such as GoPro or the camera embedded in smartphones which are widely being used in daily life. The procedure can be categorized onto 4 parts: (1) Camera Calibration, (2) Feature Detection, (3) Object Tracking, and (4) Displacement Measurement. Camera needs to be first calibrated to remove optical distortion artifacts in the images. Next, the images are extracted from the video and features are detected from each images. We use Viola-Jones algorithm to extract features from images. Kanade-Lucas-Tomasi feature tracker is used to track the features over the time, and finally the displacement can be calculated. The proposed method was validated in lab-scale test, and the showed reasonable result compared to sensor based measurements.

9436-20, Session 5
Optical excitation and detection of a quartz crystal resonator

Nan Wu, Univ. of Massachusetts Lowell (United States); Lijun Yang, Haifeng Zhang, Univ. of North Texas (United States); Xingwei Wang, Univ. of Massachusetts Lowell (United States)

Optical excitation and detection of a quartz crystal resonator have been realized experimentally. Optical fibers have been used to excite the crystal through the thermoelastic effect. The resonator vibration was detected through another piece of optical fiber. The results provided a foundation for future remote optical excitation of resonant sensors for sensing application in extreme environments.

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9436-21, Session 5

Temperature compensation in CNT-composite distributed strain sensors

D. Roy Mahapatra, Vivek T. Rathod, S. Venkatesh, Indian Institute of Science (India)

Carbon Nanotube (CNT) based nano-composite sensors have potential applications in distributed strain sensing due to their high sensitivity, potential for distributed patterning, embedding in composite structures and low cost. Strain sensors are used often under varying temperature conditions and these conditions affect the performance of these sensors depending on the heat transfer and thermal expansion characteristics of the integrated system. To address the problem of sensor signal correlation, a temperature compensation method is proposed. CNT nano-composite sensor is fabricated on an elastic polymer beam as substrate. Strain is induced on the sensor by bending the beam under simply supported configuration. Response of the sensor is measured using a Wheatstone bridge circuit and four-point probe method. Induced strain in the beam is determined using large deflection theory. The sensors are then characterized at various temperatures and the influence of the temperature on the sensor output voltage signal sensitivity is studied analytically. Various sources of strain and temperature dependent electronic transport are modeled in the composite in a simplified and phenomenological way in order to make the problem analytically tractable. The variation of sensitivity for different CNT concentrations is also studied. The results show that the CNT-composite strain sensors can be used under varying temperature conditions with temperature compensation scheme implemented either in the sensor hardware design or through signal processing. The developed CNT sensors are easy to fabricate in complex patterns with excellent repeatability and do not require bonding layer.

9436-22, Session 5

Strain sensors based on pencil-drawn stacked graphite sheets on paper substrate at percolation threshold zone

Jinbao Jiang, Harbin Institute of Technology (China)

This paper concentrates on the strain sensing properties of micro-nano crack network of conductive films. Chinese ink with nano carbon black was used and self-assembled to conductive film on substrate with the evaporation of water. Heat treatment was taken to further reduce water and generate micro-nano crack network of shrinkage. Resistance was measured with copper electrodes sputtered at the ends of the film, and further as strain sensing signals when loading. Results showed that such a micro-nano crack network of conductive film was quite sensitive to strain with gauge factor as large as the order of 100. Compared to network of conductive nanoparticles, such a crack network of conductive film could be seen as a network of micro-nano insulators. Percolation theory and electron tunneling theory could also be applied to explain such a piezoresistivity phenomenon. However, such micro-nano crack network was easier to generate and the multiscale of the cracks' width led to higher sensitivity.

9436-23, Session 6

Phonon-based scalable quantum computing and sensing

Ihab El-Kady, Sandia National Labs. (United States)

Quantum computing fundamentally depends on the ability to concurrently entangle and individually address/control a large number of qubits. In general, the primary inhibitors of large scale entanglement are qubit dependent; for example inhomogeneity in quantum dots, spectral crowding brought about by proximity-based entanglement in ions, weak interactions of neutral atoms, and the fabrication tolerances in the case of Si-vacancies

or SQUIDs. We propose an inherently scalable solid-state qubit system with individually addressable qubits based on the coupling of a phonon with an acceptor impurity in a high-Q Phononic Crystal resonant cavity.

Due to their unique nonlinear properties, phonons enable new opportunities for quantum devices and physics. We present a phononic crystal-based platform for observing the phonon analogy of cavity quantum electrodynamics, called phonodynamics, in a solid-state system. Practical schemes involve selective placement of a single acceptor atom in the peak of the strain field in a high-Q phononic crystal cavity that enables strong coupling of the phonon modes to the energy levels of the atom. A qubit is then created by entangling a phonon at the resonance frequency of the cavity with the atomic acceptor states. We show theoretical optimization of the cavity design and excitation waveguides, along with estimated performance figures of the phonon system. Qubits based on this half-sound, half-matter quasi-particle, may outcompete other quantum architectures in terms of combined emission rate, coherence lifetime, and fabrication demands.

9436-24, Session 6

Unidirectional dual spectral gaps of low symmetry phoxonic assemblies

Vassilios Yannopapas, Univ. of Patras (Greece); Ioannis E. Psarobas, Univ. of Ioannina (Greece)

We demonstrate theoretically the existence of one-way phoxonic band gaps, i.e., gaps which are experienced by electromagnetic (elastic) waves impinging on a particular face of a finite phoxonic crystal slab. These one-way spectral gaps emerge in the absence of time-reversal symmetry breaking as it is the case, e.g., in the presence of magnetic fields in magneto-photonic crystals, but they result from the low symmetry of the crystal such as the monoclinic phoxonic crystals considered here possessing a single mirror plane. We report the existence of unidirectional frequency band gaps which may span over extended regions of the Brillouin zone and can find application in trapping EM and elastic waves in properly designed multilayered structures.

9436-25, Session 6

Chiral phononic structures

Ioannis E. Psarobas, Univ. of Ioannina (Greece); Dimitrios A. Exarchos, Theodore E. Matikas, Univ. of Ioannina (Greece)

A full elastodynamic multiple scattering approach is employed to investigate the behavior of nonreciprocal phononic structures consisting of periodic helical assemblies of spheres. We report on cases of dense and sparse helical chains, cases with size variation and low frequency behavior with locally resonant units.

9436-26, Session 6

High-frequency phononic crystal structures based on metallic pillars on piezoelectric membranes

Reza Pourabolghasem, Ali A. Eftekhari, Saeed Mohammadi, Ali Adibi, Georgia Institute of Technology (United States)

No Abstract Available

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9436-33, Session 6

Standardization in fiber-optic sensing for structural safety: activities in the ISHMII and IEC (*Invited Paper*)

Wolfgang R. Habel, Katerina Kriebber, Werner Daum, Bundesanstalt für Materialforschung und -prüfung (Germany)

No Abstract Available

9436-2, Session PTues

Nondestructive characterization of phononic heterostructures

Ioannis E. Psarobas, Dimitrios A. Exarchos, Theodore E. Matikas, Univ. of Ioannina (Greece)

This work deals with the development of a new class of metamaterials based on phononic composite structures that can offer vibration protection in a wide range of applications. Such phononic metamaterials is a class of phononic crystals that exhibit spectral gaps with lattice constants of a few orders of magnitude smaller than the relevant acoustic wavelength. The design of a phononic composite metamaterial is based on the formation of omnidirectional frequency gaps. This is very much relevant to the dimensionality of a finite slab of the crystal. In this respect, two dimensional structures are used to cutoff acoustic waves. Ultrasonic evaluation of phononic composite structures designed to eliminate specific frequency ranges of vibrations is performed using spectral analysis of the transient response of the phononic structures in the presence of an acoustic field. The phononic materials are tested in both in pulse-echo and through transmission configurations, at frequencies of a few hundreds of kHz to a few MHz

9436-14, Session PTues

Acoustic emission monitoring of recycled aggregate concrete under bending

Anna A. Tsoumani, Nektaria-M. Barkoula, Theodoros E. Matikas, Univ. of Ioannina (Greece)

The amount of construction and demolition waste has increased considerably over the last few years, making desirable the reuse of this waste in the concrete industry. In the present study concrete specimens are subjected at the age of 28 days to four-point bending with concurrent monitoring of their acoustic emission (AE) activity. Several concrete mixtures prepared using recycled aggregates at various percentages of the total coarse aggregate and also a reference mix using natural aggregates, were included to investigate their influence of the recycled aggregates on the load bearing capacity, as well as on the fracture mechanisms. The results reveal that for low levels of substitution the influence of using recycled aggregates on the tensile strength is negligible while higher levels of substitution lead into a deterioration of the tensile strength. The total AE activity, as well as the AE signals emitted during failure, was related to tensile strength. The results obtained during test processing were found to be in agreement with visual observation. Overall, AE proved a useful tool for the fracturing behavior of concrete in a way that is not possible by any other conventional measurement.

9436-27, Session PTues

A novel processing route for carbon nanotube reinforced glass-ceramic matrix composites

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The current study reports the establishment of a novel feasible way for processing glass- and ceramic- matrix composites reinforced with carbon nanotubes (CNTs). The technique is based on high shear compaction of glass/ceramic and CNT blends in the presence of polymeric binders for the production of flexible green bodies which are subsequently sintered and densified by spark plasma sintering. The method was successfully applied on a borosilicate glass / multi-wall CNT composite with final density identical to that of the full-dense ceramic. Preliminary non-destructive evaluation of dynamic mechanical properties such as Young's and shear modulus and Poisson's ratio by ultrasonics show that property improvement maximizes up to a certain CNT loading; after this threshold is exceeded, properties degrade with further loading increase.

9436-29, Session PTues

The effect of different surfactants/plastisizers on the electrical behavior of CNT nano-modified cement mortars

Panagiota T. Dalla, Panagiota Alafogianni, Ilias K. Tragazikis, Dimitrios A. Exarchos, Nektaria-M. Barkoula, Konstantinos G. Dassios, Theodore E. Matikas, Univ. of Ioannina (Greece)

Cement-based materials have in general low electrical conductivity. Electrical conductivity is the measure of the ability of the material to resist the passage of electrical current. The addition of a conductive admixture such as Multi-Walled Carbon Nanotubes (MWCNTs) in a cement-based material increases the conductivity of the structure. This research aims to characterize nano-modified cement mortars with MWCNT reinforcements. Such nano-composites would possess smartness and multi-functionality. Multifunctional properties include electrical, thermal and piezo-electric characteristics. One of these properties, the electrical conductivity, was measured using a custom made apparatus that allows application of known D.C. voltage on the nano-composite. In this study, the influence of different surfactants/plastisizers on CNT nano-modified cement mortar specimens with various concentrations of CNTs (0.2% wt. cement CNTs - 0.8% wt. cement CNTs) on the electrical conductivity is assessed.

9436-30, Session PTues

Determination of the dynamic elastic constants of recycled aggregate concrete

Anna A. Tsoumani, Nektaria-M. Barkoula, Theodoros E. Matikas, Univ. of Ioannina (Greece)

Nowadays, construction and demolition waste constitutes a major portion of the total solid waste production in the world. Due to both environmental and economical reasons, an increasing interest concerning the use of recycled aggregate to replace aggregate from natural sources is generated. This paper presents an investigation on the properties of recycled aggregate concrete. Concrete mixes are prepared using recycled aggregates at a substitution level between 0 and 100% of the total coarse aggregate. The influence of this replacement on strengthened concrete's properties is being investigated. The properties estimated are: density,

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dynamic modulus of elasticity and Poisson's ratio at the age of both 7 and 28 days. The determination of the dynamic elastic modulus and the Poisson's ratio was made using the ultrasonic pulse velocity method. The results reveal that the existence of recycled aggregates affects the properties of concrete negatively; however, in low levels of substitution the influence of using recycled aggregates is almost negligible. Concluding, the controlled use of recycled aggregates in concrete production may help solve a vital environmental issue apart from being a solution to the problem of inadequate concrete aggregates.

9436-32, Session PTues

**Parallel multi-join query optimization
algorithm for distributed sensor network in
the internet of things**

Yan Zheng, Heilongjiang Institute of Technology (China)

Internet of things (IoT), focusing on providing users with information exchange and intelligent control, attracts a lot of attention of researchers from all over the world since the beginning of this century. IoT is consisted of large scale of sensor nodes and data processing units, and the most important features of IoT can be illustrated as energy confinement, efficient communication and high redundancy. With the sensor nodes increment, the communication efficiency and the available communication band width become bottle necks. Many research work is based on the instance which the number of joins is less. However, it is not proper to the increasing multi-join query in whole internet of things. To improve the communication efficiency between parallel units in the distributed sensor network, this paper proposed parallel query optimization algorithm based on genetic algorithm. The storage information relations and the network communication cost are considered in this algorithm, and an optimized information changing rule is established. The experimental result shows that the algorithm has good performance, and it would effectively use the resource of each node in the distributed sensor network. Therefore, executive efficiency of multi-join query between different nodes could be improved.

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Monday - Thursday 9 -12 March 2015

Part of Proceedings of SPIE Vol. 9437 Structural Health Monitoring and Inspection of Advanced Materials, Aerospace, and Civil Infrastructure 2015

9437-1, Session Key

Novel ultrasound sensors and transducers for non-destructive testing (*Keynote Presentation*)

Xiaoning Jiang, North Carolina State Univ. (United States)

No Abstract Available

9437-2, Session 1

Characterization of complex materials with elastic discontinuities using scanning acoustic microscopy

Xin Li, Jeong Nyeon Kim, Richard L. Tutwiler, Judith A. Todd, The Pennsylvania State Univ. (United States); Ik-Keun Park, Seoul National Univ. of Science and Technology (Korea, Republic of)

Ceramics to metal joints may develop flaws due to residual stresses that develop during the cooling process. Scanning acoustic microscopy is a well-recognized tool for characterizing elastic properties and can be applied to materials with elastic discontinuities such as debonding at ceramic/metal interface. Acoustic information is obtained using the $V(z)$ curve method, which measures the output signal of a transducer as a function of the distance between the transducer and a specimen. The velocity of the surface acoustic waves, V_{saw} , can be calculated from the $V(z)$ curve. In this work, a simulation of the $V(z)$ curve was updated. The pupil-function splitting method was combined with the angular-spectrum approach of $V(z)$ theory in order to obtain the $V(z)$ curve for interfaces between different materials. The V_{saw} values at the interface was calculated from the simulated $V(z)$ curve. A series of experiments were performed to measure the V_{saw} values at the interface of a Si₃N₄/Cu joint using the scanning acoustic microscope. By comparing the measured values with the calculated values, the reliability of this simulation was verified. The simulation can be used to test the boundary conditions of bimaterial samples.

9437-3, Session 1

FRP/steel composite damage acoustic emission monitoring and analysis

Dongsheng Li, Dalian Univ. of Technology (China)

FRP is a new material with good mechanical properties, such as high strength of extension, low density, good corrosion resistance and antifatigue. FRP and steel composite has gotten a wide range of applications in civil engineering because of its good performance. As the FRP/steel composite get more and more widely used, the monitor of its damage is also getting more important. To monitor this composite, acoustic emission (AE) is a good choice. In this study, we prepare four identical specimens to conduct our test. Two of them are under uniaxial loading and the other two are under cyclic uniaxial loading. During the testing process, the AE characteristic parameters and mechanics properties were obtained. Damaged properties of FRP/steel composite were analyzed through acoustic emission (AE) signals. By the growing trend of AE accumulated energy, the severity of the damage made on FRP/steel

composite was estimated. The AE sentry function has been successfully used to study damage progression and fracture energy release rate of composite laminates. This technique combines the cumulative AE energy with strain energy of the material rather than analyzes the AE information and mechanical separately. Index of damage (ID) was proposed based on the relation between the cumulative AE energy and plastic strain energy of the specimens. This method is well-suited to assess the damage of the structures which are under cyclic loading.

9437-4, Session 2

Experimental evaluation on the effectiveness of acoustic-laser technique towards the FRP-bonded concrete system

Qiwen Qiu, Denvid Lau, City Univ. of Hong Kong (Hong Kong, China)

Non-destructive evaluation (NDE) is essential for the detection of defects in the externally bonded fiber reinforced polymer (FRP) concrete, especially such bonded system can be readily found in strengthened and retrofitted structures nowadays. Among all the current NDE methods, acoustic-laser technique is a brand-new and non-contact methodology, with a high applicability to defect near-surface defect with the validation by both numerical and experimental approaches. Despite the validation of its applicability, there have been no systematic studies that examine how the acoustic location or other factors affects the measurement response. The present study, from the experimental perspective, focuses on the sensitivity of acoustic-laser technique when it is applied to the interfacial defect in FRP-bonded concrete system. Several parameters affecting the sensitivity are discussed here including (i) acoustic distance, (ii) acoustic angle, (iii) acoustic amplitude and (iv) the incident angle of the laser beam. Based on our experimental measurement, an optimal range of the concerned parameters is found, and it is believed that such finding can improve the reliability of the acoustic laser-technique for defect detection.

9437-5, Session 2

Non destructive testing techniques based on non-linear methods for assessment of debonding in single lap joints

Gennaro Scarselli, Univ. del Salento (Italy); Francesco Ciampa, Dmitri Ginzburg, Michele Meo, Univ. of Bath (United Kingdom)

The different Non Destructive Testing (NDT) methods suitable for the identification of defects within adhesive bonds rely on mechanical waves for the evaluation of the bond strength. Hence different parameters such as frequency, shape, amplitude of the response signal coming back from the adhesive joint are key criterion for understanding the quality of the adhesive joint. The main NDT techniques for inspection of adhesive bonds are based on ultrasounds and laser. In this paper the non-linear content of the structural response of a single lap joint subjected to ultrasonic harmonic excitation is evaluated to identify and characterize the defects within the bonded region. Different metallic samples with the same geometry have been experimentally tested. The defect has been artificially introduced bonding partially two plates. Two piezoelectric sensors (one exciting, one receiver) have been attached on each sample. The experimental tests were

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aimed at characterizing the debonding, evaluating the signals acquired by the sensors through bispectral analysis that does not request any baseline. In the structural dynamic response of the damaged samples, together with the harmonic response due to the harmonic excitation, other non-linear contributions have been identified: higher harmonics (2nd, 3rd) and subharmonics. These contributions are clearly due to non-linear effects induced by the "kissing bond" that are theoretically explained in the paper. A numerical model has been developed in LS Dyna, introducing a non-linear forcing term, related to the defect, acting together with the harmonic excitation and applied in the debonded region where the non-linearities are originated.

9437-6, Session 2
Selection of sensors based on their damage detection capabilities in aero structures

Frank Abdi, Harsh K. Baid, Farid Taleghani, Ernie Cochran, AlphaSTAR Corp. (United States); Andre Luz, Glexys (Portugal); Ali Nobari, Kamran Nikbin, Imperial College London (United Kingdom)

ABSTRACT

This paper addresses determination of suitable combinations of sensors to monitor damage or potential damage detected after entry into service of metallic and composite components in aircraft structures. Wireless strain gauges and Fibre optic (FBG) sensors and Piezoelectric Sensors, PZT may in principle provide detection and localization of debonding and large impact damage. Inverse correlations of measured strain changes in damaged panel vs. healthy baseline values using the GENOA software can provide estimation of damage location, size and type. In this paper the analysis will be based on a number of scenarios which might not have been anticipated during design of structure. These would consist of in-service accidental damages, tracking of repairs or monitoring of findings reported in airframes. Flexible, non-expensive and easy-to install solutions for autonomous ad-hoc monitoring (either interim or permanent) will be assessed. This work is intended to determine feasibility of synergy of heterogeneous sensors, with special focus on wireless transmission of data. Aim is to determine type, number and arrangement of sensors needed to characterize a given structural damage (diagnosis) along with prediction of its future evolution (prognosis), including technological aspects associated with hardware platform needed. Process involves studies about compatibility and complementariness of different combination of sensors, along with testing in real environments.

It is likely from previous experience that the detection of damage will be based mainly on a network of suitable active Piezoelectric Sensors, PZT which will undergo verification tests. PZT actuators will generate Lamb wave packets at controlled ultrasonic frequencies in pitch-catch and/or pulse-echo modes. Investigation of wave propagation and changes in time of flight is anticipated to detect and localize damage. Furthermore, damage type and size will be determined using healthy specimens as a reference. Active Lamb wave methods are highly sensitive to PZT sensor size, damage size and location. In effect, the generation of specific frequencies can reveal the quality of stiffener bonding, and by fine tuning of frequency range in order to maximize the sensitivity of the method to each of the above damage type/size the data can be quantified. Modeling tools are also developed in GENOA software using algorithm of triangulation technique, adaptive meshing, and structural influence coefficient together with experimental data to assess the effectiveness of different combinations of sensors on structures.

9437-7, Session 2
Characterization of the multi-modal sensing properties of photoactive structural coatings

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This study aims to characterize the multi-modal sensing properties of photoactive structural coatings designed for monitoring aerospace structures. Unlike conventional sensing technologies, these structural coatings are capable of selectively detecting multiple types of damage and do not require an external electrical power supply. Instead, it uses light as its source of energy and generates direct current (DC) that is correlated to different damage stimuli. Furthermore, the structural coatings can be applied onto the surface of various aerospace structures without increasing payload, due to it being a thin film. In previous studies, it was shown that the structural coatings could selectively detect multiple types of damage (i.e., cracks and corrosion) using two different bandwidths of light (i.e., blue- and infrared-light), respectively. Despite this, it remains necessary to characterize and improve their multi-modal sensing properties, specifically, their performance and selectivity when sensing tensile strain and pH (i.e., for corrosion monitoring). First, using ultraviolet-visible (UV-Vis) spectroscopy, the optical properties of various components of this multilayered thin film or coating were characterized in response to different levels of applied stimuli (i.e., tensile strain and pH). Second, the results from UV-Vis were used to improve sensor sensitivity (for each sensing modality) by optimizing the light wavelength range used for sensor interrogation. Lastly, the influence of environmental effects (e.g., temperature and humidity, among others) was investigated to quantify their effects on sensor performance.

9437-8, Session 2
Modelling of thermal wave propagation in damaged composites with internal source

Francesco Ciampa, Stefano Angioni, Fulvio Pinto, Univ. of Bath (United Kingdom); Gennaro Scarselli, Univ. del Salento (Italy); Darryl P. Almond, Michele Meo, Univ. of Bath (United Kingdom)

SMARt Thermography exploits the electrothermal properties of multifunctional smart structures, which are created by embedding shape memory alloy (SMA) wires in traditional carbon fibre reinforced composite laminates (known as SMARt composites), in order to detect the structural flaws using an embedded source. Such a system enables a built-in, fast, cost-effective and in-depth assessment of the structural damage as it overcomes the limitations of standard thermography techniques. However, a theoretical background of the thermal wave propagation behaviour, especially in the presence of internal structural defects, is needed to better interpret the observations/data acquired during the experiments and to optimise those critical parameters such as the mechanical and thermal properties of the composite laminate, the depth of the SMA wires and the intensity of the excitation energy. This information is essential to enhance the sensitivity of the system, thus to evaluate the integrity of the medium with different types of damage.

For this purpose, this paper aims at developing an analytical model for SMARt composites, which is able to predict the temperature contrast on the surface of the laminate in the presence of in-plane internal damage (delamination-like) using pulsed thermography. Such a model, based on the Green's function formalism for one-dimensional heat equation, takes into account the thermal lateral diffusion around the defect and it can be used to compute the defect depth within the laminate. The results showed good agreement between the analytical model and the measured thermal waves using an infrared (IR) camera. Particularly, the contrast temperature curves were found to change significantly depending on the defect opening.

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9437-9, Session 3

The exploration study of fire-damaged concrete specimen using x-ray computed tomography

Yu-Min Su, National Kaohsiung Univ. of Applied Sciences (Taiwan)

Portland Cement Concrete (PCC) loses the evaporable water at about 100 °C, decomposes C-S-H at about 200 °C, and dehydrates CH at about 500 °C, and deconstruct C-S-H at about 900 °C. The concrete degradation or cracks are caused by several possible parameters, such as vapor pressure in pores, thermal gradient, and varied expansion rates of cement pastes and aggregates. The objective of the exploration study was to assess the porosity before and after conditioning of high temperature in the laboratory with the medical X-ray computed tomography. The experimental program was determined to identify the mineral properties of the aggregates used and determine the consensus properties of compressive, splitting tensile, and flexural strengths. Concrete cylinders were subject with two different temperature conditioning, namely 400 °C and 600 °C. The X-ray CT, before and after high temperature conditioning, was administrated on the concrete cylinders to inspect the depth of the damage zone, which shall consist of more porosity than undamaged one. The damage zone will be examined and identified through the changes in porosity of concrete paste and aggregates within a concrete cylinder. The significance of the exploration study was to provide an in-depth insight to define the damaged zone for a better understanding of the following repairing and reinforced work.

9437-10, Session 3

Development of a health monitoring method for solid rocket propellant

Craig Lopatin, Technion-Israel Institute of Technology (Israel); Dan Grinstein, Israel Ministry of Defense (Israel)

Changes in the mechanical properties of solid propellant due to aging can lead to defects that limit the service lifetime of solid rocket motors. The use of embedded sensors is an approach that is being explored to augment legacy inspection and prediction methods. We present here a method that is particularly suited for monitoring the properties of solid propellant, as it does not introduce electrical wires into the motor. Based on the use of magnetic induction for excitation and an optical fiber Bragg grating sensor to measure deformation, it can be used to characterize the properties of a material with which it is in contact. We first present experiments demonstrating the utility of the method in characterizing the viscosity of an epoxy resin during cure. We next apply the method to solid propellant, and demonstrate that the method can characterize the deflection-load curve of an aluminized HTPB propellant. We also show that the observed strain rate sensitivity matches that found in the literature and that it has adequate resolution to detect the changes in material properties due to aging.

9437-11, Session 3

Damage criticality and inspection concerns of composite-metallic aircraft structures under high energy blunt impact

Duo Zou, Cord Haack, Peter W. Bishop, Abraham Bezabeh, Bishop GmbH (Germany)

The concept of smart structures has gained increasing acceptance and could result in better competitiveness in the field of aerospace. Such design considers damage as a critical phenomenon. Indeed, damage can weaken the structural reliability and performance in life cycles. The aviation industry has acknowledged the risks associated with serious ground operation incidents and accidents. Consequences of these events result in aircraft

damage, delays and financial cost to the industry. Currently there are few research efforts spending on how to reduce the criticality of damage under impact and provide reliable recommendations for safety and inspection technologies, therefore, the improved understanding of blunt impact damage is still required.

The present work considers a further study of high energy low velocity blunt impact damage on a representative aircraft structure, which characterizes mainly the damage formation and inspection by using non-destructive inspection technique. The structures here investigated are a composite-metallic 4-hat-stiffened and 5-frame panel as shown. The research begins with the design, manufacturing and finite element analysis under static loading. The test fixtures for quasi-static tests are developed based on the results of numerical analyses of the test panel finite element models and the full fuselage barrel model. After unloading, a visual examination of the outer skin side and clips is performed. The results of numerical analyses are compared to the experimental ones in terms of load-shortening curves, impact deformations and damage mechanisms.

This study, providing methodologies based on validated finite element analyses, can contribute to improved safety of composite aerospace structures and can also support the design of current and future aircraft.

9437-12, Session 3

Design, application, and validation of embedded ultrasonic sensors within composite structures

Jamie S. Chilles, Univ. of Bristol (United Kingdom)

The layer wise construction of laminated composites offers the potential to permanently embed sensors within composite structures. One possible solution is the embedding of sensors that are inductively coupled to an external probe; this allows for the efficient transfer of electrical signal between the embedded sensor and processing equipment. However for this system to be viable the embedment of the sensors must result in minimal degradation of the laminates mechanical performance. This piece of work focuses on designing inductively coupled sensors to be as unobtrusive as possible. This is achieved by identifying a suitable sensor coating that ensures strong adhesion both within the sensor and between the sensor and composite host. The geometry of the sensor has then been designed so as to cause minimum disruption to the laminates internal fibre architecture. The sensors chosen geometry is coupled with the possible method for embedding the sensor within the laminate. Both the effects of sensor geometry and embedding method have been assessed using four point bend testing and finite element analysis. In addition to assessing the mechanical performance, the ability of the embedded sensors to monitor the host laminates cure cycle is shown. The embedded sensors consist of two types; bulk and guided wave sensors which operate within thick laminates and thin plate structures respectively. This novel method of cure cycle monitoring is then benchmarked against an industrially accepted dielectric cure monitoring technique.

9437-14, Session 3

A Supervised Outlier Analysis for Risk Assessment in Composite Wing Structures

Yingtao Y. Liu, The Univ. of Oklahoma (United States); Bach Duong, University of Oklahoma (United States)

A methodology based on Lamb wave analysis and statistical analysis has been developed for damage detection and classification of composite structures. Because the Lamb wave signals are complex in nature, robust statistical analysis techniques are required to extract damage features. In this paper, Lamb wave mode conversion is used to detect the damage in composite structures. Multiple statistical classification algorithms were investigated and compared. Results of numerical Lamb wave propagation simulations and experiments using orthotropic composite plate structures

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are presented. The capability of the proposed damage classification algorithm is demonstrated by detecting seeded delamination in the composite plate samples. The advantages of the methodology include accurate classification capability, robustness to noise, high computational efficiency and ease of post-processing.

9437-15, Session 3
Quantitative characterization of composite materials using thermographic signal reconstruction (TSR)

Steven M. Shepard, Maria Frendberg Beemer, Thermal Wave Imaging, Inc. (United States)

Active thermography has become a widely accepted method for NDT of composite structures. In its most basic form, the surface of a sample is heated and viewed with an infrared (IR) camera as it cools. At present, most composite NDT applications of thermography are qualitative, based on visual identification of anomalous regions that appear as discrete "hot spots" in the IR image, indicating possible flaws such as delaminations, voids or inclusions. Quantification is limited to flaw sizing, and to a lesser extent, measurement of flaw depth. In the Thermographic Signal Reconstruction (TSR) method, the time derivative of the logarithmic temperature-time history of each pixel is computed and analyzed, and an image based on results from all pixels is reassembled. The resulting logarithmic derivative images allow detection of weak subsurface features that do not appear in the conventional IR image sequence. In addition to providing increased accuracy in flaw size and depth measurements, the use of TSR derivatives allows quantitative characterization of the interface between flaw and host materials, and measurement of substrate thermal properties. Materials characterization, where no discrete flaw necessarily exists, can also be performed by analysis of the logarithmic time derivatives and their attributes. Using this approach, it is possible to measure composite porosity to a degree of accuracy comparable to ultrasonic attenuation.

9437-16, Session Key
Transforming SHM research to practice in bridge maintenance (Keynote Presentation)

Genda Chen, Missouri Univ. of Science and Technology (United States)

Structural health monitoring (SHM) for bridges has been an emerging research topic in the past 15 years. Its outcomes are vast in terms of publications and researcher training but significantly less in terms of practical applications. One reason for the research-practice gap is attributed to bridge characteristics, such as large scale, large inventory, harsh operation environment, multiple deteriorations and failure modes, and exposure to multiple hazards. The main reason, however, is the incoherent design and operation conditions of bridges, which makes it a challenge to get practical engineers interested in long-term implementation of most SHM technologies currently available in literature. To the SHM community, the incoherent conditions thus require further research, development, and education of a suite of monitoring technologies to quantify multiple damage/deterioration modes in a straightforward and autonomous manner, such as crack, fatigue, yielding/buckling, scour, and corrosion. In this presentation, societal needs on civil SHM will be reviewed based on past bridge safety records and maintenance practices. The review data will lead into several new perspectives on future research directions by re-aligning SHM outcomes to daily practices in bridge inspection and maintenance. The common attributes of the new perspectives will be discussed and exemplified in terms of sensor design, data acquisition and analysis, and integration of monitoring into mitigation effort. Current sensor technologies and future opportunities along this line of research will be discussed with several examples. A roadmap is developed to directly apply sensing technologies for critical data sets that are much needed in bridge maintenance.

9437-17, Session 4
Strain distribution in thin concrete pavement panels under three-point loading to failure with pre-pulse-pump Brillouin optical time domain analysis

Yi Bao, John Cain, Yizheng Chen, Missouri Univ. of Science and Technology (United States); Ying Huang, North Dakota State Univ. (United States); Genda Chen, Missouri Univ. of Science and Technology (United States); Leonard Palek, Minnesota Dept. of Transportation (United States)

Thin concrete panels reinforced with alloy polymer macro-synthetic fibers have recently been introduced to rapidly and cost-effectively improve the driving condition of existing roadways by laying down a fabric sheet on the roadways, casting a thin layer of concrete, and then cutting the layer into panels. This study is aimed to understand the strain distribution and potential crack development of concrete panels under three-point loading. To this end, six full-size 6ft² concrete panels were tested to failure in the laboratory. They were instrumented with three types of single-mode optical fiber sensors whose performance and ability to measure the strain distribution and detect cracks were compared. Each optical fiber sensor was spliced and calibrated, and then attached to a fabric sheet using adhesive. A thin layer of mortar (0.25 - 0.5 in thick) was cast on the fabric sheet. The three types of distributed sensors were bare SM-28e+ fiber, SM-28e+ fiber with a tight buffer, and concrete crack cable, respectively. The concrete crack cable consisted of one SM-28e+ optical fiber with a tight buffer, one SM-28e+ optical fiber with a loose buffer for temperature compensation, and an outside protective tight sheath. Distributed strains were collected from the three optical fiber sensors with pre-pulse-pump Brillouin optical time domain analysis in room temperature. Among the three sensors, the bare fiber was observed to be most fragile during construction and operation, but most sensitive to strain change or micro-cracks. The concrete crack cable was most rugged, but not as sensitive to micro-cracks and robust in micro-crack measurement as the bare fiber. The ruggedness and sensitivity of the fiber with a tight buffer were in between the bare fiber and the concrete crack cable. The strain distribution resulted from the three optical sensors are in good agreement, and can be applied to successfully locate cracks in the concrete panels. It was observed that the three types of fibers were functional until the concrete panels have experienced inelastic deformation, making the distributed strain sensing technology promising for real applications in pavement engineering.

9437-18, Session 4
Detection of delaminations in concrete slabs combining infrared thermography and impact echo techniques

Fuad H. Khan, Drexel Univ. (United States); Matteo Mazzotti, Univ. degli Studi di Bologna (United States); Ivan Bartoli, Drexel Univ. (United States)

Inspection of bridge decks is of primary importance in the field of bridges maintenance since, unlike other structural components, they are more subjected to degradation and traffic-induced deterioration phenomena. Among the various deterioration mechanisms, delaminations are generally difficult to detect because no visible effects are usually observed on the deck surface. Since the entity of the damage progressively increases during time, methodologies able to effectively detect these horizontal flaws at an early stage are needed in order to reduce maintenance costs.

In this work, the results obtained using two different nondestructive techniques, namely the impact echo (IE) method and the infrared thermography (IR), are compared. Experimental tests have been performed on a 20 cm thick concrete slab with delaminations of various extensions embedded at specific locations.

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As classically done in impact-echo test, ultrasonic waveforms have been acquired at different points along the slab surface and then analyzed in the frequency domain. From the frequency response spectrum of the slab, delaminations have been detected by observing, among other features, the shifts in the peaks of the so called return frequencies.

The IE results obtained on a grid of points along the slab surface have been compared with those extracted using the infrared thermography. The main concept behind the use of the IR is that embedded horizontal interfaces can result in different temperature regions along the slab surface.

A discussion on the pro and cons of the two methodologies is finally provided as well as possible strategies to fuse the two techniques.

9437-19, Session 4

Boundary condition identification for a grid model by experimental and numerical dynamic analysis

Qiang Mao, Mustafa Furkan, Drexel Univ. (United States); Matteo Mazzotti, Univ. degli Studi di Bologna (United States); Ivan Bartoli, Ahmet E. Aktan, Drexel Univ. (United States)

There is a growing need to characterize unknown foundations and assess substructure in existing bridges. It is becoming an important issue for the serviceability and safety of bridges as well as for the possibility of partial reuse of existing infrastructures.

This paper investigates the possibility of identifying, locating and quantifying changes of boundary conditions, by leveraging a simply supported grid model with a composite deck. Impact tests are operated for this grid model with changes at the supporting bearings, by replacing steel cylindrical rollers with rollers of compliant material. As a result of impact based modal analysis, global modal parameters such as damped natural frequencies, mode shapes and flexibility matrix are first used as indicators of boundary condition changes.

Model updating methods using global optimization algorithms are leveraged to create a detailed ABAQUS model of the grid. The ABAQUS model that simulates the supporting bearing with springs is used to predict the change of the boundary conditions.

Finally, the feasibility of using local modes to investigate changes of boundary conditions is considered. Impact tests are conducted in close proximity of the supports with different bearings. This method is also explored numerically by explicit finite element analysis based on a refined ABAQUS model.

9437-20, Session 4

Development and evaluation of a long range image-based monitoring system for civil engineering structures

Matthias Ehrhart, Werner Lienhart, Technische Univ. Graz (Austria)

Today, many large-scale civil engineering structures are permanently monitored to provide early warnings and to initiate counter actions from structural failure. Total station measurements are commonly used to determine 3D movements with measurement intervals of several minutes or hours. However, these measurements do not provide information on the vibration behavior of the structures. For this purpose other sensors like accelerometers have to be installed on the object. In this paper we present a monitoring system based on an image-assisted total station (IATS) suitable for the determination of absolute 3D coordinates of selected points and the determination of the structure's eigenfrequencies.

Using conventional total station measurements (angles and distance), the 3D coordinates of selected points can be determined with an accuracy

of a few millimeters. For the determination of the eigenfrequencies, the telescope camera of the IATS is used in combination with dedicated image processing algorithms optimized for different target shapes. The usage of the telescope camera is beneficial since the 30x optical magnification of the telescope results in a high spatial resolution (approx. 2 arcsec/pixel) of the image data. Thus, large distances to the object to be monitored are possible while retaining a high accuracy in the detected movements and vibrations.

While the determination of 3D coordinates based on total station measurements is common practice, the idea of using the total station's image data for frequency analysis is new and investigations on the achievable performance are pending for commercially available total stations. We therefore evaluate the potential of this technique at a life-size footbridge. The results are compared with accelerometer measurements, which are conventionally used for frequency analysis. We demonstrate that with our developed monitoring concept and state of the art hardware accelerometer measurements can be replaced in several monitoring situations by image processing techniques.

9437-21, Session 5

Research of a health monitoring system of a prestressed concrete box-girder bridge

Lei Wang, Pengfei Wei, Shifeng Huang, Xin Cheng, Univ. of Jinan (China)

Taking a 22-span prestressed concrete continuous box-girder bridge as a research object, a structural health monitoring system has been implemented on one of its spans, which cross over a high-speed railway. The bridge is precast and simple supported and has four lanes in two ways and been in service since 2005. For its importance, a health monitoring system is required to instrument. First, a finite element model was built to calculate strains and deflections of box girders of the bridge, based on which the measurement points are chosen. Then, the acceleration and fiber-Bragg grating strain sensors, a weigh-in-motion system, a deflection monitoring system, the acoustic emission technique and several video cameras are integrated in the health monitoring system. Four fiber-Bragg grating sensors are fixed at the middle point of span of four box-girders, and deflection monitoring points at the same places. 6 acceleration sensors are implemented on the deck to monitoring vertical frequencies. The weigh-in-motion system is buried in the asphalt layer. 8 acoustic emission sensors are implemented near the supports. 8 Video cameras are fixed on the piers to view the whole scene under the bridge. State estimation and early warning system is built to acquire the bridge managers. The monitoring system operates continuously and evaluates the bridge safety conditions in real-time.

9437-22, Session 5

Non-contact main cable NDE technique for suspension bridge using magnetic flux-based B-H loop measurements

Seunghee Park, Ju-Won Kim, Sungkyunkwan Univ. (Korea, Republic of); Dae-Joong Moon, EJtech (Korea, Republic of)

In this study, a noncontact cable NDE method that can detect both external and internal cross-sectional loss of main cables has been developed. This cable NDE method utilizes the direct current (DC) magnetization and a searching coil-based total flux measurement. A total flux sensor head prototype was fabricated for real field application. It consists of an electro-magnet yoke to magnetize the cable specimen and a searching coil sensor to measure the total magnetic flux from the magnetized specimen. To obtain a B-H loop, a magnetic field for magnetizing the cable specimen was generated by applying a cycle of low frequency direct current to the electro-magnet yoke. During the magnetization, a search coil sensor measures the electromotive force from magnetized cable. The magnetic flux that passes

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through the whole inner area of search coil sensor was measured based on the faraday's law of induction. Total flux was calculated by integrating the measured magnetic flux using a fluxmeter. A B-H loop is obtained by using relationship between a cycle of input DC voltage and measured total flux. The B-H loop can reflect the property of the ferromagnetic materials. Therefore, the cross-sectional loss of cable can be detected using variation of features from the B-H curve. To verify the feasibility of the proposed steel cable NDE method, a series of experimental studies using a main-cable mock-up specimen that has several types of external and internal cross-sectional damages have been performed in this study.

9437-23, Session 5

Data analysis for decision making: a long-term wireless monitoring demonstration of the Telegraph Road bridge

Sean M. O'Connor, Yilan Zhang, Jerome P. Lynch, Univ. of Michigan (United States)

Advances in wireless sensor technology have enabled low cost and extremely scalable sensing platforms prompting high density installations. Wireless sensing has shown great success in short term monitoring applications. Still, permanent monitoring demonstrations are needed to highlight the reliability of wireless systems to environmental exposure and harsh environmental conditions, as well as demonstrate to bridge managers the decision making information revealed by permanent monitoring. High density long-term monitoring generates a wealth of data demanding an efficient means of data storage and data processing for information extraction. This paper reports on decision making inferences drawn from big data processing of long-term highway bridge data. The Telegraph Road Bridge (TRB) demonstration testbed for sensor technology innovation and data processing tool development has been instrumented for long-term wireless structural monitoring and damage detection since September, 2011, utilizing physical (e.g., acceleration, strain) and environmental (e.g., temperature) response to address stated concerns by the Michigan Department of Transportation regarding pin and hanger bridges. The sensing strategy is designed to conform with specific damage modalities common to multi-girder steel concrete composite bridges using link plate assemblies. To efficiently store and process long-term sensor data the TRB monitoring system operates around the SenStore database system, which combines sensor data with bridge information (e.g., material properties, boundary conditions) and exposes an application programming interface to enable data extraction by processing tools. Bridge data is uploaded to SenStore via cellular modem. This paper presents damage detection strategies directly relevant to pin and hanger type bridges as well as decision making inferences drawn from long-term data sets.

9437-24, Session 5

Monitoring of transverse displacement of reinforced concrete beams under flexural loading with embedded arrays of optical fibers

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We present results of an ongoing study of structural health monitoring of concrete elements by means of arrays of telecommunications-grade optical fibers embedded in such elements. In this work, we apply this technique for monitoring the transverse displacement of the reinforced concrete beams under flexural loading. We embedded a number of multimode optical fibers of silica core and polymer cladding in a mold with preinstalled reinforcing

steel bars and fresh concrete mix. Then the concrete was compacted and cured. Some optical fibers were broken during the fabrication process. The fiber survival rate varied with concrete grade, compacting technique and optical fiber type. The fibers that survived the fabrication process were employed for the monitoring. They were connected to the optical transmitter and receiver that formed a part of a larger measurement system. The system continuously measured the optical transmission of all optical fibers while the reinforced concrete beams were subjected to incremental flexural loading. We observed a quasi-linear decrease in optical transmission in all optical fibers of the array vs. the applied load and respective flexural displacement. Although the underlying phenomena that lead to such a variation in optical transmission are not clear yet, the observed behavior might be of interest for assessing the transverse displacement of the reinforced concrete beams under flexural load.

9437-25, Session 5

Concrete bridge deck early problem detection and mitigation using robotics

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More economical management of bridges can be achieved for early problem detection and mitigation. The paper describes development and implementation of two fully automated (robotic) systems for nondestructive evaluation (NDE) and minimally invasive rehabilitation. The NDE system named RABIT was developed with the support from Federal Highway Administration. It implements multiple NDE technologies, namely: electrical resistivity (ER), impact echo (IE), ground-penetrating radar (GPR), and ultrasonic surface waves (USW). In addition, the system utilizes advanced vision to substitute traditional visual inspection. The RABIT system collects data at significantly higher speeds than it is done using traditional NDE equipment. The associated platform for the enhanced interpretation of condition assessment in concrete bridge decks utilizes data integration, fusion, and deterioration and defect visualization. The interpretation and visualization platform specifically addresses data integration and fusion from the four NDE technologies. The data visualization platform facilitates an intuitive presentation of the main deterioration due to: corrosion, delamination, and concrete degradation, by integrating NDE survey results and high resolution deck surface imaging. The rehabilitation robotic system was developed with the support from National Institute of Standards and Technology-Technology Innovation Program. The system utilizes advanced robotics and novel materials to repair problems in concrete decks, primarily early stage delamination and internal cracking, using a minimally invasive approach. Since both systems use global positioning systems for navigation, some of the current efforts concentrate on their coordination for most effective joint evaluation and rehabilitation.

9437-27, Session 6

High piezoelectric properties of cement piezoelectric composites containing Kaolin

Huang Hsing Pan, Ruei-Hao Yang, Yu-Chieh Cheng, National Kaohsiung Univ. of Applied Sciences (Taiwan)

For engineering applications of sensors and actuators in civil engineering structures, cement-based piezoelectric composites as sensors and actuators were developed to overcome the matching problem that conventional piezoelectric ceramics or polymers do not contact synchronously with concrete. The manufactures of cement-based piezoelectric composites having high piezoelectric and dielectric constants are still ongoing. Here, a PZT/cement composite with kaolin was fabricated and polarized by 1.5kV/mm electric field for 40 min, in which lead zirconate titanate (PZT) with

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50% by volume was used. Specimens were made by applying a 80MPa compression to form a disk-like shape, and cured for 1 day at 90° and 100% relative humidity. After the polarization, piezoelectric properties were measured until 150 days. Results indicated that relative dielectric constant (ϵ_r) and piezoelectric strain constant (d_{33}) increase with aging day, and approach to a saturated value after 70 days. Temperature is a dominate factor to enhance piezoelectric properties. In the beginning the d_{33} and ϵ_r values of PZT/cement composites were 57pC/N and 275 at the 70th aging day respectively, and then reached 106pC/N and 455 in turn with 150° treatment, that is a relative high value of piezoelectric and dielectric constant. The composite contains 4% kaolin having the optimum value of d_{33} =111pC/N and ϵ_r =495. The porosity, electromechanical coupling coefficient and impedance- frequency spectra of the composites were also discussed.

9437-28, Session 6

Adhesive disbond detection using piezoelectric wafer active sensors

William Roth, Victor Giurgiutiu, Univ. of South Carolina (United States)

The aerospace industry continues to increase the use of adhesives for structural bonding due to the increased joint efficiency (reduced weight), even distribution of the load path and decrease in stress concentrations. However, the limited techniques for verifying the strength of adhesive bonds has limited its use on primary structures and requires an intensive inspection schedule. This paper discusses potential structural health monitoring (SHM) techniques for the detection of disbands, intended to be used for the in situ inspection of adhesive joints. This is achieved through the use of piezoelectric wafer active sensors (PWAS), thin unobtrusive sensors which are permanently bonded to the aircraft structure. Two detection methods are investigated; local vibration based SHM and wave propagation. The local vibration inspection technique involves the use of electromechanical impedance spectroscopy. This method detects disbands from the change in the mechanical impedance of the structure surrounding the disbond. The wave propagation method uses the pitch catch technique, which sends guided waves across the structure through the adhesive joint and is then received on the opposite side of the joint. Changes in the signal as it passes through the disbond region are detected by the receiving sensor. These inspection schemes have been evaluated using the finite element method, and the results were verified experimentally using a large aluminum test article, and included both pristine and disbond coupons.

9437-29, Session 6

Ultrasonic measurement and monitoring of loads in bolts used in structural joints

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The paper is an overview of work by the author in measuring and monitoring loads in bolts using an ultrasonic extensometer. A number of cases of bolted joints are covered. These include, a clamped joint with clearance fit between the bolt and hole, a clamped joint with the bolt in an interference fit with the hole, a flanged joint which allows the flange and bolt to bend; and a shear joint in a clevis and tang configuration. These applications were initially developed for measuring and monitoring preload in the NASA Space Shuttle Orbiter critical joints but are also applicable for monitoring loads in other critical bolted joints of structures such as transportation bridges and other aerospace structures. The paper explains how to set-up a model to estimate the load factor and accuracy for the ultrasonic preload application in a clamped joint with clearance fit. The ultrasonic preload application for clamped joint with bolt in an interference fit can also be used to measure diametrical interference between the bolt shank and hole; and interference pressure on the bolt shank. Model and experimental data are given to demonstrate use of ultrasonic measurements in a shear joint. A bolt in a flanged joint experiences both tensile and

bending loads. This application involves measurement of bending and tensile preload in a bolt. The ultrasonic beam bends due to the bending load on the bolt. A numerical technique to compute the trace of ultrasonic ray is presented.

9437-30, Session 6

Nonlinear acoustics for practical applications

To Kang, Korea Atomic Energy Research Institute (Korea, Republic of) and Sungkyunkwan Univ. (Korea, Republic of); Jeong Na, Wyle Labs. (United States); Sung-Jin Song, Sungkyunkwan Univ. (Korea, Republic of); Jin-Ho Park, Korea Atomic Energy Research Institute (Korea, Republic of)

Three different ultrasonic nonlinearity parameter measurement methods are available: the capacitive detection method to measure absolute values of nonlinearity parameters; the laser interferometry detection as a non-contact method; the contact piezoelectric transducer based relative measurement method. Among all these three methods, the contact piezoelectric transducer detection technique has been used as the most practical approach due to its operational simplicity for fatigue damage assessments. One of the main drawbacks of this technique, however, has been the low sensitivity of the receiving transducers, especially for the second harmonic components, causing a high uncertainty in measurements. In this work, it is demonstrated with a Copper [100] single crystal that high-Q valued band-pass filters and low-noise preamplifiers introduced in the system not only improve the measurement accuracy but also determine absolute values of nonlinearity parameters without using the capacitive detection method. The new improved contact piezoelectric transducer based nonlinearity parameter measurement system employs a pair of narrow-band high-rejection bandpass filters, low-noise preamplifiers, and a particle displacement calibration procedure to be able to determine absolute values of nonlinearity parameters without using a capacitive detection system in addition to an improvement in reduction of measurement uncertainty.

9437-47, Session 6

Fibre Optic sensors for load-displacement measurements and its comparisons to piezo sensor based electromechanical admittance signatures

Muneesh Maheshwari, Venu Gopal Madhav Annamdas, John H. L. Pang, Swee Chuan Tjin, Anand K. Asundi, Nanyang Technological Univ. (Singapore)

Damage investigation in different beam configurations using Fiber Optic Polarimetric Sensors has already been performed. These investigations were based on the change in frequency of first fundamental mode due to the damage. It is well established that the frequency of first fundamental mode of any beam structure goes down when damages occur. In this paper, the effect of change in the boundary conditions on the frequencies of both first and second fundamental modes of a fixed-fixed beam has been studied. It was found that if a force was applied on one end of a fixed-fixed beam to change the boundary conditions, the frequencies of both fundamental modes increased contrary to case of damage. Therefore, just by looking at the change in fundamental frequencies it could be inferred conveniently whether the beam was damaged or the boundary conditions were changed. This information can be used for the purpose of structural health monitoring of beam.

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9437-96, Session 6

**Bearing fault component identification
using information gain and machine
learning algorithms**

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Various researchers have used different techniques to identify faults in bearings. In the present study an attempt has been made to identify various bearing faults using machine learning algorithm. For this purpose, vibration signals obtained from faults in inner race, outer race, rolling element and combined faults are considered. Raw vibration signal are masked by noise and can not be directly used for fault detection. To overcome this difficulty a combination of time domain and frequency domain method such as wavelet transformation is used. Further wavelet selection criteria based on minimum permutation entropy is employed to select most appropriate base wavelet. Statistical features from selected wavelet coefficients are calculated to form feature vector. To reduce size of feature vector information gain attribute selection method is employed. Modified feature set is fed in to machine learning algorithm such as random forest and self-organizing map for getting maximize fault identification efficiency. Results obtained revealed that attribute selection method shows improvement in fault identification accuracy of bearing components.

9437-26, Session PTues

**Monitoring the integrity of massive
aluminum structures using PZT transducers
and the technique of impedance**

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Safety, performance, economy and durability are essential items to qualify materials for the manufacturing of structures used in different areas. Generally, the materials used for this purpose are formed by composites and sometimes they can present failure during the manufacturing process. Such failures can also occur during use due to fatigue and wear, causing damage often difficult to visually detect. In these cases, the use of non destructive testing (ND) has proven to be a good choice for assessing the materials quality. The objective of this work was the electromechanical impedance evaluation of massive aluminum structures using ultrasonic transducers to detect discontinuities in the material. The tests have been done using an impedance analyzer (Agilent 4294A), an ultrasound transducer (1.6 MHz of central frequency) and six aluminum samples (250 x 50 x 50 mm) with the transducer placed at four different regions. One sample was kept intact (reference) and the others were drilled in 3 positions with different sizes of holes. The electromechanical impedance was recorded for each sample. The root mean square deviation index (RMSD) between the impedance magnitude of the reference and damaged samples was calculated and it was observed an increase in the RMSD due to the increase of the diameter of the holes (failures) in the samples completely drilled. The results show that the proposed methodology is suitable for monitoring the integrity of aluminum samples. The technique may be evaluated in characterizing other materials to be used in the construction of prostheses and orthoses.

9437-79, Session PTues

**Foam metal metamaterial panel for
mechanical waves isolation**

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Technology (China)

This paper presents modeling, analysis techniques and experiment of foam metal metamaterial panel for Broadband Vibration Absorption. For a unit cell of an infinite foam metal metamaterial panel, governing equations are derived using the extended Hamilton principle. The concepts of negative effective mass and stiffness and how the spring-mass-damper subsystems create a stopband are explained in detail. Numerical simulations reveal that the actual working mechanism of the proposed metamaterial panel is based on the concept of conventional mechanical vibration absorbers. It uses the incoming elastic wave in the panel to resonate the integrated membrane-mass-damper absorbers to vibrate in their optical mode at frequencies close to but above their local resonance frequencies to create shear forces and bending moments to straighten the panel and stop the wave propagation. Moreover, a two-dimension acoustic foam metal metamaterial panel consisting of lumped mass and elastic membrane is proposed in the lab. We do experiments on the model and The results validate the concept and show that, for two-dimension acoustic foam metal metamaterial panel do exist two vibration modes. For the wave absorption, the mass of each cell should be considered in the design. With appropriate design calculations, the proposed two-dimension acoustic foam metal metamaterial panel can be used for absorption of low-frequency waves and hence expensive micro-manufacturing techniques are not needed for design and manufacturing of such foam metal metamaterial panel for low-frequency waves absorption/isolation.

9437-81, Session PTues

**Quick seismic intensity map investigation
and evaluation based on cloud monitoring
method using smart mobile phone**

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Qinghua Zhu, Yan Yu, Mingchu Li, Jinping Ou, Dalian Univ.
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Seismic intensity map which reflects the actual situation of destruction in a certain area after the earthquake, and it is of great significance in guiding relief work and assessing damage loss. Earthquake professionals make intensity map usually through visiting sites personally, sometimes combining with strong motion records analysis and remote sensing seismic interpretation. However, these methods tend to spend a lot of time, especially in the case that the earthquake-affected area is very large.

Based on cloud monitoring method proposed, we developed software, which can quickly investigate the seismic intensity distribution and draw the intensity map after the earthquake using the big data collected by individual smart phone questionnaire in earthquake zone. According to seismic attenuation law, we generated some seismic intensity values to test our system and successfully drawn out of the seismic intensity map.

When earthquake occurred in a certain area, all the people who equipped this software on their smart phones, can fill in the intensity questionnaire and take scene photos, then submit these to our server through the software. Questionnaires and scene photos can be classified by our server. When the amount of data submitted meets the requirements, the server can draw the accurate intensity map in a few seconds.

9437-82, Session PTues

**Rapid condition assessment of structural
condition after a blast using state-space
identification**

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After a blast event, it is important to quickly quantify the structural

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damage for emergency operations. With the increasing global threat of terrorism, the ability to quickly assess a buildings structural condition after a terrorist bombing is of great concern. Visual inspections are a common method of structural assessment after a bombing. In order improve the speed, accuracy, and efficiency of condition assessments after a blast, the authors have previously presented work to develop a methodology for rapid assessment of the structural condition of a building after a blast. This previous method involved determining a post-event equivalent stiffness matrix using vibration measurements and a finite element (FE) model. A structural model was built for the damaged structure based on the equivalent stiffness, and inter-story drifts from the blast are determined using numerical simulations, with forces determined from the blast parameters. The inter-story drifts are then compared to blast design conditions to assess the structures damage. However, the previous approach still involved engineering judgment in terms of determining significant frequencies, which can lead to error, especially with noisy measurements. To improve accuracy and automate the process, this paper incorporates the subspace state-space identification algorithm in a rapid condition assessment procedure. Validation on the blast damage assessments using P-I diagrams is provided, which present the condition limits across many different blast parameters. Comparisons between P-I diagrams generated using the true system parameters and equivalent parameters shows the accuracy of the rapid condition based blast assessments.

9437-83, Session PTues

Acoustic metamaterial panels based on multi frequency vibration absorbers

Hongwei Sun, Jiangsu Automation Research Institute (China); Guochang lin, Harbin Institute of Technology (China)

Presented here is a new metamaterial panel based on multi-frequency vibration absorbers for broadband vibration absorption. The proposed metamaterial panel consists of a uniform isotropic panel and small two-mass spring-mass-damper sub systems at many locations along the panel to act as multi-frequency vibration absorbers. The existence of two stopbands 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. For a finite metamaterial panel, because these two idealized models can not be used for finite panels and/or elastic waves having short wavelengths, a finite-element method is used for detailed modeling and analysis. The concepts of negative effective mass and effective stiffness and how the spring-mass-damper subsystem creates two stopbands are explained in detail. For an incoming wave with a frequency in one of the two stopbands, the absorbers are excited to vibrate in their optical modes to create shear forces to straighten the panel and stop the wave propagation. For an incoming wave with a frequency outside of but between the two stopbands, it can be efficiently damped out by the damper with these cond mass of each absorber. Hence, the two stopbands are connected in to a wide stopband. Numerical examples validate the concept and show that the structures boundary conditions do not have significant influence on the absorption of high-frequency waves. However, for absorption of low- frequency waves, the structures boundary conditions and resonance frequencies and the location and spatial distribution of absorbers need to be considered in design, and it is better to use heavier masses for absorbers.

9437-84, Session PTues

Thermal protection system monitoring with linear and nonlinear elastic waveguides

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This paper addresses the problem of nondestructively evaluation the performance and condition of thermal protection systems (TPSs) as they are undergoing severe heat loads. A challenge in conducting both ultrasonic and acoustic emission (AE) sensing of TPS systems is that the backside surfaces are too hot for traditional high-frequency piezoelectric sensors. An alternative technique is to use an elastic waveguide to enable placing the sensor at a remote and cooler location, while transmitting ultrasonic and or AE signals between the TPS surface and sensor. The waveguide must be able to transmit the elastic waves with sufficient fidelity to enable effective sensing. The waveguide must also act as a thermal insulator to prevent overheating of the sensor. Designs and test results from using the linear and nonlinear elastic waveguides are presented. The linear waveguide is an elongated copper pipe. It has the advantage of potential wideband fidelity for transmitting elastic waves, but has the disadvantage of high thermal conductivity. The nonlinear waveguide is a granular ball chain. These waveguides can transmit certain solitary waveforms with ease, while rejecting others, with the potential for being tuned to transmit specific ultrasound and/or AE signals. The ball chain geometry is particularly advantageous for low thermal conductivity. Design issues of impedance matching, weight and overall geometric dimensions of both types of waveguides. Test results include those from testing in a high-temperature inductively coupled plasma torch facility.

9437-85, Session PTues

Physics driven pitting corrosion modeling in 2024-T3 aluminum alloys

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Material degradation due to corrosion and corrosion fatigue has been recognized to significantly affect the airworthiness of civilian and military aircraft, especially for the current fleet of airplanes that have served beyond their initial design life. The ability to predict the corrosion damage development in aircraft components and structures, therefore, is of great importance in managing timely maintenance for the aging aircraft vehicles and in assisting the design of new ones. The assessment of aircraft corrosion and its influence on fatigue life relies on appropriate quantitative models that can evaluate the initiation of the corrosion as well as the accumulation during the period of operation. Beyond the aircraft regime, corrosion has also affected the maintenance, safety and reliability of other systems such as nuclear power systems, steam and gas turbines, marine structures and so on.

In the work presented in this paper, we are focused on developing physics based pitting corrosion models. The classic work of particle induced pitting corrosion by Wei and Harlow is reviewed in details. Two types of modeling, a power law based simplified model and a microstructure based model, are developed and compared for 2024-T3 alloy. Data from literature are used as model inputs. Parametric study is performed to understand the dependence of pitting corrosion on temperature and material microstructural parameters. The paper ends with conclusions and envisions of future work.

9437-86, Session PTues

Damage detection of plate-like structures using computational intelligence concepts

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Cracks in structural element are some of the main reasons for damaging the entire structure. In this study, a novel two stage methodology is proposed for the damage detection of flexural plates based on artificial

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neural network. In the first stage, damage location detection of plates is investigated using different damage indices such as curvature-moment and curvature moment derivative. First, the structure is modeled utilizing OpenSees software and damages are simulated as reduction in the thickness of the elements. Then, the data for the fundamental mode shape of the damaged structure is obtained. The damaged areas are appeared as pick points using the damage indices. The results show a high accuracy of curvature-moment derivative method in detecting the damage locations, especially at the corners of the plate. After detecting the damaged areas, the equations for damage severity detection are solved via Bat optimization (BA) algorithm. In the second stage, in order to efficiently reduce the computational cost of model updating during the optimization process of damage severity detection, multiple damage location assurance criterion (MDLAC) index based on the frequency change vector of structures are evaluated using properly trained cascade feed-forward neural network (CFNN). To validate this proposed solution method, two examples are presented. The results indicate that after determining the damage location using curvature moment derivative, the proposed solution method for damage severity detection leads to significant reduction of computational time compared with direct finite element method. Furthermore, integrating BA algorithm with the efficient approximation mechanism of finite element (FE) model, maintains the acceptable accuracy of damage severity detection. Also, one of the distinct aspects of the research, presented in this work, compared with other methodologies is that the damage location detection is performed by using only the damaged structural response without the need for prior knowledge about the undamaged structural response. We should point out that the proposed method is based on the assumption that the structural behavior remain linear after the occurrence of damage.

9437-87, Session PTues

Multi-physics modeling and simulation of a frequency doubling antenna sensor for passive wireless strain sensing

Chun Hee Cho, Yang Wang, Georgia Institute of Technology (United States)

This research proposes a multi-physics simulation framework of a frequency doubling antenna sensor for passive wireless strain measurement. The frequency doubling antenna sensor consists of three main components, i.e. a receiving patch antenna (resonance frequency at 5.8 GHz), a transmitting patch antenna (resonance frequency at 11.6 GHz), and a matching network with a Schottky diode. The diode is adopted to generate the doubled frequency $2f$ (at the 2nd harmonic wave) upon reader interrogation at frequency f around 5.8 GHz. Therefore, the matching network integrates the two antennas to function as a frequency doubling antenna sensor. To improve the accuracy of matching network design, Spice model parameters of the Schottky diode are updated through the experimental characterization. Through frequency doubling, the signal backscattered by the antenna sensor (at frequency $2f$) can be easily distinguished from environmental reflection to reader interrogation (at frequency f). If the receiving patch antenna of the sensor is bonded to a structural surface, experiencing strain, the deformation of the antenna changes resonance frequency of the antenna, and causes variation in the peak frequency of the backscattered signal around $2f$. Since frequency change is correlated with structural deformation, strain sensing can be achieved by the wireless interrogation. To accurately model the mechanical and electromagnetic behaviors of the frequency doubling antenna sensor, a multi-physics coupled simulation approach is proposed. For accurately simulating both the antenna behavior under strain/deformation and the matching network performance, two commercial software packages, COMSOL and ADS, are combined to leverage the strength of each package.

9437-88, Session PTues

Considerations for ultrasonic testing application for on-orbit NDE

Ajay M. Koshti, NASA Johnson Space Ctr. (United States)

The paper addresses some on-orbit NDE needs of NASA for International Space Station (ISS). The presentation gives NDE requirements for inspecting suspect damage due to micro-meteoroids and orbital debris (MMOD) impact on the pressure wall of the ISS. This inspection is meant to be conducted from inside of the ISS module. The metallic wall of the module has a fixed wall thickness but also has integral orthogrid ribs for reinforcement. Typically, a single MMOD hit causes localized damage in a small area causing loss of material similar to pitting corrosion but cracks may be present too. The impact may cause bulging of the wall. Results of the ultrasonic and eddy current demonstration scans on test samples are provided. The ultrasonic technique uses shear wave scans to interrogate the localized damage area from the surrounding undamaged area. The scanning protocol results in multiple scans, each with multiple "vee" paths. A superimposition and mosaic of the three dimensional ultrasonic data from individual scans is desired to create C-scan images of the damage. This is a new data reduction process which is not currently implemented in the state-of-art ultrasonic instruments. Results of ultrasonic scans on the simulated MMOD damage test plates are provided. The individual C-scans are superimposed manually creating mosaic of the inspection. The resulting image is compared with visibly detected damage boundaries, X-ray images, and localized ultrasonic and eddy current scans for locating crack tips to assess effectiveness of the ultrasonic scanning. The paper also discusses developments needed in improving ergonomics of the ultrasonic testing for on-orbit applications.

9437-89, Session PTues

Evaluation of sub-surface residual stresses in a dissimilar welded plate by using finite element and ultrasonic method

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This paper investigates ultrasonic-stress-measurement in a plate with dissimilar joint (TP-304 stainless steel to A106 carbon steel). The ultrasonic-stress-measurement is implemented by using longitudinal critically refracted (LCR) waves, which are able to propagate parallel the material surface in a predetermined penetration depth. By employing four different series of the ultrasonic probes (1 MHz, 2 MHz, 4 MHz and 5 MHz), penetrating in four different depths of the material would be practical leading to evaluation of sub-surface residual stresses in various depths. A finite element (FE) model of welding process is also used to verify the ultrasonic-stress-measurement results. By combination of the FE and the LCR method (known as the FELCR method), a comprehensive distribution of the welding residual stress is achieved. It has been shown that the sub-surface residual stresses could be accurately evaluated by the FELCR method in a dissimilar welded plate.

9437-90, Session PTues

The study of compressive sampling in ultrasonic computerized tomography

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This paper proposes a novel and effective method in the field of Non-Destructive Evaluation (NDE). Traditional ultrasonic computerized tomography (UCT) is an heavy task to detect the damages in the object for the numerous measuring times and the huge cost of manual labor. However,

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utilizing the method proposed in this paper can effectively overcome this great disadvantage, the essence of the application of Compressive Sampling (CS) in the detection of the object is to selectively choose a small quantity of measuring path in the huge number of total measurements. Due to the sparsity of damages in concrete structure, the usage of CS is available. Firstly, we divide the object entirely into numerous grids in order to image the internal situation of the object respectively. Secondly, a measurement matrix to massively decline the quantity of the measuring time should be computed. Thirdly, the travel time of each path we selected according to the matrix should be acquired, utilizing these travel time by adopting the l1-minimization program can we consequently obtained the slowness of the elements inside the object, thus reconstruct the internal situation of the object clearly and effectively. Furthermore, by applying this method we proposed in this paper into the simulation we can not only determine the damage location but also figure the size of it out. Because of the massive decline of the measuring times and accurate reconstruction, we substantiate CS method applied into the monitoring of concrete structure proves to be a shortcut in the field of NDE.

9437-91, Session PTues

Crack visualization of metallic structures in wide area using time-domain reflectometry with two-dimensional microstrip lines

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The present study investigated crack visualization in metallic structures using time-domain reflectometry (TDR) with a two-dimensional microstrip line (MSL). 2D inspection was enabled by covering the inspected structure surface with the microstrip conductor to compensate for the lack of information in the transverse direction. Crack visualization experiments were conducted using the proposed TDR with single ended and differential circuit of 2D MSL for different crack length. In both cases, the experimental results demonstrated that crack propagation could be clearly visualized. However, in the case of single ended, false cracks appeared at the same position regardless of the crack position. To observe the time change of the electric field, the electromagnetic field was numerically simulated using the finite-difference time-domain method. The electromagnetic field simulation results clarified that the false cracks observed in the experiments were caused by cross talk voltage because of the interference of adjacent MSL. On the other hand, in the case of differential circuit, the experimental results were found that it enables to suppress the cross talk voltage causing false cracks confirmed in single ended. Furthermore, the electromagnetic field simulation results clarified that the cross talk voltage decreased, because the electric field caused by interference of adjacent MSL was in phase. Thus, these results indicate that the proposed TDR with 2D MSL can be applied to crack visualization of metallic structures. Moreover, it argues that differential circuit is more effective in suppressing the cross talk voltage than single ended.

9437-92, Session PTues

Damage detection and quantification in a structural model under seismic excitation using time-frequency analysis

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In civil engineering, health monitoring and damage detection are typically carry out using some form of modal updating and system identification. These methods typically rely on the extraction of modal properties to infer

damage. The parameters use to infer damage are natural frequencies, mode shapes which represent global characteristics of a structure. However, global dynamics are not always sensitive to local damage, especially when the damage is very small. In this study a damage detection approach based on time-frequency analysis of structural response is presented. Two examples are used to demonstrate the proposed algorithms: one the 3-story steel frame with the abrupt change of stiffness in one of the bracing system. And the other is a two-story one-bay reinforced concrete frame under weak and strong seismic excitation. Vibration signals measured for the dynamic response of structure with different defect conditions are first decomposed into multiple sub-frequency bands by means of wavelet packet transform (WPT). Generally, this time-frequency multi-scale wavelet processing generates discrete energy density distribution. The distribution can be processed using singular-value decomposition (SVD). Exploit the capacity of SVD to demonstrate between damage-related events and the intrinsic non-stationary nature of the structural system. This paper address the non-linear feature extraction scheme from the time-domain feature with wavelet packet pre-processing and frequency-domain features of the vibration signals using principal component analysis. Experimental results show that the proposed approach can be used to not only quantify the damage extent but also determine the damage type.

9437-93, Session PTues

Structural health monitoring and assessment aided by building information modeling techniques

Dryver R. Huston, Dylan Burns, Mandar Dewoolkar, The Univ. of Vermont (United States)

Building Information Modeling (BIM) systems provide a methodology for assembling and processing information concerning architectural, mechanical and structural systems. This information is assembled and presented in a layered hierarchical format that provides information to the user in an application- appropriate level of development or level of detail (LOD). This paper discusses some of the techniques that can extend BIM methods into the realm of structural health monitoring (SHM) and assessment. The discussion centers on a plausible scheme for a BIM SHM LOD organization. A construction-detail LOD is a relatively simple set of detailed construction and structural registration details for the SHM system. A medium LOD uses the low level BIM database to form parts lists, construction details, sensor network maps and perhaps data logs. A higher LOD uses the data to support feed interactions of architects, engineers, analysts, detailers, designers, fabricators, contractors, financiers, etc. in structural health management decision making. Examples will be presented from structural assessments of bridge health and BIM integration. One uses an array of point sensors for a vibration assessment of span stiffness and condition. The second uses BIM to provide registration and data logging support for ground penetrating radar maps. The third uses stereo-imaging cameras to provide photogrammetric point clouds to build and as-built BIM model of a highway overpass pier strengthened by a fiber reinforced polymer retrofits.

9437-94, Session PTues

Vibrational energy harvesting structure health monitoring of critical interdependent infrastructure systems

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Bridges interconnecting street networks are bottle necks of the built infrastructure. Disruption due to poorly maintained infrastructure, specifically progressing fatigue damage from initiation to conditions which are ultimately unsafe for operation, is leading to closure or even collapse of bridges. Currently, in the US alone, 149,000 bridges have been deemed either functionally deficient or obsolete. Such a sorry state of

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affairs can be directly attributed to a lack of appropriate infrastructure maintenance and operational procedures, i.e. structure health monitoring: There is no continuous structure health monitoring in place. Instead bridge infrastructure is inspected in 2-year intervals, which is not enough to detect damage progression in time. Continuous health monitoring would ensure that maintenance measures are taken in time when the damage is still small, and when preventive maintenance is most cost-effective, and without requiring closure of the bridge.

This paper addresses the insufficient maintenance of bridges within a network of interdependent infrastructure systems and presents an around-the-clock monitoring system which powers itself through the mechanical vibrations of the bridge. Our prototype of a Vibration Energy Harvesting for Structural Health Instrumentation (VEHSHI) can detect when there is a change in the consistency of frequencies, displacements and strain, beyond what the human eye can see during the routine two-year inspections. VEHSHI sends out an alert when there is a cause for alarm. The main challenges in this research are efficient energy harvesting, structure health monitoring and large data transmission and evaluation in real time. The paper comprises experimental data of this patent-pending technology.

9437-95, Session PTues

Artificial intelligence and signal processing for infrastructure assessment

Khaled Assaleh, Tamer Shanableh, Sherif Yehia, American Univ. of Sharjah (United Arab Emirates)

The Ground Penetrating Radar (GPR) is being recognized as an effective nondestructive evaluation technique to improve the inspection process. However, data interpretation and complexity of the results impose some limitations on the practicality of using this technique. This is mainly due to the need of a trained experienced person to interpret images obtained by the GPR system. In this paper, an algorithm to classify and assess the condition of infrastructures utilizing image processing and pattern recognition techniques is discussed. Features extracted from a dataset of images of defected and healthy slabs are used to train a computer vision based system while another dataset is used to evaluate the proposed algorithm. Initial results show that the proposed algorithm is able to detect the existence of defects with about 77% success rate.

9437-97, Session PTues

Disbond detection using guided wave Pzt excitation in honeycomb composite sandwich structure

Chandrakant B. Pol, Indian Institute of Technology Bombay (India)

A promising new in-situ Health monitoring technique is developed for Honeycomb Composite Sandwich Structures HCSS. The semi-analytical method based upon Global Matrix approach is used to study the dispersion characteristics of the Honeycomb Composite Sandwich Structure (HCSS). The specimen HCSS plate is modeled and analyzed for various load cases using this technique and compared these results with a similar HCSS model developed using Finite Element based software LS-DYNA. The results are found in excellent agreement for the developed HCSS models.

9437-31, Session 7

Simulating the x-ray image contrast to set-up techniques with desired flaw detectability

Ajay M. Koshti, NASA Johnson Space Ctr. (United States)

The paper builds on the previous work by the author in developing a model for estimating detectability of crack-like flaws in radiography. The methodology is developed to help in implementation of NASA Special X-ray radiography qualification, but is generically applicable to radiography. While previous work provided the model, this paper focuses on the simulation runs using the model. Resolution of the detector used in these simulation runs uses the definition given in ASTM E 2737-10 standard practice for digital detector array performance evaluation and long-term stability. The paper describes a model for simulating the detector resolution. A computer calculator application, discussed here, also performs ASTM contrast and noise calculations. Results of various simulation runs in calculating crack flaw size parameter and image contrast for varying input parameters such as crack depth, crack width, part thickness, X-ray angle, part-to-detector distance, part-to-source distance, source sizes, and detector sensitivity and resolution are given as 3D surfaces. These results demonstrate effect of the input parameters on the flaw size parameter and the simulated image contrast of the crack. These simulations demonstrate utility of the simulation and the flaw size parameter in setting up X-ray techniques that provide desired flaw detectability in radiography. The method is applicable to film radiography, computed radiography, and digital radiography.

9437-32, Session 7

Infrared contrast data analysis method for quantitative measurement and monitoring in flash infrared thermography

Ajay M. Koshti, NASA Johnson Space Ctr. (United States)

The paper provides information on a new infrared (IR) image contrast data post-processing method that involves extracting normalized contrast versus time evolutions from the flash infrared thermography inspection video data. Thermal measurement features such as peak contrast, peak contrast time, persistence time, and persistence energy are calculated from the contrast evolutions. In addition, simulation of the contrast evolution is achieved through calibration on measured contrast evolutions from many flat bottom holes in a test plate of the subject material. The measurement features are used to monitor growth of anomalies and to characterize the void-like anomalies. The method was developed to monitor and analyze void-like anomalies in reinforced carbon-carbon (RCC) materials used on the wing leading edge of the NASA Space Shuttle Orbiters, but the method is equally applicable to other materials. The thermal measurement features relate to the anomaly characteristics such as depth and size. The contrast calibration is used to provide an assessment of the anomaly depth and width which correspond to the depth and diameter of the equivalent flat bottom hole from the calibration data. An edge detection technique called the half-max is used to measure width and length of the anomaly. Results of the half-max width and the equivalent flat bottom hole (EFBH) diameter are compared with actual widths to evaluate utility of the IR contrast method. Results of IR contrast method on RCC hardware are provided. An example is provided to demonstrate use of the normalized contrast as the signal response in probability of detection analysis.

9437-33, Session 8

Application of firefly algorithm to dynamic model updating problem

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Full-scale, in-situ dynamic experimental investigations of civil engineering structures have gained increasing popularity as they enable identification of the actual dynamic properties useful in performance and health monitoring as well as for maintenance. Information from such experiments can more effectively be used by correlating the experimental data with analytical models. A method often used for such correlation is model updating where optimal values of the parameters of an analytical model, such as stiffness,

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mass and/or boundary conditions, are searched for in order to match analytical responses with those identified experimentally. As the number of experimental measurements is usually much smaller than the number of uncertain parameters, and, consequently, not all uncertain parameters are selected for model updating, different local minima may exist in the solution space. Experimental noise further exacerbates the problem. The attainment of the global minimum in multi-dimensional search space is a challenging optimization problem.

The nature-inspired algorithms have gained increasing attention in the previous decade for solving complex optimization problems. This study applies the novel Firefly Algorithm (FA), a global optimization search technique, to a dynamic model updating problem. This is to the authors' best knowledge the first time FA is applied to model updating. The FA is inspired by the flashing characteristics of fireflies. Each firefly represents a randomly generated solution which is assigned brightness according to the performance of the objective function. The physical structure under consideration is a full scale cable stayed pedestrian bridge with composite bridge deck. Data from dynamic testing of the bridge was used to correlate and update the initial model by using FA. The algorithm aimed at minimizing the difference between the natural frequencies and mode shapes of the structure. The performance of the algorithm is analysed in finding the optimal solution in a multi dimensional search space. The paper concludes with an investigation of the efficacy of the algorithm in obtaining a reference finite element model which correctly represents the as-built original structure.

9437-34, Session 8

Verification of Recursive Probabilistic Integration (RPI) Method for
Fatigue Life Management using Non-destructive Inspections

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The Army is transforming its way in conducting maintenance in numerous ways. Most pronounced in this transformation is the move toward a condition-based maintenance (CBM) strategy. This approach makes it more effective in Army's ability to rapidly repair platforms by seamlessly collecting critical platform information that can be used for risk and remaining useful life assessment. Since fatigue is the major contribution to the structure degradation, the probabilistic analysis method considering the effects of the random fatigue damage growth, maintenance planning and other uncertainties needs to be developed for risk assessment analysis of the systems.

Recursive probabilistic integration (RPI) algorithm was developed for damage tolerance analysis of fatigue life. RPI is an efficient simulation method which repeatedly uses of the baseline crack growth histories for various maintenance plans under various uncertainties, such as variation of material properties, initial flaw size, repair quality, random processes of the flight loading, and inspection reliability represented by probability of detection (POD).

In order to fully appreciate the RPI method, a rigorous verification procedure must be conducted.

Due to its robustness and generality, Monte Carlo (MC) simulations is the most accepted method, if not the only method, to verify the efficient probabilistic methodologies. In this study, MC simulations in the orders of several trillion simulations were conducted for various flight conditions, material properties, inspection scheduling, POD and repair/replacement strategies.

Since the MC simulations are time-consuming methods, the simulations were conducted parallel on DoD High Performance Computers (HPC) using a specialized random number generator for parallel computing.

Three cases were selected for verification purpose. MCS were also conducted as "gold standards" to verify the cumulative probability of failure, the single flight probability of failure by the RPI methods. General speaking, the RPI method is several orders faster than Monte Carlo simulations.

9437-35, Session 8

Damage localization for multi-story buildings focusing on shift in the center of rigidity using an adaptive extended Kalman filter

Tsubasa Takeuchi, Akira Mita, Keio Univ. (Japan)

Recently Structural Health Monitoring (SHM) has been once again under the spotlight due to the extensive damage on building structures caused by the Tohoku earthquake in 2011. To detect damage, shear structure model is often used for modeling building structures. However, it is hard to detect damage of members (e.g., columns and beams) with that model. Despite that frame structure model should be used to localize damage, it is complicated and it needs lots of sensors. In this study, we propose a damage localization method for columns of multi-story buildings using Multi-Input Multi-Output (MIMO) shear structure model. This model has three degree-of-freedom (i.e., two translational and one rotational direction) in each floor, and each column is modeled separately. To conduct system identification, only accelerations of the center of gravity in each floor are used. Also, an extended Kalman filter, which can estimate a state and uncertainties of a dynamical system at the same time, is used for identification. Although in most of previous researches, different algorithms are used for detecting damage of stories or of members, this extended Kalman filter enables detecting damage of members directly. Firstly in this research, we conducted a numerical simulation using multi-story models, and then we verified proposed damage localization method with a shaking table test. This study shows our proposed method is capable of localizing damage of columns of multi-story buildings. Estimating corresponding damage severity is a nearest task of this research.

9437-36, Session 8

Finite element analysis for the damage detection of light pole structures

Qixiang Tang, Univ. of Massachusetts Lowell (United States); Mark Jen, Parsons Corp. (United States); Tzu Yang Yu, Univ. of Massachusetts Lowell (United States)

Failures of aging light poles can jeopardize the safety of residents and damage adjacent structures. The need for reliable and efficient damage detection methods is raised recently. Any change in structural properties (e.g., mass, stiffness) can lead to differences in the dynamic response of structures (i.e., modal frequencies and mode shapes). Inversely, changes in dynamical responses can be used as indicators for damage detection. In this study, the relationships among damages and dynamic responses were determined by investigating the differences in dynamic responses of intact and damaged light pole models using the finite element method (FEM). The FE models are built with 5529 C3D8R elements in ABAQUS®, All dynamic responses were obtained with Lanczo's Eigenvalue Extraction Method. New parameters – 'sensitive' and 'insensitive' modes were defined and used to evaluate the sensitivity of the first ten modes due to the presence of artificial damages. It is found that the combination of sensitive and insensitive modes is unique for each damage location and can be used to locate artificial damages in light pole models. Two empirical equations were proposed to qualify damage level and size. A damage detection methodology was developed by using these relationships.

9437-37, Session 9

A Comparison of Different Statistical Approaches to Strain-Based Structural Health Monitoring under Uncertainty

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**Conference 9437: Structural Health Monitoring and Inspection of
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The Univ. of British Columbia (Canada)

A major concern in developing any robust Structural Health Monitoring (SHM) system is the impact of uncertainty of input parameters (including manufacturing/testing errors and loading variation) in accuracy and reliability of the final product. In this study, advanced statistical pattern recognition techniques capable of considering variations in input parameters is being investigated.

The neural networks are the basis of the majority of SHM systems reported in the literature, and for this reason were the first algorithm considered for health monitoring of the composite airfoil samples. The reliability and robustness of the developed network was assessed in the presence of noisy input caused by inaccurate production process (thickness variation of composite plies). The poor predictability of the network can only be corrected by adding huge database of all the noisy scenarios which is practically unacceptable both time- and budget-wise. Then, the concept of Signal-to-Noise (SN) ratio analysis was implemented to weight the first layer of the network in case of uncertain inputs. This idea worked remarkably well, but still a major concern persists and that is the precise estimation of the weighting factors.

At the end, the Gaussian Processes (GP) was used to train the SHM system in the presence of uncertainty effects. The GP proved to be quite capable of analyzing the input data and distinguishing the noise-free patterns. The precision reached by GP was quite confident and the architecture optimization time was insignificant compared to the conventional neural network algorithms.

9437-38, Session 9

Using a general purpose finite element approach to attain higher fidelity rotordynamic analyses

Andrew L. Gyekenyesi, Ohio Aerospace Institute (United States) and NASA Glenn Research Ctr. (United States); Adam C. Wroblewski, Cleveland State Univ. (United States)

By utilizing a general purpose finite element (FE) code, the dynamic response of a rotor system is numerically studied in order to assess physical effects which are typically not taken into account using traditional rotordynamic codes. This includes the allowance for disk flexibility as well as varying temperatures in the axial and radial directions. Additionally, a dynamic bearing stiffness is also considered as a function of rotor speed and temperature. Here, the numerical analyses utilize a generic, compressor with a shrouded impeller model, without extensive geometric simplification. The Campbell diagrams and the mode shapes show that neglecting any of these additional influences may cause significant errors regarding the rotor's dynamic response. By increasing the fidelity of the rotor model and accounting for the various effects, the slight signal modifications due to damage can be more easily recognized allowing for increased accuracy during rotor health monitoring.

9437-39, Session 9

Nonlinear dynamics and health monitoring of 6-DOF breathing cracked Jeffcott rotor

Jie Zhao, Schlumberger Ltd. (United States); Hans DeSmidt, The Univ. of Tennessee Knoxville (United States); Wei Yao, The University of Tennessee (United States)

In this paper, Jeffcott rotor is employed to explore the vibration response of breathing cracked system with unbalance mass. Based on the energy method and Lagrange principle, 6 degree-of-freedom equation of motion of the rotor system is derived in the fixed coordinate system. The crack model is established using strain energy release theory of fracture mechanics. The stiffness matrix induced by the crack is changing with the variation of crack open area during the rotation of rotor. The changing crack open area is

calculated at every time step using crack closure line determined by Zero stress intensity factor (SIF) method. By integrating compliant coefficients over newly determined crack open area, the stiffness matrix is updated and vibration response is iterated by Gear's method. In addition, the breathing behavior of the crack is investigated in terms of eccentricity phase and rotation speed in order to provide effective and comprehensive guidance for health monitoring of the rotor under different working conditions. Finally, the coupled lateral, longitudinal and torsional vibration induced by the damage is studied under external torsional and axial loading. It is shown that the coupling of lateral, torsional and longitudinal vibration can be used as an indicator of damage diagnosis and health monitoring.

9437-40, Session 9

Finite element modeling, numerical calculation, and experimental researches for evaluating the seismic stability of the power units of Ukrainian nuclear power plants

Volodymyr V. Skliarov, National Scientific Ctr. "Institute of Metrology" (Ukraine)

The investigation approach of strength properties of the equipment by means of the finite elements method using software package when assessing the resistance of industrial project to seismic impacts is considered. The paper gives the results of using the experiment-calculated method when evaluating the seismic stability of equipment in order to determine the possibility of prolonging the project operational lifecycle of the power units of nuclear power plants.

9437-41, Session 9

Nonlinear structural finite element model updating and uncertainty quantification

Hamed Ebrahimian, Rodrigo Astroza, Joel P. Conte, Univ. of California, San Diego (United States)

This paper presents a framework for nonlinear finite element (FE) model updating, in which state-of-the-art nonlinear structural FE modeling and analysis techniques are combined with the maximum likelihood estimation method (MLE) to estimate time-invariant parameters governing the nonlinear hysteretic material constitutive models used in the FE model of the structure. Using the MLE as a parameter estimation tool results in a nonlinear optimization problem, which can be efficiently solved using gradient-based optimization algorithms such as the interior-point method. Gradient-based optimization algorithms require the FE response sensitivities to the material parameters to be identified, which are computed accurately and efficiently using the direct differentiation method (DDM). The estimation uncertainties are evaluated based on the Cramer-Rao lower bound (CRLB) theorem. A proof-of-concept example, consisting of a cantilever steel column representing a bridge pier, is provided to verify the proposed nonlinear FE model updating framework. The simulated responses of this bridge pier to a set of earthquake ground motions are polluted with artificial output measurement noise and used to estimate the unknown material parameters. The example illustrates the excellent performance of the proposed parameter estimation framework even in the presence of high measurement noise.

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9437-42, Session 10

**A Novel Approach for Detection of
Anomalies using Measurement Data of the
Ironton-Russell Bridge**

 Fan Zhang, Mehdi Norouzi, Victor J. Hunt, Arthur Helmicki,
Univ. of Cincinnati (United States)

Damage detection and damage localization using long term structural health monitoring data have been received significant attention in recent years and researchers have used different numerical methods to detect and classify damages, however, few of these methods have been implemented successfully on field structures because of limited access to damaged state of complex structures or difficulty of classification of changes that are caused by environmental variations from changes that are caused by damages.

This paper explores the suitability of an approach to damage detection using field measurement strain data from a major in-construction cable stayed bridge across Ohio and Kentucky. The approach combines the methods of auto regressive integrated moving average model (ARIMA) and artificial neural network (ANN). First, the time series data is modelled by an ARIMA model, and then some of the model's parameters are added to the datasets which will be used by the ANN to compensate for non-linear responses.

The results show that this approach is qualified to serve as a diagnostic tool for the health of the bridge studied and its application is extendable to other structures.

9437-43, Session 10

**Evaluation of bridges by recovered
curvature data from responses due to
moving truck loading**

 Chih-Peng Yu, Chia-Chi Cheng, Chih-Hung Chiang, Ying-
Tzu Ke, Keng-Tsang Hsu, Chaoyang Univ. of Technology
(Taiwan)

In the authors' previous work, a rapid testing scheme for bridge assessment without the need of prior tests nor numerical simulations was proposed. The proposed methodology utilizes the dynamic influence line of the bridge to compute curvature data in which genuine displacement responses were obtained by the interferometer. To facilitate the methodology to a variety of span types, the curvature data of the tested span are obtained with a symmetrical pair of point loads which would allow the follow-up analysis task to be performed without the need of presumable moment diagrams. The previous work indicated that the proposed testing scheme gives promising results for continuous spans under the assumption of constant truck speed. Current work aims at extending the application of such testing scheme to access bridges while truck speed varies with time.

Since the ideal assumption of truck's moving in constant speed is rarely satisfied in the field tests. The original methodology may not be as effective as expected during a field test. While the real histogram of moving speed of the truck can be recorded and analyzed, it is still possible to carry out corrections accordingly. This paper continues to explore the feasibility of using the quasi-static displacement influence line obtained from a heavy truck moving with non-constant speed. The preliminary study indicated that the proposed testing scheme gives acceptable results for continuous spans provided that certain key modifications can be carried out in the analysis scheme.

9437-44, Session 10

**Health assessment of a multi-storey shear
structure using modal curvature method
and genetic algorithm**

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Central Building Research Institute (India)

A minor damage at any floor of a multi storey structure reduces the strength of the structure and leads to a major failure. Generally, multi storey structures are modeled as shear structure. This paper presents a procedure to identify the damaged floor of multi storey shear structures using modal curvature method with genetic algorithm as an optimisation algorithm. Here, first modal curvature based method is used to locate the damaged floor. Next, the concept of the residual force vector along with Genetic Algorithm has been implemented to get both the location and extent of damage. Prior knowledge of location of damage using modal curvature method makes the residual force vector method along with GA more powerful for exact identification and quantification of damage in noisy environment. Frequencies at different number of modes with corresponding mode shape are used as input to the model. Experimental data are simulated numerically by solving eigen value problem of the damaged structure with inclusion of random noise on the vibration characteristics. Reliability of the procedure has been shown by various examples of multi storey structure with different damaged situations. The model is also validated with experimental results obtained from experiment conducted at laboratory level on a five story shear structure to show the efficacy of the methodology.

9437-45, Session 10

**Damage assessment of the Truss system
with uncertainty using frequency response
function based damage identification
method**

 Jie Zhao, Schlumberger Ltd. (United States); Hans
DeSmidt, The Univ. of Tennessee Knoxville (United States);
Wei Yao, The University of Tennessee (United States)

The mass/stiffness uncertainties in truss system are detected by Frequency Response Function (FRF) based damage identification method. This method utilizes damage-induced changes of frequency response functions to estimate the severity and location of structural damage. This approach enables the possibility of arbitrary interrogation frequency and multiple inputs/outputs which greatly enrich the dataset for damage identification. The dynamical model of truss system is built using the finite element method and the crack model is based on fracture mechanics. The damage identification algorithm is developed in the frequency domain on the basis of Least Square method and Newton-Raphson method. The FRF changes from multiple sensors are used as the input of the algorithm and then the mass/stiffness uncertainties for the truss members can be estimated. The initial guess of the damage parameters is given by Least Square method and then iterated by Newton-Raphson method. The effectiveness of this method is demonstrated via a 19-bar truss system with mass and stiffness uncertainties. It is shown that the location and severity of the uncertainty can be effectively detected by using this method. In addition, it is noted that the mass and stiffness perturbation matrix should be both included in the damage identification algorithm in order to obtain accurate detection results.

9437-46, Session 10

**Mass and stiffness estimation using mobile
devices for structural health monitoring**

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(United States)

In the structural health monitoring (SHM) of civil infrastructure, dynamic methods using mass, damping, and stiffness for characterizing structural health have been a traditional and widely used approach. Changes in these system parameters over time indicate the progress of structural degradation or deterioration. In these methods, capability of predicting system parameters is essential to their success. In this paper, research work on the development of a dynamic SHM method based on perturbation analysis is reported. The concept is to use externally applied mass to perturb an unknown system and measure the natural frequency of the system. Derived theoretical expressions for mass and stiffness prediction are experimentally verified by a building model. Dynamic responses of the building model perturbed by various masses in free vibration were experimentally measured by a mobile device (cell phone) to extract the natural frequency of the building model. Single-degree-of-freedom (SDOF) modeling approach was adopted for the sake of using a cell-phone. From the experimental result, it is shown that the percentage error of predicted mass reduces when actual mass increases. This work also demonstrated the potential use of mobile devices in the health monitoring of civil infrastructure.

9437-48, Session 10

Time frequency analyses of vibrations of wind turbine towers

Chih-Hung Chiang, Keng-Tsang Hsu, Chi-Lung Huang, Chia-Chi Cheng, Chih-Peng Yu, Chaoyang Univ. of Technology (Taiwan); Lai Jiunnren, Chaoyang Univ of Technology (Taiwan)

Transient vibrations of the tower supporting a horizontal-axis wind turbine were recorded using a microwave interferometer. Variations in dominant frequencies have been reported in the previous study. Signal analyses aiming to uncouple different frequency components were performed using a new time-frequency representation. This procedure was developed based on the reassigned short time Frequency transform. Optimal resolutions in both time and frequency domains were first investigated using synthetic signals. The goal was to seek out the favorable combinations of window size and overlapping portions of adjacent windows for a data sequence at a given sampling rate. Applications to transient vibration data for wind turbine towers will be presented.

9437-49, Session 10

Estimation of dynamic characteristics of artificial and natural approaches

Minsun Kim, Byungkwan Oh, Tongjun Cho, Yousok Kim, Hyo Seon Park, Yonsei Univ. (Korea, Republic of)

This study focuses on estimating dynamic characteristics of beam-column structure using two different approaches.

First approach is a natural approach based on output-only ambient vibration (AV) test using frequency domain decomposition for operational modal analysis. This approach proceeds on the installment of high-performance servo accelerometers which measure ambient vibrations. Natural wind and a shaker are used for the wind-induced and nearby traffics/pedestrian AV excitation sources, respectively. Operational modal analysis has a difficulty on laboratory test because of the AV conditioning that has to be stochastic white noise. Therefore, the AV experiments were conducted at different conditions that changes the magnitudes and propagation distances of the AV sources and boundary conditions of the structure.

As second approach, a forced-vibration test is employed for an artificial approach. Impact hammer test is conducted in order to extract modal parameters. The conventional input-output modal analysis is conducted to analyze modal parameters of the structure. In accordance with these approaches, the comparison between the two approaches is discussed.

9437-50, Session 11B

Separation of Lamb waves modes using polarization filter for the 3D wave motion signals

Lukasz Ambrozinski, Tadeusz Stepinski, Tadeusz Uhl, AGH Univ. of Science and Technology (Poland)

Interpretation of Lamb waves signals can raise serious difficulties due to their multi-modal nature. The presence of multiple wave-modes propagating with different velocities hinders detection of the damage reflected components. As a solution to this problem we propose technique capable of mode separation by means of a polarization filter.

Both S0 and A0 Lamb modes exhibit elliptical polarization, however, their polarization parameters, i.e., the ratios of in-plane and out-of-plane displacements as well as phase-shifts between these components are different. Furthermore, these parameters can be considered constant in a narrow frequency band. Therefore, if both vertical and horizontal components of the wave motion are available, it is possible to apply signal processing technique referred to as oblique polarization filter. This operation is based on a phase-shifts and amplifications of the in and out-of-plane components, which results in orthogonal, linearly polarized A0 and S0 wave signals.

In this paper the proposed filtering technique will be illustrated using both numerical simulations and experimental data. First, results of the wave propagation simulations performed using the local interaction simulation approach (LISA) assuming isotropic material will be presented. Then the experiments performed using 3D laser scanning Doppler vibrometer, which allows to capture the in-plane and out-of-plane wave components, will be demonstrated.

9437-51, Session 11B

Corrosion damage estimation in multi-wire steel strands using guided ultrasonic waves

Alireza Farhidzadeh, Univ. at Buffalo (United States); Arvin Ebrahimkhanlou, Univ at Buffalo (United States); Salvatore Salamone, Univ. at Buffalo (United States)

This study presents a nondestructive evaluation method based on guided ultrasonic waves (GUW) to estimate corrosion in steel strands. Steel strands are one of the main components in constructing prestressed structures. Hidden corrosion in these structures has become a concern for designers, owners and regulators as it can eventuate in disastrous failure. In this study, a reference-free algorithm is proposed to quantify the extent of corrosion through estimating the cross section loss using dispersion curves and the velocity of certain frequency components in the waveform. Experimental test setups were designed to accelerate corrosion on two similarly loaded steel strands. One strand was embedded in concrete (to simulate a prestressed concrete beam) and the other was free (to resemble a prestressed cable). Visual inspection, half-cell potential, and mass loss measurements were employed as supporting evidences for the state of corrosion. An uncertainty analysis was also carried out to investigate how close this method can estimate the diameter of wires in a strand. The method could reasonably estimate the diameter of the wires without a reference baseline.

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9437-52, Session 12A

**In situ monitoring of multi-stage rail
surface defects in three dimensions using
mobile ultrasonic technique**

 Sakdirat Kaewunruen, Transport for NSW (Australia);
Makoto Ishida, Nippon Koei Co. Ltd., (Japan)

Rail squats and studs are typically classified as the growth of any cracks that have grown longitudinally through the subsurface and some of the cracks propagating to the bottom of rails transversely have branched from initial longitudinal cracks with a depression of rail surface. The rail defects are commonly referred to as 'squats' when they were initiated from damage layer caused by rolling contact fatigue, and as 'studs' when they were associated with white etching layer caused by the transform from pearlitic steel due to friction heat generated by wheel sliding or excessive traction. Such above-mentioned rail defects have been often observed in railway tracks catered for either light passenger or heavy freight traffics and for low, medium or high speed trains all over the world for over 60 years except some places such as sharp curves where large wear takes place under severe friction between wheel flange and rail gauge face. It becomes a much-more significant issue when the crack grows and sometimes flakes off the rail (by itself or by insufficient rail grinding), resulting in a rail surface irregularity. Such rail surface defect induces wheel/rail impact and large amplitude vibration of track structure and poor ride quality. In Australia, Europe and Japan, rail squats/studs have occasionally turned into broken rails. The root cause and preventive solution to this defect are still under investigation from the fracture mechanical and material scientific point of view. Some patterns of squat/stud development related to both of curve and tangent track geometries have been observed, and squat growth has also been monitored for individual squats using ultrasonic plotting techniques. This paper highlights the field monitoring of squat/stud distribution and its growth. Squat/stud growth has been determined and plotted using the ultrasonic measurement device on a grid applied to the rail surface. The crack depths at each grid node form a three dimensional contour of rail squat crack. Basically crack propagation is getting not simple and non-linear relation with repeated train loads in the case the crack is getting larger. But in this study the crack propagation of squats/studs is roughly estimated to be almost linear to repeated train loads called as accumulated passing tonnages up to a certain degree of propagated crack length.

9437-53, Session 12A

**Identification and prioritization of rail
squat defects in the field using rail
magnetisation technology**

Sakdirat Kaewunruen, Transport for NSW (Australia)

Rail squats and studs are continuing to be a serious problem for railway organisations around the world in the 21st century. They are typically classified as the growth of any cracks that have grown longitudinally through the subsurface and some of the cracks propagating to the bottom of rails transversely, and have branched from initial longitudinal cracks with a depression of rail surface. The horizontal crack, which results in a depression of rail surface, induces increased maintenance level, more frequent monitoring, compromised rail testing (as the crack shields the signal echoes), and possible broken rails. This paper presents field investigations using a magnetised-rail testing device developed by MRX Technologies to identify the rail squats. Most of the in situ squats were found on the high rail of the transition (variable-radius curved track), which is associated with rolling contact fatigue (RCF). This investigation highlights the field performance of the MRX's surface crack detection technology in comparison with the traditional ultrasonic method and detailed walking inspection. It was found in the field that the size of the RCF-squats varies from very small to moderate. The predicted crack data were obtained by scanning the magnetised rails. The comparison of the actual crack depths (ultrasonic) and the predicted crack depths (MRX device) shows:

- A possible correlation for small RCF/ squat cracks.
- Poor interpretation of larger defects and welds.

The field assessment also suggests some aspects required for further development, including the detection of rail spalling, deep transverse crack, welding, and so on.

9437-54, Session 12A

**Development of a low-cost cableless
geophone and its application in a
micro-seismic survey at an abandoned
underground coal mine**

Kaoshan Dai, Xiaofeng Li, Tongji Univ. (China); Chuan Lu, Qingyu You, Institute of Geology and Geophysics (China); Zhenhua Huang, H. Felix Wu, Univ. of North Texas (United States)

There are many abandoned underground mines existing at different locations across China. Due to the urbanization in China, more and more building construction sites are planned on the areas above these abandoned underground mines. Therefore, the stability of these sites is becoming a concern and reliable site investigations are becoming more important. Various geotechnical and geophysical techniques are available for such site investigations, among which includes the array-based surface wave method. With its nonintrusive, cost-efficient, and environmentally friendly features, the array-based surface wave method has the potential for conducting large-scale field surveys at the areas above underground mines. However, the dense deployment of conventional geophones requires heavy digital cables, which inconveniences survey work. In addition, the bulky and expensive standard stand-alone seismometers limit the number of stations for the array measurements. Therefore, this study developed a low-cost cableless geophone for the array-based surface wave survey. The hardware design of the cableless geophone is described in this paper. To validate the functionality of this cableless geophone, field array-based surface wave survey testing was conducted at an abandoned underground mine site in China. Both one-dimensional and two-dimensional arrays were designed and deployed. A detailed testing procedure, including instrument deployment, data acquisition, and data processing is reported in the paper. With the collected micro-seismic data, the survey testing successfully identified the structure of the underground mine. This field survey case study demonstrated the effectiveness of the low-cost cableless geophones. The information obtained from the array-based surface wave survey can be used by geotechnical engineers to plan the drilling locations for geotechnical site investigations.

9437-55, Session 12A

**Health State Evaluation of Shield Tunnel
SHM Using Fuzzy Cluster Method**

Fa Zhou, Wei Zhang, Nanjing Univ. (China)

Fine analysis on the mass measurements of the shield tunnel health monitoring remains a real challenge, since the measurements originate from a number of sensors belonging to multiple types. This paper addressed a fuzzy cluster analysis model for this issue. This model used transitive closure algorithm for clustering, based on fuzzy equivalence relation. Three types of indicators, namely soil pressure, pore water pressure and steel strain, were chosen to develop the model clusters. A case study on Nanjing Yangtze River Tunnel was also presented to apply this model. Engineering geological conditions were used to validate the clustering results. The dynamic clustering pattern of the model was proven to be capable of efficiency in identifying the tunnel health condition, compared with other single-factor methods. The investigation indicated the proposed fuzzy cluster analysis model was well capable of distinguishing the differences of the evaluation factors and identifying the tunnel health condition.

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9437-56, Session 12B

**Non-destructive evaluation of coating
thickness using guided waves**

 Pierre-Claude Ostiguy, Nicolas Quaegebeur, Patrice
Masson, Univ. de Sherbrooke (Canada)

Among existing strategies for non-destructive evaluation of coating thickness, ultrasonic methods using high frequency pulses to measure the Time-of-Flight (ToF) of bulk waves propagating through the thickness of a structure are widespread. However, these methods only provide a very localized measurement of the coating thickness and the precision on the results is widely affected by the surface roughness, porosity or multi-layered nature of the host structure. Moreover, since the measurement is very local, inspection of large surfaces can be time consuming. This article presents a robust methodology for coating thickness estimation based on the generation and measurement of guided waves. Guided waves have the advantage over ultrasonic bulk waves of being less sensitive to surface roughness, and of measuring an average thickness over a wider area, thus reducing the time required to inspect large surfaces. The approach is based on an analytical multi-layer model and inter-correlation of reference and measured signals. The method is first assessed numerically for an aluminum plate, where it is demonstrated that coating thickness can be measured within a precision of 5 micrometers using the S0 mode at frequencies below 500 kHz. Then, an experimental validation is conducted and experimental results show that coating thickness can be estimated from 10 to 200 micrometers with a precision of 10 micrometers of the exact coating thickness on this type of structure.

9437-57, Session 12B

**The study of damage identification based
on compressive sampling**

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This paper proposes a novel and effective method to identify the damage in the 2-D beam via Lamb wave. Two problems in the structural damage identification: damage location and damage severity are solved based on the theory of compressive sampling (CS) which indicates that sparse or compressible signals can be reconstructed using just a few measurements. Because of the sparsity nature of the damage, a database of damage features is established via a sparse representation for damage identification and assessing. Specifically, this proposed method consists of two steps: damage database establishing and feature matching. In the first step, the features database of both the healthy structure and the damaged structure are represented by the Lamb wave which propagates in the 2-D beam. Then in the matching step, expressing the test modal feature as a linear combination of the bases of the over-complete reference feature database which is constructed by concatenating all modal features of all candidate damage locations builds a highly underdetermined linear system of equations with an underlying sparse representation, which can be correctly recovered by ℓ_1 -minimization based on CS theory; the non-zero entry in the recovered sparse representation directly identifies the damage location and severity. In addition, numerical simulation is conducted to verify the method. This method of identifying damage location and assessing damage severity, using limited Lamb wave features, obtains good result.

9437-58, Session 12B

**Numerical and experimental
demonstration of shear stress
measurement at thick steel plates using
acoustoelasticity**

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(United States)

The purpose of this article is to numerically quantify the stress state of complex loaded thick steel plates using the fundamental theory of acoustoelasticity, which is the relationship with stress and ultrasonic velocity in the nonlinear regime. The normal and shear stresses of a thick plate can be measured using a phased array placement of ultrasonic sensors and Rayleigh ultrasonic waves. Three measurement angles (i.e., 0, 45 and 90 degrees) are selected since three measurements are needed to solve the stress tensor in an isotropic plate. The ultrasonic data is influenced significantly by the frequency of the Rayleigh waves as well as the thickness of the plate being examined; consequently the overall experimental process is influenced by the measurement parameters. In this study, a numerical demonstration is implemented to extract the nonlinearity coefficients using a 3D structural geometry and Murnaghan material model capable of examining the effects of various plate thicknesses and ultrasonic frequencies on the shear stress measurement. The purpose is that as the thickness becomes smaller, the shear stress becomes negligible at the angled measurement. For thicker cross section, shear stress becomes influential if the depth of penetration of Rayleigh wave is greater than the half of the thickness. The correlation between the depth of penetration and shear stress is then obtained. The numerical results are compared with 1 MHz ultrasonic frequency and a 3/8 inch thick steel plate loaded uniaxially while the measurement direction is angled to have the presence of shear stress in the measurement direction.

9437-59, Session 12B

**Sparse representation of guided-waves
for damage diagnosis in pipelines with
temperature variation**

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Variation in environmental and operational conditions (EOCs) degrades the performance of guided-wave based damage diagnosis, by masking and/or appearing as the changes caused by damage. Effects of EOCs on guided-waves have been widely studied. However, reviewing the work to-date in guided-wave based testing, it becomes apparent that there is a disconnect between the studies investigating the effects of EOCs and damage diagnosis methods. The missing physical and analytical intuition about the way EOCs affect different aspects of these approaches limits their extensibility to different operating conditions. To address such gaps, two questions need to be answered: (1) what are the effects of EOCs on damage diagnosis methods? (2) how can these effects be incorporated into damage diagnosis process? In this study, we investigate these questions regarding the effects of temperature variation on damage diagnosis of pipes. First, effects of temperature on guided-waves in industrial-scale pipes are simulated. Dispersion curves at different temperatures, and sensitivities of wave modes to temperature variations at various frequencies are calculated. The simulation results emphasize the fact that different wave modes have different sensitivities to temperature variations. This raises challenges such as shape distortion and nonlinear relations between signals at different temperatures. Later in this paper, we describe a laboratory setup designed to control the temperature variation in pipes from 24 ° up to 44 ° with 0.5° increments. Finally, to examine the second question above, we investigate the effectiveness of current methods used for incorporating temperature effects into baseline-subtraction damage diagnosis approaches, namely baseline stretching methods. The reasons for failure of stretching methods in compensating the effects of large temperature variations (above -10 °) are discussed. Moreover, the ineffectiveness of these methods for compensating smaller temperature variations in diffuse-field guided-waves is investigated. This paper elaborates on the nature of temperature effects on diffuse-field guided-waves in pipes, and provide insight for alternative approaches that incorporate temperature effects into damage diagnosis of pipes.

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9437-60, Session 13A

**Extracting full-field dynamic strain
response of a rotating wind turbine using
photogrammetry**

Javad Baqersad, Peyman Poozesh, Christopher Niezrecki, Peter Avitabile, Univ. of Massachusetts Lowell (United States)

Health monitoring of wind turbines is typically performed using conventional sensors (e.g. strain-gages and accelerometers) that are usually mounted to the nacelle or gearbox. Although many wind turbines stop operating due to blade failures, there are few to no sensors mounted on the blades. Placing sensors on the rotating parts of the structure is a challenge due to the wiring and data transmission constraints. Within the current work, an approach to monitor full-field dynamic response of rotating structures (e.g. wind turbine blades or helicopter rotors) is developed and experimentally verified. A wind turbine rotor was used as the test structure and was mounted to a block and horizontally placed on the ground. A pair of bearings connected to the rotor shaft allowed the turbine to freely spin along the shaft. Several optical targets were mounted to the blades and a pair of high-speed cameras was used to monitor the dynamics of the spinning turbine. Displacements of the targets during rotation were measured using three-dimensional point tracking. The point tracking technique measured both rigid body displacement and flexible deformation of the blades at target locations. In order to minimize the effects of rigid body spinning of the turbine, only flap displacements of optical targets (displacements out of the rotation plane) were used in strain prediction process. The measured displacements were expanded and applied to the finite element model of the turbine to extract full-field dynamic strain on the structure. The proposed approach enabled the prediction of dynamic response on the outer surface as well as within the inner points of the structure where no other sensor could be easily mounted. In order to validate the proposed approach, the predicted strain was compared to strain measured at four locations on the spinning blades using a wireless strain-gage system.

9437-61, Session 13A

**An acoustic-array based structural health
monitoring technique for wind turbine
blades**

Peyman Poozesh, Christopher Niezrecki, Kai Aizawa, Univ. of Massachusetts Lowell (United States); javad baqersad, umass lowell (United States)

Wind turbines operate autonomously and can possess reliability issues attributed to manufacturing defects, fatigue failure, or extreme weather events. In particular, wind turbine blades can suffer from leading and trailing edge splits, holes, or cracks that can lead to blade failure and loss of energy revenue generation. Poor reliability and damage leads to excessive repair costs that raise the cost of wind generated energy. In order to help identify damage, several approaches have been used to detect cracks in wind turbine blades, however most of these methods require transducers to be mounted on the turbine blades, are not effective, or require visual inspection.

This paper proposes a non-contact measurement technique for health monitoring of wind turbine blades using acoustic beamforming techniques. The technique works by mounting an audio speaker inside a wind turbine blade and observing the sound radiated from the blade to identify cracks or damages within the structure (see Figure 1). The structural damage or cracks on the surface of a composite wind turbine blade can result in changes in the sound radiation characteristics of the structure. Two preliminary measurements were carried out on a composite box and a section of a wind turbine blade to validate the methodology. The composite box and the blade contained holes of differing dimensions and line cracks. An array with 62 microphones is used to measure the sound radiation from

the structures when the speaker is working inside the box and blade. A phased array beamforming technique and CLEAN-based Subtraction of Point spread function from a Reference (CLSPR) are employed to locate the damages on both composite box and the wind turbine blade. Another experiment using a commercially available 48 channel acoustic ring array was also used to compare the results (see Figure 2). It was shown that acoustic beamforming and CLSPR can be used to identify the location of the damages in the sample structures with high fidelity.

9437-62, Session 13A

**Deflection monitoring of pipelines using
Fiber Bragg grating sensors**

Jin-Hyuk Lee, Heon-Young Kim, Seoul National Univ. of Science and Technology (Korea, Republic of); Dae Hyun Kim, Seoul National Univ. of Technology (Korea, Republic of)

Pipes are widely used in various industries and infrastructures. The pipe has long length than cross sectional area. And the pipe structures are usually installed with supports or fixtures which are located with long distance. So deflection and deformation could easily occur in the structures. Shape-monitoring of the pipe is effective to evaluate a safety of the structures. A fiber Bragg grating (FBG) sensor has an advantage of multiplexing. Therefore, the sensor could be usefully applied to the long length structure, such as blades, bridges, pipelines, etc. In this study, FBG sensors were used to measure strains at multi-points of the pipe. To monitor the shape of the pipe, 3-dimensional shape-estimation-technique based on the strains was proposed. Then, an experiment was carried out to verify the performance of the proposed technique. A pipe specimen of the experiment was installed with restrained ends to imitate an environment of real pipe. The estimated result of the pipe structure based on the technique represented the shape according to the deformation of the specimen. Also, a deflection of the pipe was verified by comparing the estimated result with a real deflection which is measured by a micrometer. Consequentially, the shape-estimation-technique could provide effective information for monitoring of the pipeline status to evaluate a safety of structures.

9437-63, Session 13A

**Mechanical strength of FBG sensors
exposed to periodic thermal load in
structural health monitoring**

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Fiber Bragg grating (FBG) sensors are currently the most prevalent due to their own unique advantages such as multiplexing easiness and capability of absolute measurement. If FBG sensors are applied to structural health monitoring (SHM) for various structures in field, they are exposed to thermal load induced by temperature changes from environments. Temperature changes caused by the thermal load are about 80 oC during the whole year in Korea and they have influence on the mechanical strength of FBG sensors as a result. For this reason, the mechanical strength of FBG sensors that are under periodic thermal load in a thermal chamber was investigated in this paper. The temperature was changed from -20oC to 60oC for one cycle and the test was performed for 300 periodic cycles in total in a thermal chamber. After that, the mechanical strength of FBG sensors was measured by tension tests at several steps of thermal cycles, namely pristine, 100, 200, 300 cycles, respectively. From the results, the mechanical strength of FBG sensors decreased about 7-10% as thermal cycles increased up to 100 cycles and it remained steady until the final cycle. From SEM photos of the surface of FBG sensors, it was considered that the main causes on the decrease of

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mechanical strength of FBG sensors were aging effects induced by thermal load during the repetitive thermal cycles. Consequently, it is successfully shown that FBG sensors can have the degradation in mechanical strength if exposed to repetitive thermal load for a long-time SHM.

9437-64, Session 13A

**Structural temperature numerical analysis
of a large rigid-continuous concrete bridge**

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Harsh service environment degenerates the performance of bridges even leads to catastrophic collapse. Structural temperature has been widely recognized as one of the most negative environmental effects on bridge. In this study, the temperature distribution of a large rigid-continuous concrete box girder bridge is investigated combining the numerical simulation and the field measurements. A fiber bragg grating temperature sensor system has been installed on the bridge for field monitoring the structural temperature. For simulation study, the fine two-dimensional finite element (FE) model of box girder section is first constructed. Then, the time-dependent thermal boundary conditions are determined to extensively take account of environmental factors resulting of thermal effects on bridge. At last, transient heat transfer analysis is implemented on FE model and corresponding time-dependent temperature distribution is obtained. The analytical results are compared with the measurements for validation the thermal analysis method. The results have very good agreements with the measurements, and the temperature variations exactly explicate the changes of environmental conditions such as solar radiation and ambient temperature of daily. The temperature simulation provides a foundation for the structural analysis of temperature induced effects.

9437-65, Session 13B

**Multifrequency, multimodal sparse
reconstruction in Lamb wave based
structural health monitoring**

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In structural health monitoring, Lamb waves are employed extensively to examine and monitor thin structures, such as plates and shells. Typically, a network of piezoelectric transducers is affixed to the structural plate member and used for both transmission and reception of the Lamb waves. The signals scattered from defects in the plate are recorded by employing the transducers in pitch-catch pairings. In this paper, we propose a multi-frequency, multi-modal sparse reconstruction approach for localizing defects in thin plates. We simultaneously invert Lamb wave based scattering models for both fundamental propagating symmetric and anti-symmetric wave modes, while exploiting the inherent sparsity of the defects. We construct dictionaries for both fundamental wave modes, which account for associated dispersion and attenuation as a function of frequency. We collect signals at two independent frequencies; one at which the fundamental symmetric mode is dominant, and the other at which only the fundamental anti-symmetric wave mode is present. This provides distinct and separable multi-modal contributions, thereby permitting sparse reconstruction of the region of interest under the multiple measurement vector framework. The proposed defect localization approach is validated using simulated and real data for an aluminum plate.

9437-66, Session 13B

**Modeling ultrasonic NDE and guided-
wave-based structural health monitoring**

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Ray tracing techniques are vital simulation tools to visualize the wave path inside a material. These techniques also help in optimizing the location of transducers and their orientation with respect to the zone of interrogation. It helps in increasing the chances of detection and identification of a flaw in that zone. While current state-of-the-art techniques such as ray tracing based on geometric principle help in such visualization, other information such as signal losses due to spherical or cylindrical shape of wave front are rarely taken into consideration. The problem becomes a little more complicated in the case of dispersive guided wave propagation and near-field defect scattering. We review the existing models and tools to perform ultrasonic NDE simulation in structural components. As an initial step we develop a ray-tracing approach combining a spectral element method over a finite element like mesh, where phase and spectral information are preserved. This enables one to study wave scattering beyond simple time of flight calculation of rays. Challenges in terms of theory and modelling of defects of various kinds are discussed. Various additional considerations such as signal decay and physics of scattering are reviewed and realistic computational implementation challenges are discussed. Potential application of this approach to SHM system design is highlighted and by applying this to complex structural components such as airframe structures, SHM is demonstrated to provide additional value in terms of lighter weight and/or longevity enhancement resulting from an extension of the damage tolerance design principle not compromising safety and reliability.

9437-67, Session 13B

**Nonlinear feature extraction methods for
removing temperature effects in multi-
mode guided-waves in pipes**

Matineh Eybpoosh, Mario Bergés, Hae Young Noh, Carnegie Mellon Univ. (United States)

Effects of environmental and operational conditions (EOCs) (e.g., temperature, stress/loading, coupling material, etc.) on guided-waves have been widely studied. The majority of these studies investigate the EOC effects on individual wave modes, excited using an array of transducers with narrow-band frequencies. However, guided-waves obtained from complex structures operating under varying EOCs, such as pipes, are the results of complex superposition of multiple modes travelling through multiple paths, and are known as diffuse-field waves. Different wave modes propagate with different velocities that are usually a function of frequency, and as illustrated in the initial phase of this study, have different sensitivities to variation of EOCs (i.e., temperature in this work). We have shown that these complexities prevent current compensation methods to be successful for incorporating temperature effects into damage diagnosis of pipes. The effects of EOC variations on different aspects of a damage diagnosis method need to be known for these methods to be extensible to different EOC scenarios. In this paper, linear decomposition methods are investigated since they have shown high potentials in separating arrivals from damaged and undamaged paths as uncorrelated bases of the data space. We formally investigate how the changes in amplitude and propagation velocities of wave modes in a diffuse-field signal affect the performance of linear methods that use principal components as damage-sensitive features. To verify the analysis, the results of simulating temperature effects on pipe waves and ultrasonic pitch-catch measurements from an industrial-scale aluminum pipe recorded under thermally controlled laboratory conditions are used. This study shows that amplitude effects (1) may separate the projection of observations on principal components, thus, increase the chance of false positives if these projections are used for detection, and (2) may alter the principal components and prevent damage components to

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be completely separable from undamaged components in the data space, thus, increase the chance of false negatives. Moreover, different sensitivities of mode velocities to temperature variations make the observations at different temperatures to be nonlinearly related to each other. Such effects will also increase the chance of false negatives since nonlinear relations cannot be completely separable by linear methods. At the end, the potentials of nonlinear decomposition methods are evaluated through comparing their detection performance with that of linear methods for different temperature scenarios.

9437-68, Session 13B

Sparse representation of guided-waves for damage diagnosis in pipelines with damage size, damage location, and temperature variation

Matineh Eybpoosh, Mario Bergés, Hae Young Noh, Carnegie Mellon Univ. (United States)

Dispersive guided-waves travelling in complex media, like operating pipes, will include multiple modes propagating in multiple paths. This is mainly because of reflections and refractions from the features of the structure (e.g., pipe welding, boundaries, damage, etc.), and the complex superposition of these reflections. Environmental and operational conditions (EOCs), such as temperature variation, fluid inside the pipe, or applied stress/load further increases these complexities. Therefore, guided-waves in operating pipes usually propagate in diffuse-field regime. Complexity of diffuse-field signals makes guided-wave based nondestructive evaluation (NDE) of operating pipes a challenging task, since destructive wave superposition and EOC effects can easily mask the changes caused by damage, or appear as damage. During the past two decades, a number of studies have addressed this challenge. Reviewing approaches to-date for reducing the complexity of guided-waves, this paper highlights the criteria that needs to be satisfied for pipeline NDE so that denoising the signal not only removes random noise and increase signal to noise ratio, but also the arrivals that have less contribution in damage diagnosis so that it improves damage diagnosis performance through retaining damage information. A sparse linear discriminator is formulated that imposes both compression of the signal and discrimination of damaged and undamaged observations. The results are sparse signals that retain time-domain information of damage resulting in high detection accuracy. The general concept of the methodology is proved using ultrasonic pitch-catch measurements from an industrial-scale aluminum pipe in a thermally controlled laboratory. Robustness of the methodology to temperature variations are investigated for different temperature scenarios.

9437-69, Session 13B

Experimental validation of analytical model for Lamb wave interaction with geometric discontinuity

Banibrata Poddar, Victor Giurgiutiu, Univ. of South Carolina (United States)

The non-destructive testing of materials can be conducted by various techniques. Amongst these, methods based on ultrasonic waves are one of the most common one. Of these ultrasonic waves Lamb waves are of particular interest for the inspection of large structures for various reasons. Scattering of Lamb waves from flaws has generated a considerable amount of research over last couple of decades. Most of the work has been done using computational tools like Finite Element Methods and experimental technique. In this paper an analytical approach is presented to develop a fundamental understanding of the scattering of Lamb waves from geometric discontinuities in two dimensions. We have considered simplest of all geometric discontinuities – a step, as this fundamental understanding

can easily be extended to corrosion or crack. However the analysis is complex as the scattered wave field is composed of infinite number of Lamb wave modes with variation along the thickness direction. The analytical model uses complex mode expansion to express the complicated wave field near discontinuity and then project the boundary conditions on to the eigen space of the wave field itself. This allows us to take advantage of the complex reciprocity principle thereby obtaining a quicker convergence of the solution. The solution gives us reflection and transmission coefficients of the Lamb wave modes. The coefficients of the propagating modes are then compared with the experimental results for its validation.

9437-70, Session 14A

A Hessian-based methodology for automatic surface crack detection and classification from pavement images

Sindhu Ghanta, Salar Shahini Shamsabadi, Jennifer Dy, Ming Wang, Ralf Birken, Northeastern Univ. (United States)

Around 3,000,000 million vehicle miles are annually traveled utilizing the US transportation systems alone. In addition to the road traffic safety, maintaining the road infrastructure in a sound condition promotes a more productive and competitive economy. The detection and classification of different crack types in road pavements is essential as cracks are a major contributor to the overall safety, health, and serviceability of the road infrastructure. Due to the significant amounts of financial and human resources required to detect surface cracks by visually inspecting a whole road network and to classify them in longitudinal, transversal, block, and alligator categories, detection of these surface defects are often delayed. That translates into not being able to perform timely cost-effective maintenance operations due to a lack of information.

This paper introduces a methodology for automatic detection, classification, and evaluation of pavement surface cracks by unsupervised analysis of images collected from a camera mounted on rear end of a moving vehicle. A Hessian-based multi-scale filter has been applied to detect ridges in these images at various scales. Post-processing on the extracted features has been implemented to produce statistics of length, width, and area covered by cracks. This process has been realized on three sets of roads with different pavement conditions in the city of Brockton, MA. A ground truth dataset labeled manually for validation purposes is made available to evaluate this algorithm. Results rendered more than 90% correlation with the ground truth images which demonstrates the feasibility of employing this approach at a larger scale.

9437-71, Session 14A

Monitoring of pre-release cracks in prestressed concrete using fiber optic sensors

Hiba Abdel-Jaber, Branko Glisic, Princeton Univ. (United States)

Prestressed concrete structures experience low to no tensile stresses, which results in limiting the occurrence of cracks in these structures. However, the nature of construction requires that the structure is not subjected to the compressive force from the prestressing tendons until after the concrete has gained sufficient compressive strength. Although the structure is not subjected loads during this period, it is influenced by shrinkage and thermal variations. Thus, the concrete structure can experience tensile stresses before the required compressive strength has been attained, which can result in the occurrence of “pre-release” cracks. Such cracks are visually closed after the release of the prestressing force. However, structural capacity and behavior can be impacted if cracks are not sufficiently closed. This paper researches an SHM method for the verification of the status of pre-release cracks after the prestressing force is applied. The method relies on measurements from parallel long-gauge fiber optic sensors embedded

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in the concrete prior to pouring. The same sensor network is used for the detection and characterization of cracks, as well as the monitoring of the prestressing force transfer and the determination of the extent of closure of pre-release cracks. This paper outlines the researched method and presents its application to a real-life structure, the southeast leg of Streicker Bridge on the Princeton University campus. The application structure is a curved continuous girder that was constructed in 2009. Its deck experienced four pre-release cracks that were closed beyond the critical limits based on the results of this study.

9437-72, Session 14A
Deterioration modeling for condition assessment of flexible pavements considering extreme weather events

Yasamin Sadat Hashemi Tari, Salar Shahini Shamsabadi, Ralf Birken, Ming Wang, Northeastern Univ. (United States)

Accurate pavement management systems are essential for states' Department Of Transportation and roadway agencies to plan for cost-effective maintenance and repair (M&R) strategies. Pavement deterioration model is an imperative component of any pavement management system since the future budget and M&R plans would be developed based on the predicted pavement performance measures. It is crucial for the pavement deterioration models to consider the factors that significantly aggravate the pavement condition. While many studies have highlighted the impact of different environmental, load, and pavement's structure on the life cycle of the pavement, effect of extreme weather events such as Floods and Snow Storms have often been overlooked.

In this study, a pavement deterioration model is proposed which would consider the effect of traffic loads, climate conditions, and extreme weather events. Climate, load and performance data has been compiled for over twenty years and for seven states using the Long Term Pavement Performance (LTPP) database. A stepwise regression approach is undertaken to quantify the effect of these parameters on the pavement performance quantified in terms of International Roughness Index (IRI). Final results rendered more than 90% correlation with the quantified impact values of extreme weather events.

To employ the final model for predicting the conditions in the future years, influential parameters were forward projected using seasonal autoregressive moving average models. Prediction results of the proposed model were then compared with the predicted results of PAVER, a popular Markov Chain deterioration model.

9437-73, Session 14A
Conductive paint-filled cement paste sensor for accelerated percolation

Simon Laflamme, Sari Kharroub, Hussam S. Saleem, Mohamed Elkashef, Kejin Wang, Eric Cochran, Iowa State Univ. (United States)

Concrete-based strain sensors can be used as robust monitoring systems for civil engineering applications, such as road pavements and historic structures. To enable large-scale deployments, the fillers used in creating a conductive material must be inexpensive and easy to mix homogeneously. While carbon black is inexpensive and available in large quantities, it is unclear whether the heterogeneous geometry of its particles enables the fabrication of conductive materials that behave linearly upon strain. In this paper, the authors investigate carbon black as a filler for fabricating concrete-based strain sensors. The percolation threshold is studied for concrete as a function of aggregate size, and is compared against the percolation threshold of mortar and cement mixes. The sensitivity and linearity of concrete sensors is also studied under different carbon black ratios. Results show that it is possible to fabricate a concrete-based strain sensor using carbon black as a filler.

9437-74, Session 14A
Seebeck coefficient as a thermoelectric indicator for damage assessment of plain cement pastes

Tsung-Chin Hou, Ko-Hung Tai, National Cheng Kung Univ. (Taiwan)

Sensing refers to the phenomenon with which electric signals (ex. voltage, current) are generated by mechanical stimuli (ex. strain, stress, vibrations, thermals). These phenomena are utilized in manufacturing various commercial sensors such as displacement transducers, strain gauges, accelerometers, thermal couples, and many others. The phenomenon is also reversible with which mechanical responses can be generated by providing electric stimuli, and serves as the basis for actuators, motors, and controllers. Sensing materials are conventionally metals and semiconductors, as they cannot be electrical insulators. Cement, such as Portland cement, is conductive, although it is far less conductive than metals. Cement reacts with water through hydration and forms cement pastes that serve as the adhesive matrices for concrete and mortars. Since concrete is a widely used material for buildings and construction, and energy saving and structural integrity are important for most structures, it is desirable to exploit the self-sensing behavior of concrete. This study attempts to use Seebeck coefficient as a thermoelectric indicator for damage assessment of cementitious materials. Investigation is performed solely using plain cement pastes so as to enhance the sensitivity for thermoelectric power measurement. Sequential loading (compressive and flexural)-curing testing procedures followed by thermoelectric power measurements are made and the changes of Seebeck coefficient with respect to different loading types and levels are observed and interpreted. The detection hypothesis based on electrical charge diffusion under applied thermal fields is validated by the study results and the sensing features of Seebeck coefficient for damage assessment of cementitious materials is addressed.

9437-75, Session 14B
Forward and inverse dielectric modeling of oven-dried cement paste specimens in the frequency range of 1.02 GHz to 4.50 GHz

Jones Owusu Twumasi, Tzu Yang Yu, Univ. of Massachusetts Lowell (United States)

The use of radar non-destructive evaluation (NDE) technique for condition assessment of deteriorated civil infrastructure systems is an effective approach for preserving the sustainability of these systems. Radar NDE utilizes the interaction between radar signals (electromagnetic waves) and construction materials for surface and subsurface sensing based on dielectric properties and geometry. In the success of radar inspection, it is imperative to develop models capable of predicting the dielectric properties of the materials under investigation. The dielectric properties (dielectric constant and loss factor) of oven-dried cement paste specimens with water-cement (w/c) ratios (0.35, 0.40, 0.45, 0.5, 0.55) in the frequency range of 1.02-4.50 GHz were studied and modeled using modified Debye's models. An open-ended coaxial probe and a network analyzer were used to measure dielectric properties. Forward models are proposed and inverted for predicting the w/c ratio of a given oven-dried cement paste specimen. Modeling results agreed with the experimental data. The proposed models can be used for predicting the dielectric properties of oven-dried cement paste specimens. Also the modeling approach can be applied to other cementitious materials (e.g., concrete) with additional modification.

9437-76, Session 14B

OFDM and Compressive Sensing based GPR Imaging using SAR Focusing Algorithm

Yu Zhang, Tian Xia, The Univ. of Vermont (United States)

To secure the transportation infrastructure safety, it is critically important to develop effective and efficient inspection technologies to monitor the subsurface structural conditions. This paper focuses on the design of a novel high efficient stepped frequency continuous wave (SFCW) ground penetrating radar (GPR) subsurface objects imaging architecture. On the data acquisition end, a novel approach to elevate SFCW's data acquisition speed and scanning efficiency is proposed. This approach combines orthogonal frequency division multiplexing (OFDM) and compressive sensing (CS). In OFDM, the transmit signal is encoded on multiple carrier frequencies, which are constructed orthogonally between each other. With OFDM technique, all frequency components can be transmitted concurrently, which boost the SFCW radar operating speed and efficiency. Applying compressive sampling, a signal can be reconstructed with reduced samplings below the Nyquist rate. With CS technique, GPR can operate with fewer frequency components while maintain the same level inspection accuracy, which further increases GPR efficiency. On the image reconstruction end, the traditional B-Scan GPR image has the hyperbolic distortion due to the electro-magnetic (EM) wave travel time varies as the scanning radar is moving. Since the GPR B-Scan imaging procedure is very similar as stripmap SAR, in this paper, a SAR-based focusing technique is applied for GPR imaging to mitigate the hyperbolic distortion and reconstruct the buried object. This proposed SFCW GPR-SAR imaging architecture coupled with the OFDM-CS algorithm will be evaluated with channel models obtained with finite-difference time-domain (FDTD) technique. Laboratory experiments will be conducted with hardware setup and measurement results collection and characterization.

9437-77, Session 14B

Sand moisture assessment using instantaneous phase information in ground penetrating radar data

Yu Zhang, The Univ. of Vermont (United States); Dylan Burns, Dryver Huston, Univ of Vermont (United States); Tian Xia, The Univ. of Vermont (United States)

Saturated sand region in road subsurface layer is a sign of the early stage of sinkhole formation, ballast contamination and sub-base degradation. Non-destructive test of the subsurface saturated region can prevent safety hazards and costly emergency repair on roadway and railway. Ground penetrating radar (GPR) is the main subsurface imaging tool for non-destructive infrastructure inspection. In this paper, a method using the instantaneous phase information of the reflection GPR signal to detect the variation in sand moisture is proposed. GPR transmits electro-magnetic (EM) into the subsurface medium and characterizes the subsurface condition by analysis of reflected EM signal. Subsurface features experience phase delays when EM wave travels through the medium. The variations in material moisture change the dielectric constant of the medium, and result in speed variations of the wave penetrating through the medium, which can be characterized through EM wave signal phase parameters. Based on this principle, our proposed method extracts the instantaneous phase information of the reflected GPR signal by Hilbert Transform, which indicates the local feature of the reflected GPR signal at each time point. An EM wave transmission model is also presented to interpret the observed phase behavior and sand moisture. For test evaluation, lab experiments with sand moisture level changing from 0 (dry) - 10 (saturated) are performed using the ground coupled 2.3 GHz Mala CX as data acquisition system.

9437-78, Session 14B

Phased array and nonlinear ground penetrating radar development

Dryver R. Huston, Jonathan Razinger, Dylan Burns, Tian Xia, The Univ. of Vermont (United States)

Phased array and nonlinear methods allow for the possibility of creating new operating modes and feature extraction techniques with ground penetrating radars (GPRs). This paper presents some of the underlying principles and test results from studies aimed at using phased array and nonlinear methods in GPR applications. Phased array methods use multiple antennas to send microwave signals into structures under test in a coordinated manner that exploits superposition effects to advantage. Focusing and steering of the waves onto subsurface features is a primary item of interest. Experiments are conducted on an initial array of two antennas driven by a 4-channel network analyzer operated in a 2-channel phase offset source mode. The ability to control the resulting interference pattern and detection of subsurface features is demonstrated. Confounding issues of direct coupling between channels and subsurface lensing distortion due to chloride-infiltration are discussed. This phased array testing is conducted with a nonlinear vector network analyzer that also has the capability of measuring the presence of nonlinear effects, especially amplitude-dependent harmonic and intermodulation distortions. Some literature suggests that corrosion, ferromagnetic, multi-ferroic and nonlinear dielectric materials can be detected with these techniques. Experimental results from tests on materials in a waveguide chamber and in a GPR configuration are reported.

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Monday - Thursday 9 -12 March 2015

Part of Proceedings of SPIE Vol. 9438 Health Monitoring of Structural and Biological Systems 2015

9438-1, Session 1

A closed form solution of the torsional wave scattered amplitude in a pipe by the reciprocity theorem (*Invited Paper*)

Younho Cho, Jaesun Lee, Pusan National Univ. (Korea, Republic of); Jan D. Achenbach, Northwestern Univ. (United States)

The use of guided wave is suitable for inspection of large scale structure. Surface corrosion is often found as major defect type in such large scale structure as a pipeline. Guided wave interaction signal with the surface corrosion can provide useful feature for sizing and classification. The elastodynamic reciprocity is a well-established theorem to allow us to formulate the complicate scattering problem in a simpler manner. The approach has been already applied to the plate problem like scattering of Rayleigh and Lamb waves for the closed form solutions of scattered amplitude. However, the case for pipe in the cylindrical coordinates has not been reported yet. In this paper, the scattering of torsional wave, which is widely used in commercial units, is explored by the reciprocity theorem base approach. The wave field superposition technique in the frame work of the reciprocity theorem simplifies the scattering problem with closed form solution which can play a significant role in quantitative signal interpretation.

9438-2, Session 1

Multi-helical ultrasonic imaging MHUI for corrosion monitoring of cylindrical structures

Brennan Dubuc, Univ at Buffalo (United States); Ehsan Dehghan Niri, Salvatore Salamone, Univ. at Buffalo (United States)

Corrosion is a major concern of aging metallic cylindrical structures such as pipelines and pressure vessels in petrochemical industry. This paper presents a new imaging method called Multiple Helical Ultrasonic Imaging MHUI for health monitoring of metallic cylindrical structures. Generating and receiving high-order helical guided waves around the cylindrical structure enables MHUI to artificially increase the ray density/resolution or network coverage without increasing the number of sensors. To validate the proposed method, a network of six permanently installed PZT patches was employed for monitoring the condition of a 2 m steel pipe. Corrosion was simulated using two methods: 1. a magnet was mounted at a known location, and 2. three thickness recesses simulating corrosion were engineered by machine cutting. Experimental results demonstrated the efficacy of the proposed approach to successfully identify the simulated damages at the correct locations and qualitatively monitor the damage growth.

9438-3, Session 1

Enhanced signal processing method for monitoring the height of condensed water in steam pipes

Shyh-Shiuh Lih, Hyeong Jae Lee, Yoseph Bar-Cohen, Jet Propulsion Lab. (United States)

An enhanced signal processing method has been developed to monitor

the height of condensed water through the steel wall of steam pipes. An ultrasonic pulse-echo setup with transducers and signal processing software were developed to measure the time of flight and determine the water height. The authors' previously reported research consisted of applying various signal processing techniques to determine the water height when the top surface is reasonably stable. To monitor the variation of the water level under anomalous conditions, an enhanced correlation method that is based on the modified Hilbert transform and energy methods will be described and discussed. The method can also be used to monitor the thickness of the pipe using the local envelope of the ringing reflection signal.

9438-4, Session 1

Guided wave technique for non-destructive testing of StifPipe

Umar Amjad, Susheel K. Yadav, Chi Hahn Nguyen, The Univ. of Arizona (United States); Mohammad R. Ehsani, QuakeWrap Inc. (United States); Tribikram Kundu, The Univ. of Arizona (United States)

Pipes are often exposed to severe environmental conditions; hence, they are susceptible to damage. Damages can result from adverse environments such as high humidity and temperature variations, aging and natural disasters like earthquakes. Guided waves have been used widely in non-destructive testing (NDT) and structural health monitoring (SHM) of various engineering structures including pipes.

The newly-developed StifPipe® is an effective technology for repair and strengthening of existing pipes and culverts. The wall of this pipe consists of a lightweight honeycomb core with carbon or glass fiber reinforced polymer (FRP) applied to the skin. The presence of the hollow honeycomb introduces challenging conditions for nondestructive inspection. In this study, guided waves are excited by a PZT (Lead Zirconate Titanate) transducer for detection of damages in StifPipe®. Multiple signal processing techniques are used for in-depth study and understanding of the recorded signals. The experimental technique for damage detection in StifPipe® material is described and the obtained results are presented in this paper.

9438-5, Session 2

Development of an electromagnetic acoustic transducer (EMAT) for the noncontact excitation of guided ultrasonic waves

Paul Fromme, Univ. College London (United Kingdom)

Fatigue damage 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 such defects in large aerospace structures. Noncontact excitation of guided waves was achieved using electromagnetic acoustic transducers (EMAT). The transducer development for the specific excitation of the A0 Lamb wave mode is explained. The transfer function and angular dependency of the excited guided wave pulses were measured using a noncontact laser interferometer. Based on the induced eddy currents in the plate a theoretical model was developed and reasonably good agreement with the measured transducer performance was achieved. The developed transducers were employed for defect detection in aluminum components using fully noncontact guided wave measurements. Excitation of the A0

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Lamb wave mode was achieved using the developed EMAT transducer and the guided wave propagation and scattering was measured using a noncontact laser interferometer. These results provide the basis for the defect characterization in aerospace structures using noncontact guided wave sensors.

9438-6, Session 2

Wavenumber study of guided waves in aluminum honeycomb sandwich structures

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Honeycomb sandwich structures (HSS) have been increasingly used for automotive, marine and aerospace applications, since they have attractive features such as high strength/stiffness-to-weight ratio, effective acoustic insulation, noise control and vibration damping. However, due to the weak shear strength of the bonding layer, the honeycomb sandwich structures are susceptible to the debonding damage along the skin-core interface, especially under an intensive or repeating loading on the honeycomb core. The hidden debonding damage must be detected and evaluated.

Ultrasonic guided waves have proven to be an effective and efficient method for damage detection and quantification in composite structures. However, the HSS has more complicated geometry thus resulting in more complicated guided wave propagation phenomenon compared to those in the traditional plate structures like metals and laminated composites. In this paper, the fundamentals of guided waves in honeycomb sandwich structures (HSS) and their ability for debonding detection are investigated through wavenumber analysis on time-space wavefield data. Guided wave propagation at various frequencies in aluminum HSS with various core dimensions and simulated debonding damage are studied. The time-space wavefield data are obtained through finite element modeling (FEM) as well as experimental measurements using a hybrid PZT-laser vibrometer sensing system. The time-space data are transformed to the wavenumber domain for further characterization using multidimensional Fourier analysis. Frequency dependence of guided wave propagation in HSS is revealed. The work presented lays the foundation for using guided waves to perform health monitoring and damage detection in HSS components.

9438-7, Session 2

On the combination of outlier analysis and ANN for the inspection of underwater plates

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This paper presents the results of an experimental study where guided ultrasonic waves were used for the structural health monitoring / nondestructive evaluation of an aluminum plate immersed in water. Leaky Lamb waves were generated by means of a pulsed laser and detected by five immersion transducers arranged in a semi-circular array. The signals were processed to extract eight damage-sensitive features from the time, frequency and joint time-frequency domains. These features were then fed to an unsupervised learning algorithm based on the outlier analysis and to a supervised learning algorithm based on artificial neural networks to identify or to classify five types of defects artificially devised on the plate. We found that the hybrid laser-immersion transducers system and both signal processing techniques enable the detection of the defects, and the neural network provides higher success rate with respect to the outlier analysis.

9438-9, Session 2

Laser ultrasonic evaluation of bonding layer in thermal barrier coating

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Two-wave mixing (TWM) technique has adaptive character which is suitable to demodulate ultrasonic waves with high frequency such as those generated by pulsed lasers or piezoelectric transducers. The aim of the present work is to investigate two types of adaptive laser interferometers based on the free-space TWM and on all-fiber TWM demodulation techniques, respectively. The free-space TWM interferometer system includes a InP:Fe crystal, continuous laser device at 1550 nm with a 20 mW, Erbium-doped optical fiber amplifier(EDFA) with amplification from sub-dBm and around 27 dBm, collimators, half-wave plates and photodetector. The all-fiber TWM interferometer system consists of a tunable Yb3+-doped fiber ring laser, a 10-m long Yb3+-doped fiber pumped with a laser diode at 980 nm through a wavelength division multiplexer, a 2-m unpumped Yb3+-doped fiber Sagnac loop for introduction of dynamic gratings by two counter-propagating mutually coherent laser waves, and one fiber Brag grating at wavelength of 1064 nm as a reflector. A PZT transducer is introduced to provide ultrasonic signals at various frequencies, and the two types of TWM interferometer systems are used to detect the ultrasonic waves. The performance characteristics of the TWM interferometer systems are evaluated in terms of adaptivity, frequency-response, and sensitivity. Applications to laser ultrasonic nondestructive evaluation are also described.

9438-10, Session 3

Uncertainty quantification of relative acoustic nonlinearity parameter of guided waves for damage detection in composite structures

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Nonlinear guided waves are found to be more sensitive to microscopic damage, which can hardly be identified by traditional ultrasonic techniques. While previous studies have demonstrated their effectiveness in detecting undersized damage in metallic plate-like structures, this study aims to extend the nonlinear guided waves to composite structures, and to explore the feasibility of using nonlinear guided waves for characterizing cyclic-loading-induced damage (CLID) in composite laminates, such as fiber/matrix cracks and delamination, in conjunction with the use of a piezoelectric sensor network. First, theoretical studies are carried out, scrutinizing wave propagation characteristics in composite laminates. A piezoelectric sensor network is configured to actively generate probing Lamb waves and acquire damage-induced nonlinear wave features. Aided with the acoustic nonlinearity parameter, which is initially developed for nonlinear Lamb waves in metals, a probability-based diagnostic imaging algorithm is further proposed, able to present the characterization results with intuitive diagnostic images. The approach is then experimentally verified using a damaged composite laminate, with reasonably good accuracy achieved.

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9438-11, Session 3

**Fatigue crack visualization using
noncontact laser ultrasonics and state
space geometrical changes**

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Fatigue crack and its precursor often serves as a nonlinear source and the nonlinear ultrasonic features created by a fatigue crack have a much higher sensitivity compared with linear features. This paper presents a fatigue crack visualization technique based on noncontact laser ultrasonics and state-space techniques. Under a broadband laser pulse excitation, defect nonlinearity exhibits modulation at multiple peaks in a spectral plot due to interactions among various input frequency components of the broadband input. These modulations are weak and can hardly be directly reflected in both the frequency and time domain. In order to detect the nonlinear changes caused by fatigue cracks in the time domain, a state-space attractor is first reconstructed using a single laser pulse response and its geometrical changes are calculated. The parameter optimization for state-space attractor reconstruction is then studied. Finally, through scanning metallic plates using a Q-switched Nd:YAG laser and laser Doppler vibrometer (LDV), the proposed method has been successfully tested for visualizing fatigue cracks.

9438-12, Session 3

**Enhanced nonlinear crack-wave
interactions for structural damage
detection based on Lamb waves**

 Kajetan Dziejach, Lukasz J. Pieczonka, Piotr Kijanka,
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Technology (Poland)

Various damage detection methods based on ultrasonic wave propagation have been developed for the last few decades. Ultrasonic guided waves – such as Lamb waves – offer the possibility of inspecting large areas of structure from a small number of sensor positions and so are particularly attractive for structural health monitoring applications. The last fifteen years have seen a significant increase in research interest related to nonlinearities in micro-cracked and cracked solids. As a result, a number of different nonlinear acoustic methods have been developed for damage detection. These methods are attractive due to their sensitivity to small damage severities. The paper proposes a new method that combines Lamb wave propagation with nonlinear acoustics. Low-frequency excitation is used to modulate Lamb waves in the presence of fatigue cracks. The work presented shows that synchronisation of the interrogating Lamb wave with the low-frequency vibration is a key element of the proposed method. Numerical simulations and experimental validation are used to demonstrate the application of the method to fatigue crack detection. The results show that baseline measurements representing undamaged condition are not needed and temperature variations are also not an issue.

9438-13, Session 3

**Monitoring accelerated carbonation on
standard portland cement mortar by
nonlinear resonance acoustic test**

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Carbonation is one of the most deleterious processes for concrete

structures. Carbonation begins when carbon dioxide (CO₂) present in the atmosphere reacts with portlandite producing calcium carbonate (CaCO₃). In severe carbonation conditions, also C-S-H gel is decomposed in silica gel (SiO₂.nH₂O) and CaCO₃. As a result, concrete pH decreases (usually below 10) and eventually steel rebars become unprotected from corrosion agents. Usually, the carbonation of the cementing matrix produces a decreasing in the porosity, because CaCO₃ crystals (calcite and vaterite) occupy more volume than portlandite. In this study, an accelerated carbonation-ageing process is conducted on Portland cement mortar samples with water to cement ratio of 0.5. The evolution of the carbonation process on mortar is monitored at different levels of ageing until the mortar is almost fully carbonated. A nondestructive technique based on nonlinear acoustic resonance is used to monitor the variation of the constitutive properties upon carbonation. At selected levels of ageing, the compressive strength is obtained. From fracture surfaces the depth of carbonation is determined with phenolphthalein solution. An image analysis of the fractured surfaces is used to quantify the depth of carbonation. The results from resonant acoustic tests revealed a progressive increase of stiffness and a decrease of material nonlinearity.

9438-14, Session 3

**Damage imaging in nonlinear vibro-
acoustic modulation tests**

 Lukasz J. Pieczonka, Andrzej Klepka, Tadeusz Uhl, Wieslaw
J. Staszewski, AGH Univ. of Science and Technology
(Poland)

The paper deals the nonlinear vibro-acoustic modulation technique (VAM) used for nondestructive damage detection in composites. In its original form the technique allows only for the determination of the presence of damage in a structure. This paper presents an enhancement of the technique that allows also for the determination of damage location and size estimation. Experimental testing of the proposed procedure is performed on carbon fiber/epoxy laminated composite plates with barely visible impact damage that was generated in an impact test. Piezoceramic actuators are used for vibration excitation and scanning laser vibrometer is used for signal acquisition.

9438-15, Session 3

**Vibration-based health monitoring of
rotordynamic system with breathing cracks**

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Wei Yao, The University of Tennessee (United States)

In this paper, a vibration-based health monitoring method is proposed and demonstrated on a breathing cracked shaft-disk system. This approach utilizes the vibration response of the rotor from the sensors to diagnose the health condition of the system. The rotor system is modeled by finite element method and the crack model is based on the released strain energy in fracture mechanics. The comprehensive study is done to investigate the breathing behavior of the transverse crack on the rotating shaft in terms of crack depth, crack location, crack phase and shaft rotation speed. Zero Stress Intensity Factor (SIF) method is employed to determine the crack closure line at each time step by calculating the stress intensity factor of opening mode for every point in crack area. The stiffness matrix of cracked element is updated at every time step by integrating compliant coefficients over instantly calculated crack open area. In addition, the coupled lateral, longitudinal and torsional vibration induced by the damage is studied under multiple loading conditions. It is shown that the vibration response can be used as health indicators of the structure during ramp up, steady state and ramp down phases.

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9438-16, Session 3

**Wavelet based simulation of a piecewise
linear SDOF oscillatory system**

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Aircraft structures are frequently exposed to damages due to high velocity impacts such as bird hit, tool drop or gust etc. The linear methods of guided wave based damage detection fail to precisely account for the super/sub harmonics generated in the frequency domain response. In this regard, nonlinear vibration analysis using the breathing cracks which takes contact nonlinear interaction into consideration, has been researched over past few years.

In this present study, damage in a structure has been modeled as a switching/breathing crack which undergoes successive opening and closing when subjected to tensile and compressive loading respectively. To analyse this effect the structure has been conceived as a piecewise linear SDOF dynamical system. The governing equation of motion involving the bilinear stiffness of the system has been solved by discrete wavelet transformation (DWT) method. DWT is chosen over fourier transform due to its ability to analyse signals of finite time length having nonperiodicity. This analytical study will help in understanding the mechanics behind interaction of damage with the vibration response of the structure in a better way. Daubechies compactly supported wavelets have been implemented to formulate the nonlinear phenomena to describe the super/sub harmonics observed in the frequency domain response of the structure when subjected to narrow banded tone burst excitation. The computationally efficient proposed formulation involves an iterative scheme which switches between time and transformed domain and is then validated by the results of time integration method of solution.

9438-17, Session 4

**Applications of matched field processing
to damage detection in composite wind
turbine blades**

 Jeffery D. Tippmann, Francesco Lanza di Scalea, Univ. of
California, San Diego (United States)

There are many structures serving vital infrastructure, energy, and national security purposes. Inspecting the components and areas of the structure most prone to failure during maintenance operations by using non-destructive evaluation (NDE) methods has been essential in avoiding costly, but preventable, catastrophic failures. In many cases, the inspections are performed by introducing acoustic, ultrasonic, or even thermographic waves into the structure and then evaluating the response. Sometimes the structure, or a component, is not accessible for active inspection methods. Because of this, there is a growing interest to use passive methods, such as using ambient noise, or sources of opportunity, to produce a passive impulse response function similar to the active excitation. Several matched field processing techniques most notably used in oceanography and seismology applications, are examined in more detail. While, parse array imaging in structures has been studied for years but all methods use an active interrogation approach, here, structural damage detection is studied by use of the reconstructed impulse response functions in ambient noise within sparse array imaging techniques, such as Matched-field processing. This has been studied in experiments using both an aluminum plate and a 9-m wind turbine blade.

9438-18, Session 4

**State sensing and awareness for the next
generation of autonomous fly-by-feel UAVs**

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Kuo Chang, Stanford Univ. (United States)

Self-sensing multifunctional materials are highly "intelligent" materials that constitute the future generation of composites for aerospace applications. Towards this end, the current research goal is the development of technologies that will lead to the next generation of autonomous fly-by-feel UAV systems that can (i) sense the environmental (temperature, ambient air pressure, etc.), (ii) sense the structural health state (damage, delamination, etc.), and (iii) effectively interpret the sensing data to achieve real-time state awareness and implement appropriate self-diagnostics under uncertainties in varying operating environments.

In this work, the complete system design, integration, and evaluation is presented for a smart composite UAV wing with self-sensing and awareness capabilities. Micro-fabricated stretchable sensor networks, including integrated piezoelectric, strain, and temperature sensors, as well as proper electronics and interface devices, are designed and monolithically embedded in the layout of a composite wing in order to enable its self-sensing capabilities. In addition, advanced signal processing, stochastic identification, and diagnostic techniques are employed in order to accurately interpret the sensing data and assess the actual structural state. The experimental evaluation and assessment of the smart wing and the employed algorithms is demonstrated via (a) wind tunnel experiments under varying angle-of-attack for the identification of the coupled airflow-structural dynamics and their correlation with airflow separation and stall, and (b) laboratory experiments under healthy and damaged structural states to evaluate both active and passive sensing structural health monitoring (SHM) approaches. The obtained results demonstrate the successful system-level integration, as well as the effectiveness of the employed data interpretation approaches, proving their integration potential into fly-by-feel UAVs and enabling their deployment for aerospace applications.

9438-19, Session 5

**Hybrid local FEM/global LISA modeling of
guided wave propagation and interaction
with damage in composite structures**

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(United States)

This paper presents a hybrid modeling technique for the efficient simulation of guided wave propagation and interaction with damage in composite structures. This hybrid approach used a local finite element model (FEM) to compute the excitability of guided waves generated by piezoelectric transducers, while the global domain wave propagation, wave-damage interaction, and boundary reflections were modeled with the local interaction simulation approach (LISA).

A small-size multi-physics FEM with non-reflective boundaries (NRB) was built to obtain the excitability information of guided waves generated by the transmitter. Frequency-domain harmonic analysis was carried out to obtain the solution for all the frequencies of interest. Fourier and inverse Fourier transform and frequency domain convolution techniques were used to obtain the time domain 3-D displacement field around the transmitter under an arbitrary excitation. This 3-D displacement field was then fed into highly efficient time domain LISA simulation module to compute guided wave propagation, interaction with damage, and reflections at structural boundaries. The multi-physics local FEM can reliably capture the detailed dimensions and local dynamics of the piezoelectric transducers and the adhesive layers. The global domain LISA can accurately solve the 3-D elastodynamic wave equations in a highly efficient manner. LISA is also capable of dealing with complex waveguide geometries and boundaries. By combining the local FEM with global LISA, the efficient and accurate simulation of guided wave structural health monitoring procedure was achieved. Two case studies will be presented: (1) guided wave propagation in a pristine composite plate; (2) guided wave propagation in a damaged composite plate. Experiments with scanning laser vibrometry were conducted on CFRP composite plates to verify the simulation results.

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9438-20, Session 5

Semi-analytical modelling of guided waves generation on composite structures using circular piezoceramics

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In Structural Health Monitoring (SHM), classical imaging techniques rely on the use of analytical formulations to predict the propagation and interaction of guided waves generated using piezoceramic (PZT) transducers. For the implementation of advanced imaging approaches on composites structures, analytical formulations need to consider (1) the dependency of phase velocity and damping as a function of angle (2) the steering effect on guided wave propagation caused by the anisotropy of the structure and (3) the full transducer dynamics. In this paper, the analytical modelling of guided waves generation by a circular PZT and propagation on composite structures is proposed. This work, based on previous work from the authors, is intended to extend a semi-analytical formulation from isotropic to visco-elastic transversely isotropic plate-like structures. The formulation considers the dependency of the interfacial shear stress under the PZT as a function of radius, angular frequency and orientation on the composite structure. Validation is conducted for a unidirectional transversely isotropic structure with a bonded circular PZT of 10 mm diameter. Amplitude curves and dispersed signals of the A0 and S0 modes obtained from the proposed formulation and the classical pin-force model are compared to Finite Element Model simulations and measurements using a 3D laser Doppler vibrometer for principal and non-principal directions on the composite. The results show the interest of considering a hybrid formulation for which the transducer dynamics and also the shear distribution under the transducer are considered in order to reproduce more precisely the generation of guided waves on composite structures.

9438-21, Session 5

Dispersion of guided waves in composite laminates and sandwich panels

Christoph Schaal, Ajit K. Mal, Univ. of California, Los Angeles (United States)

In composite structures, damages are often invisible from the surface and can grow to reach a critical size, potentially causing catastrophic failure of the entire structure. Safe operation of these structures therefore requires careful monitoring of the initiation and growth of such defects. Ultrasonic methods using guided waves offer a reliable and cost-effective method for Structural Health Monitoring in advanced structures. Guided waves allow for long monitoring ranges and are sensitive to defects within their propagation path.

In this work, properties of guided Lamb waves in composite structures are investigated. An efficient numerical approach is applied to determine dispersion characteristics, and these results are compared to theoretical solutions along with results from laboratory experiments. The experiments are based on a pitch-catch method, in which a pair of movable transducers is placed on the outside surface of the structure to induce and detect guided Lamb waves.

In addition to dispersion curves, the displacement fields of the waves are also studied to investigate the excitability of the waves, which is shown to strongly depend on the wave type and frequency, for the pitch-catch system used. The specific cases considered include an aluminum plate, a woven composite laminate and an aluminum honeycomb sandwich panel with woven composite face sheets. Good agreement between numerical and theoretical as well as experimental dispersion results is shown, and suggestions on the applicability of the pitch-catch system for precise nondestructive testing are made.

9438-22, Session 5

Guided waves based SHM systems for composites structural elements: statistical analyses finalised at probability of detection definition and assessment

Ernesto Monaco, Vittorio Memmolo, Fabrizio Ricci, Natalino D. Boffa, Leandro Maio, Univ. degli Studi di Napoli Federico II (Italy)

Maintenance approaches based on sensorised structures and Structural Health Monitoring systems could represent one of the most promising innovations in the fields of aerostructures since many years, mostly when composites materials (fibers reinforced resins) are considered. Layered materials still suffer today of drastic reductions of maximum allowable stress values during the design phase as well as of costly and recurrent inspections during the life cycle phase that don't permit of completely exploit their structural and economic potentialities in today aircrafts. Those penalizing measures are necessary mainly to consider the presence of undetected hidden flaws within the layered sequence (delaminations) or in bonded areas (partial disbonding); in order to relax design and maintenance constraints a system based on sensors permanently installed on the structure to detect and locate eventual flaws can be considered (SHM system) once its effectiveness and reliability will be statistically demonstrated via a rigorous Probability Of Detection function definition and evaluation. This paper presents a combined experimental and numerical approach for the evaluation of POD of a guided waves based SHM system oriented to delaminations detection on a typical wing composite layered panel. The experimental part is mostly oriented to characterise the statistical distribution of measurements and damage metrics as well as to characterise the detection errors distribution and to validate numerical models. Numerically it is possible instead to substitute part of the experimental tests aimed at POD. Results of both experiments and simulations are presented in the paper and analysed.

9438-23, Session 6

Design of intelligent composites with life-cycle health management capabilities

Colleen Rosania, Cecilia Larrosa, Fu-Kuo Chang, Stanford Univ. (United States)

Use of carbon fiber reinforced polymers (CFRPs) presents challenges because of their complex manufacturing processes and different damage mechanics in relation to legacy metal materials. New monitoring methods for manufacturing, quality verification, damage estimation, and prognosis are needed to use CFRPs safely and efficiently. This work evaluates the development of intelligent composite materials using integrated piezoelectric sensors to monitor the material during cure and throughout service life. These sensors are used to propagate ultrasonic waves through the structure for health monitoring. During manufacturing, data is collected at different stages during the cure cycle, detecting the changing material properties during cure and verifying quality and degree of cure. The same sensors can then be used with previously developed techniques to perform damage detection, such as impact detection and matrix crack density estimation. Real-time damage estimation can be combined with prognostic models to predict future propagation of damage in the material. In this work experimental results will be presented from composite coupons with embedded piezoelectric sensors. Cure monitoring and damage detection results derived from analysis of the ultrasonic sensor signal will be shown. Sensitive signal parameters to the different stimuli in both the time and frequency domains will be explored for this analysis. From these results, use of the same sensor networks from manufacturing throughout the life of the composite material will demonstrate the full life-cycle monitoring capability of these intelligent materials.

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9438-24, Session 6

Analysis of Lamb wave dispersion curve sensitivity to material elastic constants in composites

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The paper deals with the problem of Lamb waves dispersion curves sensitivity to the change of material elastic constants in composite materials. The framework of the present work is a more general problem of the material constants identification in thin plates made of composite materials. The approach is based on the analysis of guided waves propagation and the related dispersion curves to find the underlying material elastic constants. In present work a numerical study is performed to identify measurement directions and wave propagation modes that are the most sensitive to the change of the particular elastic constants. This approach will allow optimize the material constants identification procedure and experimental setup by specifying the preferred measurement directions and wave propagation modes. The approach can be used within the Structural Health Monitoring framework to monitor material degradation of plate-like structures made of composite materials.

9438-25, Session 6

Guided waves for detection of delamination and disbonding in stiffened composite panels

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Composite materials are susceptible to hidden defects that may occur during manufacturing and service (e.g., foreign object impact) and may grow to a critical size, jeopardizing the integrity of the structure. Among the various existing techniques, guided wave methods provide a good compromise in terms of sensitivity to a variety of damage types or defects and extent of the area that can be monitored, given the ability of this waves to travel relatively long distances within the structure under investigation. Wave propagation in composite structures presents several complexities for effective damage identification. The material inhomogeneity, the anisotropy and the multi-layered construction lead to the significant dependence of wave modes on laminate layup configurations, direction of propagation, frequency, and interface conditions. This paper is concerned with the detection and characterization of small emerging or existing defects in composite structural components using a recently developed technique employing an array of surface mounted broadband ultrasonic transducers as actuators and sensors as well as theoretical analysis to interpret the recorded signals. The technique is applied to panels with different thickness, including stiffened panels with stringer-panel disbonding. The major objectives of this research is to extend the current capabilities of ultrasonic methods to wider areas of coverage, faster inspection procedures, lower percentage of false positives and less dependence of manual operations. The method is based on the well known fact that guided waves are strongly influenced by inter-ply delaminations and other hidden defects in their propagation path.

9438-26, Session 6

Analysis of guided wave propagation in a tapered composite panel

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Many studies have been published in recent years on Lamb wave propagation in isotropic and (multi-layered) anisotropic structures. In this paper, adiabatic wave propagation phenomenon in a tapered composite panel made out of glass fiber reinforced polymers (GFRP) was considered. Such structural elements are often used e.g. in wind turbine blades and aerospace structures. Here, the wave velocity of each wave mode does not only change with frequency and the direction of wave propagation. It further changes locally due to the varying cross-section of the GFRP-material.

Elastic waves were excited using a piezoelectric transducer. Full wave-field measurements using 3D scanning Laser Doppler vibrometry have been performed to register both, in-plane and out-of-plane velocity components of guided wave modes. This approach allows the detailed analysis of elastic wave propagation in composite specimen with linearly changing thickness. It will be demonstrated here experimentally, that the wave speed changes significantly due to the tapered geometry of the structure. Hence, this work motivates the theoretical and experimental analysis of adiabatic mode propagation for the purpose of Non-Destructive Testing and Structural Health Monitoring.

9438-27, Session 6

Identification of disbond in a honeycomb composite sandwich structure using ultrasonic guided wave and embedded PWT sensors

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The honeycomb composite sandwich structure (HCSS) is a novel material which has been adopted globally as a lightweight construction material for major structural components in aerospace, marine and automotive industries. Disbond between the composite skins and honeycomb core may occur due to the aging, repeated loadings and foreign object impacts and compromises the structural safety and integrity. Initially, the disbond effects are studied by two-dimensional (2D) finite element simulations of HCSS for with and without disbond. Significant amplification of a particular guided wave (GW) mode and a little increment in group velocity of the received signal is noticed due to the presence of disbond. Then, the laboratory experiments are conducted for the validation of the numerical results, by using an embedded piezoelectric wafer transducer (PWT) network, for the guided Lamb wave propagation in the sandwich plate. The PWTs are arranged in a grid pattern on the plate top surface, in which, one of the PWT acts as an actuator and the other acts as sensor. Excellent agreement between the 2D numerical and the experimental results is observed. A probability based damage detection algorithm, based on the change in amplitude phenomenon of the received signal is applied for the identification of the disbond location in HCSS. Finally, a damage index (DI) map is plotted using an image fusion technic, which exhibits that, the proposed method can provide quantitative information about the exact location and size of disbond in the HCSS.

9438-28, Session 7

Design optimization of layered periodic composites for desired elastodynamic response

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A systematic method for design of layered periodic composites (PCs) for a prescribed elastodynamic response is presented. Our focus is on optimization problems with equality and/or inequality constraints. Constrained optimization problems are reduced to unconstrained ones and genetic algorithm is used to find the optimal design. Symmetric 3-phase layered PCs are considered and the thickness of each phase are chosen as design parameters. Three cases are presented for illustration: (1) design of a band-stop acoustic filter for maximum band-width, (2) design of a band-stop acoustic filter for maximum attenuation with band-width more than a prescribed value, and (3) design of a finite layered PC for maximum dissipation and minimum reflection.

9438-29, Session 7

Sound insulation and energy harvesting based on acoustic metamaterial plate

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The emergence of artificially designed sub-wavelength acoustic materials, denoted acoustic metamaterials (AMM), has significantly broadened the range of materials responses found in nature. These engineered materials can indeed manipulate sound/vibration in surprising ways, which include vibration/sound insulation, focusing, cloaking, ... [1]. In this work, we report both on the analysis of the airborne sound transmission loss (STL) through a thin metamaterial plate and on the possibility of acoustic energy harvesting. We first provide complete theoretical and numerical studies of the airborne STL and confronted them to the structure-borne dispersion of a metamaterial plate. Second, we propose to investigate the acoustic energy harvesting capability of the plate-type AMM.

We have developed semi-analytical and numerical methods to investigate the STL performances of a plate-type AMM with an airborne sound excitation having different incident angles. The AMM is made of silicone rubber stubs squarely arranged in a thin aluminum plate [2], and the STL is calculated at low-frequency range [100Hz to 3kHz] for an incoming incident sound pressure wave. The obtained analytical and numerical STL present a very good agreement confirming the reliability of developed approaches. A comparison between computed STL and the band structure [2] of the considered AMM shows an excellent agreement and gives a physical understanding of the observed behavior. On another hand, the acoustic energy confinement in AMM with created defects with different geometries has been investigated. The first results give a general view for assessing the acoustic energy harvesting performances making use of AMM.

[1] Z. Liu et al. Science 289, 1734 (2000)

[2] M. Oudich et al, New J. Phys. 12, 083049 (2010)

9438-30, Session 7

Active control of flexural waves in a plate using elastic metamaterials

Yangyang Chen, Guoliang Huang, Univ. of Missouri-Columbia (United States)

Elastic metamaterials have been extensively suggested in subwavelength wave propagation control, due to their frequency dependent effective material parameters. In this study, a new kind of active elastic metamaterial

with electrically tuned electrorheological (ER) elastomer is presented for plate flexural wave deflection control. We first developed a 2D coordinate transformation method to determine the material parameter profile of a plate flexural wave beam bender under conformal mapping. The active elastic metamaterial is composed of an ER elastomer ring layer sandwiched between an aluminum cylinder and an aluminum ring layer, where the effective mass density is controlled by tuning the shear modulus of ER elastomer through applying various electric fields. Negative effective mass density was found at extremely broad frequency band. A 90 degree beam bender was finally constructed and simulated in COMSOL Multiphysics. Numerical simulations reveal that this active wave bender can be electrically tuned to work at different incident frequencies and waves can be actively deflected to various angles through inactivating some of electric fields without changing its geometric structure. The proposed active design shows a great potential in serving structural health monitoring and wave controlling applications.

9438-31, Session 7

Band gap control in an active elastic metamaterial with negative capacitance piezoelectric shunting

Guoliang Huang, Yangyang Chen, Univ. of Missouri-Columbia (United States)

Elastic metamaterials have been extensively investigated due to their significant effects on controlling propagation of elastic waves. One of the most interesting properties is the generation of band gaps, in which subwavelength elastic waves cannot propagate through. In the study, a new class of active elastic metamaterials with negative capacitance piezoelectric shunting is presented. We first investigated dispersion curves and band gap control of an active mass-in-mass lattice system. The unit cell of the mass-in-mass lattice system consists of the inner masses connected by active linear springs to represent negative capacitance piezoelectric shunting. It was demonstrated that the band gaps can be actively controlled and tuned by varying effective stiffness constant of the linear spring through appropriately selecting the value of negative capacitance. The promising application was then demonstrated in the active elastic metamaterial plate integrated with the negative capacitance shunted piezoelectric patches for band gap control of both the longitudinal and bending waves. It can be found that the location and the extent of the induced band gap of the elastic metamaterial can be effectively tuned by using shunted piezoelectric patch with different values of negative capacitance, especially for extremely low-frequency cases.

9438-32, Session 7

Design of multi-stopband metamaterial plates for absorption of broadband elastic waves and vibration

Hao Peng, Univ. of Missouri, Columbia (United States); Perngjin F. Pai, Univ. of Missouri-Columbia (United States)

This paper presents the modeling technique, working mechanism and design guidelines for acoustic multi-stopband metamaterial plates for broadband elastic wave absorption and vibration suppression. The metamaterial plate is designed by integrating two-DOF (degree of freedom) mass-spring subsystems with an isotropic plate to act as vibration absorbers. For an infinite metamaterial plate without damping, a unit cell is modeled using the extended Hamilton's principle, and two stopbands are obtained by dispersion analysis on the averaged three-DOF model. For a finite metamaterial plate with boundary conditions and damping, shear-deformable conforming plate elements are used to model the whole plate, and stopbands and their dynamic effects are investigated by frequency response analysis and transient analysis by direct numerical integration. Influences of absorbers' resonant frequencies and damping ratios, plate's

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boundary conditions and dimensions, and working plate-absorber modes are thoroughly investigated. Results show that the metamaterial plate is essentially based on the concept of conventional vibration absorbers. The local resonance of the two-DOF subsystems generates two stopbands, and the inertial forces generated by the resonant vibrations of absorbers straighten the plate and attenuate/stop wave propagation. Each stopband's bandwidth can be increased by increasing the absorber mass and/or reducing the isotropic plate's unit cell mass. Moreover, a high damping ratio for the secondary absorber can combine the two stopbands into one wide stopband for vibration suppression, and a low damping ratio for the primary absorber warrants absorbers' quick response to steady and/or transient excitations.

9438-33, Session 7

Cellular phononic crystals with piezoelectric shunts for tunable directivity

Paolo Celli, Stefano Gonella, Univ. of Minnesota, Twin Cities (United States)

Phononic crystals offer vast opportunities for spatial manipulation of elastic waves. For example, they possess inherent directivity, i.e., the ability to focus waves along certain preferred frequency-dependent propagation paths. This property can be exploited for the design of directional actuators and sensors, acoustic shields and energy deflectors. A few challenges arise. The first challenge is to make the directional effects available in the low frequency range corresponding to the acoustic modes band. The second is to achieve single-beam focusing, which entails confining the energy inside a single selected quadrant of the propagation domain. Lastly, it is highly desirable to design tunable crystals with the ability to actively modify their directional properties in response to external control feeds or changes in the operating conditions. In this work, we explore an approach based on hierarchical lattices with microstructures, in which the role of the microstructures is to relax the symmetry of the host lattice structures. We have previously shown that, by microstructure-induced symmetry relaxation, it is possible to focus waves with wavelengths several times larger than the unit cell size, even in lattices with mild anisotropic index. The natural evolution of this concept is a tunable crystal with actively controlled directional properties. The concept involves the incorporation of piezoelectric elements at strategic locations within the cell and the activation of voltage-induced stress stiffening mechanisms, which trigger an active modification of the cell's effective stiffness and symmetry landscape and ultimately the activation and de-activation of a variety of propagation paths.

9438-34, Session 7

Parameter-dependence of the acoustic rotation effect of a metamaterial-based field rotator

Xue Jiang, JianChun Cheng, Bin Liang, Nanjing Univ. (China)

The field rotator is a fascinating device capable to rotate the wave front by a certain angle, which can be regarded as a special kind of illusion. We have theoretically designed and experimentally realized an acoustic field rotator by exploiting acoustic metamaterials with extremely anisotropic parameters. A nearly perfect agreement is observed between the numerical simulation and experimental results. We have also studied the acoustic property of the acoustic rotator, and investigated how various structural parameters affect the performances of such devices, including the operating frequency range and rotation angle, which are of particularly significance for the application. The inspection of the operating frequency range shows the device can work within a considerably broad band as long as the effective medium approximation is valid. The influence of the configuration of the metamaterial unit has also been investigated, illustrating the increase of anisotropy of metamaterial helps to enhance the rotator effect, which can

be conveniently attained by elongating each rectangle inserted to the units. Furthermore, we have analyzed the underlying physics to gain a deep insight to the rotation mechanism, and discussed the application of such devices for non-plane wave and the potential of extending the scheme to three-dimensional cases. The realization of acoustic field rotator has opened up a new avenue for the versatile manipulations on acoustic waves and our findings are of significance to their design and characterization, which may pave the way for the practical application of such devices.

9438-35, Session 7

A wrinkly phononic crystal

Alireza Bayat, Faramarz Gordaninejad, Univ. of Nevada, Reno (United States)

This study presents a tunable phononic crystal designed to interact with surface elastic waves. A composite structure consists of a hard film on a soft substrate is employed to develop a periodic pattern at the surface when the compressive strain reaches a critical value. Wrinkling of the thin film due to buckling induced surface instability is utilized to develop a tunable surface phononic crystal. The surface pattern, amplitude and periodicity of wrinkles depend on the material properties and geometry of the layers and are controlled by the applied compressive strain. A finite element model is used to develop the wrinkly pattern and capture the large deformations. The deformed state is used to study the dynamic response of the phononic crystal. The pattern transformation of the microstructure is used to tune the band diagram and control the bandgaps of the periodic structure. Results show that the wrinkly pattern can be used to manipulate with one-dimensional surface elastic waves in the microswitches and telecommunication devices.

9438-36, Session 7

Microstructural realization of acoustic cloak with pentamode material

Yi Chen, Xiaoning Liu, Gengkai Hu, Beijing Institute of Technology (China)

Pentamode material (PM) is characterized by an elastic tensor in which five of the six eigenvalues are zero, thus it can only support a single stress state, and recently found applications in transformation acoustics. Compared to the earlier inertial cloaks based on the anisotropic density, PM cloaks have advantages of solid form, not suffering mass singularity and theoretically broadband feature. In this work, a microstructural realization is presented for two-dimensional cylindrical acoustic cloaks by honeycomb-like unit cells with different geometric patterns, and its cloaking performance is examined by numerical experiments. The relation between the required anisotropic PM properties and the unit cell microstructural parameters are built locally in Cartesian frames, the PM unit cells are then cast into the cylindrical cloak configuration by carefully designed topological connection. Full wave simulation shows that scattering of the obstacle can be remarkably reduced by the designed cloak within discrete frequency ranges. Practically, its broadband performance is weakened by several resonant scattering peaks, due to the inevitably small shear resistance of the real PMs. However, the scattering peaks can be reduced by introducing damping factors in the material without affecting the original concealing effect.

9438-77, Session PTues

Health assessment of bolted joints in a steel planar frame structure: An experimental study

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The joints of the steel structure are often created with nuts and bolts. But, the day-to-day variations of in-service loads, environmental variability and any faults at the time of installation of bolts loosen the joints. At the end, this loosening of bolts reduces the rigidity of the joints. In the present study, the effect of the loosening of bolts in the global response of the structure is identified. For this purpose, a small-scale steel frame structure is developed in the laboratory. The beam and columns of the frame are connected with angles and nut-bolts. A bolt load cell (BLC) is developed in the laboratory environment and calibrated under the vertical load. The BLC is fitted to a joint in such a fashion, that beam-column connecting nut-bolts pass through it. Thus, any tightening of the bolts induces a compressive load to the BLC. The BLC is connected to the data acquisition system (MGC Plus) to acquire the bolt load at the joint. The study is carried out for several loosening cases. Two accelerometers are fitted horizontally at the top of the columns. The structure is excited in its natural mode of vibration and the accelerations are recorded using the MGC plus. Once the data are recorded, Fourier transform of these data are carried out. These Fourier amplitude spectra of different cases are then compared to identify the presence of loosened joints. The identified results depict that the Fourier amplitude spectra maintains the consistency and changes with the change of loosening level.

9438-78, Session PTues

A Novel Low Profile Wireless Flow Sensor to Monitor Hemodynamic Changes in Cerebral Aneurysm

Yanfei Chen, Univ. of Pittsburgh (United States); Brian T. Jankowitz, UPMC (United States); Sung Kwon Cho, Youngjae Chun, Univ. of Pittsburgh (United States)

A low-profile flow sensor was designed, fabricated, and subsequently tested to wirelessly monitor the blood flow within the sac of aneurysm until intra-aneurysmal hemodynamic quiescence is achieved. The prototype sensor contains three layers, i.e., a thin polyurethane (74-30 series from Polytek, PA) layer was sandwiched between two sputter-deposited thin film nitinol layers (6 μ m thick). A novel superhydrophilic surface treatment was used to create hemocompatible surface of thin nitinol electrode layers. We built a test platform with a z-axis translation stage and an S-beam load cell (LSB200 from Futek, CA) to compare the capacitance changes of the sensors with different parameters during deformation. An LCR meter (PXI 4072, National Instruments, TX) and oscilloscope (Tektronix, PA, USA) were used to measure the capacitance and the resonant frequency shifts, respectively. Computational structural analysis using finite element modeling (ANSYS 14.5, PA) showed that the deformation of the sensor (length (L):width (W):thickness (T) = 6mm:3mm:1mm) ranged from 66.61 μ m to 202.49 μ m when a blood pressure (120mmHg) was applied, which represented capacitance change of approximately 11.19%. The experimental compression test results showed that the corresponding capacitance increased from 2.5036pF to 2.7518pF, suggesting that the capacitance change was 9.91%. The calculated resonant frequency shifted from 9.68MHz to 9.23MHz when coupled with a 0.108mH inductor. Our recent results demonstrated a feasibility of the low-profile flow sensor for monitoring hemodynamics in cerebral aneurysm region, as well as the efficacy of the use of the surface treated thin film nitinol for the low-profile sensor materials.

9438-79, Session PTues

ANN-based persistent SHM technique for wind-induced response of tall buildings

Jinwoo Hwang, Byung Kwan Oh, Yonsei Univ. (Korea, Republic of) and Ctr. for Structural Health Care Technology in Building (Korea, Republic of); Yousok Kim, Tongjun Cho, Ctr. for Structural Health Care Technology in Building (Korea, Republic of); Hyo Seon Park, Yonsei Univ.

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The wind affects the behavior of tall buildings dominantly and results in vibration and serviceability problem for the structures. To solve these kind of problems, real time structural health monitoring (SHM) of tall buildings have been widely researched and applied to buildings recently. Through double integral of acceleration measured by accelerometer, lateral displacement on building can be estimated. This method provides only relative displacement and does not present absolute location of structures. Researches for using GPS have been tried to measure absolute displacement of tall buildings as well. However application of GPS to wind vibration monitoring represented some limitations due to installation, maintenance problems of base station and low resolution. Vision-based displacement measurement methods such as laser scanner show relatively high accuracy but it is inappropriate to measure continuously due to surrounding environment such as security of sight and weather. As described above, existing measurement methods of lateral displacement have limitations for serviceability monitoring of tall buildings. Therefore it is required to develop persistent SHM technique for wind-induced response of tall buildings. Introducing ANN to this problem, this paper proposes the technique for predicting top lateral displacement of tall buildings. Relationships between strains measured on structural elements of tall building and lateral displacement measured at top of building during the same period are established through the training in ANN. By this constituted neural network and strain data measured during another specific period, the SHM technique for predicting wind-induced lateral displacement at the top of tall building is proposed.

9438-80, Session PTues

Comparative efficacy of flaw detection in structures using piezo sensors in bonded and non-bonded configurations

Shashank Srivastava, Indira Gandhi National Open Univ. (India); Suresh Bhalla, Alok Madan, Ashok Gupta, Indian Institute of Technology Delhi (India)

Bonded piezo based sensors are conventionally been used for structural health monitoring as piezo-impedance transducer in the electro-mechanical impedance (EMI) technique. This acts as a deterring for widespread application of the technique in bio-medicine since the bond may be a cause of irritation among the subjects. This paper presents an alternate non-bonded configuration for piezoelectric ceramic (PZT) patch for acquiring diagnostic signature, which opens the possibility for opening the application of the technique for bio-medical diagnostics. In this endeavor, the very first step is to determine the efficacy of non bonded piezo sensor in comparison to the bonded piezo sensor. This paper presents the results from a set of laboratory experiments for determining the comparative efficacy of a bonded and non bonded piezo sensor. The non-bonded configuration is found to significantly capture the dynamic characteristics of the structure. This proof-of-concept demonstration has potential applications in the field of bio-medicine, where it can possibly be applied for acquiring the signature of bones to gather structural dynamic characteristics of the same to detect ailments such as osteoporosis.

9438-81, Session PTues

Electromechanical impedance monitoring of joints in space structures

Matthew Campisi, Mary Anderson, Rebecca C. Clemens, Andrei N. Zagari, New Mexico Institute of Mining and Technology (United States)

No Abstract Available

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9438-83, Session PTues

Towards a micromechanics based understanding of ultrasonic higher harmonic generation

Vamshi Krishna Chillara, Cliff J Lissenden, The Pennsylvania State Univ. (United States)

Research efforts in nonlinear ultrasonics (higher harmonic generation) have evolved from the use of bulk-waves to the use of Rayleigh waves and guided waves for early damage detection. Numerous studies have shown the sensitivity of higher harmonic generation to various changes in the microstructure. Thus, it is essential that we have a well-defined framework for understanding the effect of micro-scale degradation on ultrasonic higher harmonic generation in a more general context than that for the case of a uniaxial stress wave (bulk wave) in the material. To that end, three important aspects of micro-scale material behavior relevant to ultrasonic higher harmonic generation are identified; namely tension-compression asymmetry, shear-normal coupling and deformation induced anisotropy. Of these, tension-compression asymmetry has been found to be directly related to the second harmonic generation in polycrystals. A homogenization based approach is developed to assess the contribution of micro-scale defects like voids and cracks to second harmonic generation. The results obtained from the approach are highlighted both from qualitative and quantitative viewpoints.

9438-84, Session PTues

Medical CT image reconstruction accuracy and industrial non-destructive image quality measures using x-rays up to 1.75 MeV from a newly developed x-band linear accelerator system and an optimized flat panel imager

James E. Clayton, Varian Medical Systems, Inc. (United States)

Flat panels imagers based on amorphous silicon technology (a-Si) for digital radiography are accepted by the medical and industrial community as having several advantages over radiographic film-based systems.

Radiotherapy treatment planning systems employ computed tomographic (CT) data and projection images to delineate tumor targets and normal structures that are to be spared during treatment. CT number accuracy is crucial for radiotherapy dose calculations. Conventional CT scanners operating at kilo-voltage X-ray energies typically exhibit significant image reconstruction artifacts in the presence of metal implants in human body. Using the megavoltage X-ray energies of radiotherapy for CT scanning has problems maintaining contrast sensitivity for the same dose as kV X-ray systems.

Higher Energy X-ray sources with electron energies in the range of 1-2 MeV have been developed for CT applications, eliminating the metal artifacts while providing better contrast resolution than typical radiotherapy treatment beams.

Furthermore, not only radiotherapy but industrial nondestructive testing (NDT) imaging systems could also benefit from a more compact higher output accelerator and optimized imagers for use in pipeline, structural integrity and casting inspection as well as certain cargo screening applications.

We intend to demonstrate significant improvement in metal artifact reduction and electron density measurements using an a-Si imager obtained with an X-ray source that can operate at energies up to 1.75 MeV. Commissioning data and imaging capabilities such as focal spot size and contrast sensitivity offered by this new X-band linear accelerator for medical and industrial imaging applications will be shown.

9438-37, Session 8

What can phase contrast do for you in applications for SHM involving ultrasonic microscopy?

Wolfgang Grill, Gerhard Birkelbach, ASI Analog Speed Instruments GmbH (Germany)

Presented are applications involving SHM by ultrasonic microscopy where, with respect to standard scanning acoustic microscopy (SAM), valuable information is gained by monitoring of the phase angle in addition to the magnitude of the signal reflected from the focal region. Monitoring is based on the developed phase contrast scanning acoustic microscopy (PSAM). Examples covering frequency ranges from the MHz regime up to 1.2 GHz are presented. A variety of different applications is included in the presentation together with the discussion of basic aspects including the theoretical and technical background together with the basic underlying physics.

9438-38, Session 8

Pixelated MV detector for radiotherapy and NDE applications

George Zentai, Josh M. Star-Lack, Daniel Shedlock, James E. Clayton, Varian Medical Systems, Inc. (United States); Rebecca Fahrig, Stanford School of Medicine (United States); Gary Virshup, Varian Medical Systems, Inc. (United States)

In radiotherapy kilo-voltage (kV) CT provides very high quality images that can be used for patient positioning. However, if the patient has any metal implants then severe streaking artifacts may arise, which can impair the set-up process. It is known that operation at MeV energies eliminates these artifacts due to reduced absorption of the beam by the metal. Since the scintillator layer of a traditional MV (portal) imager, such as the Varian ASI1000 has low X-ray absorption at high energies (typically 2% at 6MV), very high doses are required to attain reasonable soft tissue contrast. To address this issue, a pixelated MV imager prototype was developed comprising 15mm thick cadmium tungstate (CdWO₄) crystal arrays, with the pixels optically isolated from each other. The zero-frequency detective quantum efficiency [DQE(0)] was between 20-25% offering over a factor of 10 improvement compared to a traditional portal imager.

In this work, further attempts have been made to increase quantum efficiencies by lowering the beam energy to 1.5MeV. At this energy, metal artifacts still can be avoided, but the DQE is increased due to high absorption in the detector. This "sweet spot" of operation results in much better image contrast-to-noise ratios (CNRs) at the same X-ray dose as a 6MV scan, or can allow for maintaining the same CNR as was attained at 6MV but using thinner scintillator pixels (price advantage).

Beam energies in the range of 1 - 1.5MV also can be used for NDT applications including pipeline inspection and security screening.

9438-39, Session 9

Determination of mode shapes using long-gage fiber optic sensors

Kaitlyn Kliewer, Branko Glisic, Princeton Univ. (United States)

Fiber Bragg grating (FBG) sensors offer a significant advantage for structural health monitoring due to their ability to monitor both static and dynamic strain while being durable, lightweight, capable of multiplexing, and immune to electro-magnetic interference. Drawing upon the benefits of FBG sensors, this research demonstrates the ability to use a series of long-gage fiber optic sensors to determine the modal shapes of a structure.

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By doing so, the same sensors can be used for both frequency and modal analysis and overcome some of the challenges associated with traditional dynamic measurement methods. Small scale experimental testing was performed using a cantilevered aluminum beam instrumented with a series of FBG optical fiber sensors. Dynamic strain measurements were obtained as the beam was subjected to various loading conditions. From the dynamic strain measurements the curvature, and consequently the deflected shape, as well as the natural frequencies of the structure could be determined. Since the total deformed shape is comprised of the sum of the displacement caused by each mode, knowing both dynamic displacement and the natural frequency values allow calculation of the structure's modal shapes. By determining the structures modal shapes, the demonstrated flexibility of FBG long-gage sensors facilitates dynamic monitoring at both the local and global scale, thus allowing full analysis of structure dynamics.

9438-40, Session 9
Monitoring viscosity in asphalt binders using an ultrasonic guided waves

Henrique L. Reis, Alexandra E. Haser, Megan E. McGovern, Behzad Behnia, William G. Buttlar, Univ. of Illinois at Urbana-Champaign (United States)

A pulse-echo ultrasonic guided wave approach capable of monitoring the viscosity of asphalt binders as function of temperature is presented. The method consists of sending a torsional wave from one end of a cylindrical steel rod embedded in asphalt binder and receiving the reflected signals. Experiments were performed on several binders of different performance grades, at temperatures ranging from 25 to 180 oC. First, the viscosity of the binders was measured using a rotational viscometer in accordance with ASTM standards. The change in signal strength of the end-of-waveguide reflection of the guided wave was also monitored for the same binders over the same range of temperatures. It was observed that the values obtained using the guided wave approach correlates well with the viscosity values obtained using the rotational viscometer. The method also appears capable of monitoring changes in viscosity due to aging of the binders. The method has the advantage of having no moving parts, which makes it attractive for the development of a system that is capable of monitoring viscosity in asphalt binders in the asphalt industry.

9438-41, Session 9
Nondestructive evaluation of piers

Ionica Negru, Gilbert-Rainer Gillich, Zeno-Iosif Praisach, Marius Tufoi, Univ. "Eftimie Murgu" Resita (Romania); Edwald-Viktor Gillich, Politehnica Univ. of Timisoara (Romania)

This paper proposes a vibration-based damage detection method designed for structural elements subjected to important vertical loads, as columns or piers. It is based on the relation existing between the energy stored in the pier in several vibration modes and the corresponding natural frequencies. For a certain mode, this energy results as sum of the energies stored in all pier slices, being dependent on the rigidity and the squared of the corresponding mode shape curvature. This means that the energy distribution along the pier is different for each mode. Thus, reducing the rigidity of one slice due to damage, the frequencies will decrease in different ways, depending on the slice location. This fact permits to contrive patterns able to characterize the effect of damage for any location along the pier. Since the mode shapes (and the natural frequencies) are influenced by inertial forces, but in the meantime by the compression and share forces induced by the top mass, the patterns have to be derived for each load case. The paper present a simple mathematical expression able to predict frequency changes if damage occurs at any location along the pier and for any top mass value. Patterns that characterize the damage location are consequently derived by using the squared mode shape curvatures of the healthy beam. The damage location becomes an inverse problem, it being

found by interpreting the results of frequency measurements for the healthy and damaged state. The process of damage location is exemplified by numerical simulations and experiments.

9438-42, Session 9
Damage identification in rectangular plates using spectral strain energy distribution

Marius Tufoi, Gilbert-Rainer Gillich, Vasile Iancu, Ionica Negru, Univ. "Eftimie Murgu" Resita (Romania)

This paper proposes a vibration-based damage detection method designed for rectangular thin plates. The method bases on the relation existing between several vibration modes and the corresponding natural frequencies given by the strain energy stored in plate. For a certain mode, this energy results as sum of the energies stored in plate, being dependent on the rigidity and the squared of the corresponding mode shape curvature. This means that the energy distribution along the plate is different for each mode. Thus, reducing the rigidity of one plate due to damage, the frequencies will decrease in different ways, depending on the damage location. This fact permits to contrive patterns able to characterize the effect of damage for any location on the plate. Since the mode shapes (and the natural frequencies) are influenced by inertial forces, but in the meantime by the compression and share forces induced by the plate mass in the embedded place, the patterns have to be derived for each damage case. The paper present a mathematical expression able to predict frequency changes if damage occurs at any location on the plate. Patterns that characterize the damage location are consequently derived by using the squared mode shape curvatures of the undamaged plate. The damage location becomes an inverse problem, it being found by interpreting the results of frequency measurements for the healthy and damaged state. The process of damage location is exemplified by experiments and numerical simulations.

9438-43, Session 10
Output-only identification of civil structures using nonlinear finite element model updating

Hamed Ebrahimian, Rodrigo Astroza, Joel P. Conte, Univ. of California, San Diego (United States)

This paper presents a novel approach for output-only nonlinear system identification of structures using data recorded during earthquake events. In this approach, state-of-the-art nonlinear structural FE modeling and analysis techniques are combined with Bayesian Inference methods to estimate (i) time-invariant parameters governing the nonlinear hysteretic material constitutive models used in the FE model of the structure and (ii) the time history of the earthquake ground motion. The output-only system identification and input estimation is accomplished through nonlinear finite element model updating using two different Bayesian Inference approaches: (i) recursive estimation based on nonlinear stochastic filtering method, and (ii) batch estimation based on maximum a posteriori estimation. A proof-of-concept example, consisting of a cantilever steel column representing a bridge pier, is provided to verify the proposed output-only system identification and input estimation approach. The simulated responses of this bridge pier to a set of earthquake ground motions are polluted with artificial output measurement noise and used to jointly estimate the unknown material parameters and the time history of the earthquake ground motion. This example illustrates the successful performance of the proposed approach even in the presence of high measurement noise.

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9438-44, Session 10

**Linear and nonlinear characterization of
weathering damage in limestone claddings**

 Henrique L. Reis, Megan E. McGovern, Univ. of Illinois at
Urbana-Champaign (United States)

Durability problems in dimension stone cladding are very costly. While its failure may be attributed to multiple causes, the most significant is stone strength reduction. No current nondestructive testing method exists that can estimate the strength of dimension stone cladding. Furthermore, experience has shown that stone durability varies from quarry to quarry and, even from location to location within the same quarry. Limestone samples with increasing levels of weathering, i.e., damage, were artificially prepared by exposing the test samples to increasing levels of temperature of 100, 200, 300, 400, and 500 oC for the period of ninety minutes. Linear and nonlinear ultrasonic characterization of weathering of limestone claddings is presented. The linear approach is based on the limestone complex moduli and the nonlinear characterization involves non-collinear mixing of longitudinal waves. It was observed that the level of damage can be estimated using both the linear and the nonlinear approach.

9438-45, Session 10

**Kalman filter based data fusion for neutral
axis tracking in wind turbine towers**

 Rohan N. Soman, Polish Academy of Sciences (Poland);
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and Warsaw Univ. of Technology (Poland); Uwe Paulsen,
Technical Univ. of Denmark (Denmark)

Wind Energy is seen as one of the most promising solutions to man's ever increasing demands of a clean source of energy. In particular to reduce the cost of energy (COE) generated, there are efforts to increase the life-time of the wind turbines, to reduce maintenance costs and to ensure high availability.

Maintenance costs may be lowered and the high availability and low repair costs ensured through the use of condition monitoring (CM) and structural health monitoring (SHM). SHM allows early detection of damage and allows maintenance planning. Furthermore, it can allow us to avoid unnecessary downtime, hence increasing the availability of the system.

The present work is based on the use of neutral axis (NA) for SHM of the structure. The NA is tracked by data fusion of measured yaw angle and strain through the use of Extended Kalman Filter (EKF). The EKF allows accurate tracking even in the presence of changing ambient conditions. NA is defined as the line or plane in the section of the beam which does not experience any tensile or compressive forces when loaded. The NA is the property of the cross section of the tower and is independent of the applied loads and ambient conditions. Any change in the NA position may be used for detecting and locating the damage. The wind turbine tower has been modelled with FE software ABAQUS and validated on data from load measurements carried out on the 34m high tower of the Nordtank, NTK 500/41 wind turbine.

9438-46, Session 10

**Quantitative evaluation of rejuvenator to
restore embrittlement temperatures to
oxidized asphalt concrete using acoustic
emission**

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 Behnia, William G. Buttlar, Univ. of Illinois at Urbana-
Champaign (United States)

As asphalt concrete (AC) is subjected to oxidative aging, the stiffness of the binder increases and its resistance to tensile stresses is reduced, which makes the embrittlement temperatures warmer. The original properties of the binder can however be restored with the application of rejuvenators, which restore its most volatile components. To evaluate the effectiveness of rejuvenators in restoring the low-temperature cracking of aged AC mixtures, test samples (5cm thick and 15cm in diameter) were cut from gyratory compacted cylinders made from AC mixtures oven-aged for 36 hours at 135 oC. These samples were then exposed to a uniform layer of rejuvenator on one side in the amount of 10% of the specimen binder (PD64-22) by weight, (i.e., -10 grams), and were then left for a dwell time of two, four, six and eight weeks. Using an acoustic emission (AE) approach, the embrittlement temperature of the virgin and the aged specimens (oven-aged for 36 hours) was estimated at -25.15 ° and -15.08 °, respectively. It was observed that on the side exposed to rejuvenator the embrittlement temperature was lowered to -26.78 °, an improvement of over 100%. On the untreated side, the embrittlement temperature was lowered to -19.83 °. On the average, the embrittlement temperature for the specimen was improved from -15.08 ° for the 36 hours aged specimen to -23.29° for the specimen treated with rejuvenator. This represents an improvement of 54.4 %. Results are consistent with mechanically obtained results using the indirect tension test, i.e., the DC(T) test.

9438-47, Session 10

**Phase-shifted helical long-period grating-
based temperature-insensitive optical
fiber twist sensors**

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Yinian Zhu, Sridhar Krishnaswamy, Northwestern Univ.
(United States)

Optical fiber twist sensors have attracted a great deal of attention over the past decade because of their particular characteristics, such as lightweight, small size, and high sensitivity. In this paper, a compact temperature-insensitive optical fiber twist sensor based on multi-phase shifted long-period gratings (LPG) is proposed and experimentally demonstrated. The helical structure of the LPG can be constructed by using a CO2 laser as the fiber is twisted by rotation. By changing the speed of the rotation, helical periods of the structure of the grating that are different from the original helical period can be written, thereby introducing a $\pi/2$ and a $3\pi/2$ phase shift in the helical LPG. The helical pitch can be effectively changed with a different twist rate, which is measured by calculating the wavelength contrast between two phase shift peaks. Although the wavelength of the phase shift peak also shifts with a change of the temperature and strain, the wavelength difference between the two phase shift peaks is constant, thereby making the sensor insensitive to temperature and strain change but sensitive to twist. The experimental results show that a twist sensitivity of up to 1.959 nm/(rad/m) is achieved.

9438-48, Session 11

**Nonlinear wave propagation in origami-
based mechanical metamaterials**

 Hiromi Yasuda, Jinkyu Yang, Univ. of Washington (United
States)

We numerically studied the nonlinear wave dynamics of origami-based mechanical metamaterials. We modeled origami crease lines by simple zig-zag shapes, where mountain and valley folds are repeated periodically through the entire origami structure. The hinges at the folding interfaces are modeled by torsional springs. First, we considered the quasi-static state to investigate the force-displacement relation of this model. Although the

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torsional spring used is linear, this model has geometric nonlinearity that provides unique characteristics in the force-displacement curve. We also observe different behavior between tension and compression regimes. Unlike conventional systems studied in nonlinear wave dynamics such as granular chains, this system exhibits a softening behavior in compression and a hardening behavior in tension. Based on this quasi-static property, we then investigated the dynamic characteristics of this system. Specifically, we conducted numerical calculations of wave propagation under an impact applied to the end of this system. In a tensile impact, an isolated tensile pulse appears and propagates through the system, similar to the compressive solitary waves that can be observed in discrete granular chains. If compression is applied, a tensile pulse appears in front of the initial compressive pulse, whose amplitude decreases as the wave propagates through the system. These unusual characteristics can lead to new metamaterials design and potential applications in impact absorption as well as energy transportation.

9438-49, Session 11

GPU accelerated variational methods for fast phononic eigenvalue solutions

Ankit Srivastava, Illinois Institute of Technology (United States)

In this paper we present accelerated phononic computation results achieved through a novel decomposition scheme of the variational phononic eigenvalue problem. The scheme is presented in a form which facilitates deep parallelism. This parallelism is exploited through the use of distributed Graphical Processing Units resulting in orders of magnitude speed up over serial computations. We present the efficacy of our implementation through fast computations of several thousand phononic eigenvalues for high contrast, multiphase 3-D unit cells. The central idea of the decompositional scheme introduced in this paper applies more generally to variational eigenvalue problems in dynamics and has the potential of introducing similar computational accelerations in other areas as well.

9438-50, Session 11

Dynamically tunable metamaterials based on helicoidal phononic crystals

Jinkyu Yang, Feng Li, Univ. of Washington (United States)

In this presentation, we report dynamically-tunable wave transmission characteristics in 1D helicoidal phononic crystals (HPCs) in a form similar to DNA structures. These helicoidal architectures develop slanted nonlinear contact among constituents, allowing strong cross-talking between out-of-plane longitudinal waves and in-plane torsional waves. We focus on demonstrating versatile wave dispersion behavior of the HPC in both wavevector and frequency domains. Based on the wave mixing effect elucidated, an acoustic transistor is further proposed, in which longitudinal waves can be turned on/off through torsional waves.

9438-51, Session 11

Anisotropic mass density by three-dimensional elastic metamaterials

Edahi A. Gutiérrez-Reyes, Ana L. González, Felipe Pérez-Rodríguez, Benemérita Univ. Autónoma de Puebla (Mexico)

We have applied a homogenization theory [1], which is based on the Fourier formalism, to calculate the effective parameters of phononic crystals having liquid inclusions embedded in a solid host matrix. The theory provides explicit formulas for determining all the components of the effective mass density and stiffness tensors, which are valid in the long wavelength limit

for arbitrary Bravais lattice and any form of the inclusions inside the unit cell. In a previous work [1], it was shown that rectangular two-dimensional lattices of water-filled holes in an elastic host matrix exhibit solid-like behavior with strongly anisotropic mass density in the low-frequency limit. Such metamaterials were called metasolids. In the present work, we analyze the metasolid behavior of liquid-solid three-dimensional phononic crystals. In particular we have analyzed the effect of the type of Bravais lattice and form of the liquid inclusions on the anisotropy of the effective mass density. In the analysis we have considered different solid host materials (Al, Si, and ribbon) with isolated inclusions of water. We have established that the anisotropy of the effective mass density is considerably strong when the homogenized phononic crystals do not possess inversion symmetry because of the inclusion shape. Our results could be useful for designing metamaterials with predetermined elastic properties.

9438-52, Session 11

Complete band gaps in an anti-symmetric piezoelectric phononic crystal slab

Kwai Zou, Yuesheng Wang, Beijing Jiaotong Univ. (China)

As a kind of periodic composites, phononic crystals have obtained great attention in recent decades due to the possibility to prohibit the propagation of some elastic waves with certain frequencies. Meanwhile, piezoelectric materials are very popular for their extensive applications in the field of industry, medical instruments, information and telecommunications and so on. Recently, piezoelectric materials are utilized gradually in the periodic structure to form piezoelectric phononic crystals, which can advance the design of new functional acoustic devices. In this study, the structure we take into account is a piezoelectric slab covered with periodically metal cuboids, which is distributed anti-symmetrically on the top and bottom surface of the slab. The dispersion relation in this structure is calculated through the finite element method. Large complete band gaps can be found in the band structure of this structure, and the effects of geometric parameters of the metal cuboids on the band gaps are discussed. From the numerical results, we can conclude that a large cover area of metal cuboids is favorable for the generation of band gaps. And the height of metal cuboids also has a strong influence on the band gap when the cover area is large enough. Through analyzing the vibration modes on the band gap edges, the mechanism of the generation of band gaps is also investigated. Analogously, a symmetric structure is studied to make a contrastive analysis. The results illustrate that the distribution of metal cuboids have significantly impacts on the band gap. This study is relevant to the application of piezoelectric phononic crystals in acoustic wave devices.

9438-53, Session 11

Nonlinear stress wave dispersion in elastic woodpile metamaterials

Eunho Kim, Noel Y. H. Kim, Jinkyu Yang, Univ. of Washington (United States)

In this presentation, we report nonlinear elastic wave dispersion in quasi-1D woodpile structures composed of slender cylindrical rods. Discrete periodic structures under a Hertzian contact (e.g., granular crystals) show interesting nonlinear wave dynamics due to the combined effect of discreteness and nonlinearity. Especially in heterogeneous chains, the wave propagation mechanism depends significantly on the sequence of the constitutive elements. Recent studies investigated nonlinear wave dynamics in various types of heterogeneous architectures, such as ordered dimer and trimer chains, tapered and decorated chains, the chains with weak/strong disorders, and etc. These studies showed that the propagating waves can be substantially attenuated due to the wave disintegration at the contact interfaces among heterogeneous particles. In this research, we numerically and experimentally investigate the effect of local resonance of slender rods on nonlinear wave dispersion in both ordered and disordered woodpile structures. We find that low frequency bending vibration modes

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of the slender rods are strongly coupled with the propagating nonlinear waves, thereby changing the propagating waveforms substantially. Also, by introducing multiple resonances at different frequencies, we can efficiently modulate and attenuate transmitted waves through the discrete structures. This wave attenuation mechanism based on the wave dispersion can be used for the development of a new type of elastic metamaterials with high stiffness and high damping characteristics. This is in contrast to conventional materials, which exhibit the inverse relationship between stiffness and damping. Moreover, this woodpile can be easily extended to stable 3D woodpile structures and have a potential for engineering applications, e.g., blast and impact mitigation.

9438-54, Session 11

Variational methods in phononics

Yan Lu, Ankit Srivastava, Illinois Institute of Technology (United States)

In this paper we present comparative results regarding the computational efficiency, speed, and versatility of three fundamental variational schemes for phononic band-structure calculation: a. traditional Rayleigh quotient where the displacement field is varied, b. inverse Rayleigh quotient where the stress field is varied, and c. mixed-method where both the displacement and the stress fields are varied. We show that the variational principles can be used for the fast evaluation of various phononic properties such as the dispersion relation, equi-frequency contours, and the density of states.

9438-85, Session 11

Design method for Hyper-elastic cloak with arbitrary configuration

Dengke Guo, Gengkai Hu, Beijing Institute of Technology (China)

Hyper-elastic Transformation obtains invariant property that a pre-strain is implemented on a homogeneous solid material with energy function delicately designed. Based on this invariant property, a Hyper-elastic cloak with arbitrary shape was designed by exert a Pre-Direchlet Boundary Condition on Semi-linear material. The numerical results show that wave Transformation property of the pre-strain region can be modified and the cloaking effect is detected as the theory indicates. A Hyper-elastic carpet cloak is also simulated, which can pretend ground plane perfectly. At the end, the limitation of Hyper-elastic was analyzed about constrain conditions during the finite deformation course.

9438-55, Session 12A

Vibration response based structural damage detection using auto correlation function

Muyu Zhang, Rüdiger Schmidt, RWTH Aachen Univ. (Germany)

Structural damage detection using time domain vibration responses attracts more and more researchers in recent years because it has advantages such as no requirement of a finite element model and simplicity in calculation. This paper proposes a new approach to detect the damage under white noise excitation using the auto correlation function. The maximum values of the auto correlation function of the vibration response signals from structure's different measurement points are formulated as a vector called Auto Correlation Function at Maximum Point Value Vector, AMV for short, which is a weighted combination of the Hadamard product of two mode shapes. AMV is normalized by its root mean square value to eliminate the influence of the excitation. Sensitivity analysis of the different parts of the normalized AMV show that the sensitivity of the normalized AMV to the

local stiffness is dependent on the sensitivity of the Hadamard product of the two lower order mode shapes to the local stiffness, which has a sharp change around the local stiffness change location. The sensitivity of the normalized AMV has the same trend which shows it is a good indicator for the damage even when the damage is very small. The relative change of the normalized AMV before and after damage is used as the damage index to detect the damage. Stiffness reduction detection of a 9-story frame structure is provided to validate the results in sensitivity analysis and illustrate the effectiveness and anti-noise ability of the proposed method.

9438-56, Session 12A

Application of support vector machine in damage detection process of beams

Satish B. Satpal, Anirban Guha, Sauvik Banerjee, Indian Institute of Technology Bombay (India)

Recently the Support Vector Machine (SVM) has been established as a promising tool for classification and regression in many research fields. Many researchers have used SVM technique in the field of Structural Health Monitoring (SHM) using parameters of the structure like natural frequency shift, Frequency Response Function (FRF) data etc. In the current research work SVM is explored to find the damage location in aluminium beam. In this approach the displacement values corresponding to first mode shape is used to predict the damage locations. Generating the data of the considered beam cases is done in two different ways, first with the help of simulation package Abaqus® and second by experimentation. Experiments are done using Laser Doppler Vibrometer (LDV). Two boundary conditions namely fixed-free and fixed-fixed are considered and damages are introduced by creating rectangular notch throughout the beam width at different locations. Finally the predictions of damage locations are done using simulated as well as experimental data and the results are validated.

9438-57, Session 12B

SHM systems in composites structural elements: summary of the main achievements in SARISTU project and follow-up scenario for next future aircrafts implementation

Ernesto Monaco, Univ. degli Studi di Napoli Federico II (Italy); Alfonso Apicella, Alenia Aermacchi (Italy); Ulrike Heckenberger, Airbus Group Innovations (Germany)

Structural Health Monitoring systems represent today a wide category of approaches combining technologies based on sensors able to acquire responses of structural components in hot spots or larger, extended areas and methodologies able to extract information from acquired data and analyse them often performing statistical evaluation of "damage metrics".

Both methodologies and technologies within the latest research programs around the world demonstrated that readiness levels between 3 and 4 have nowadays been accomplished. It is now time for researchers and industry to start to work for integrating competences and include them into a multilevel design philosophy to develop dedicated maintenance procedure aimed at operative cost reduction and successively at weight reduction of airframes. This target has been addressed in the EU funded project SARISTU as well as in new project proposals on the basis of the gained experiences.

The authors will present some main achievements in terms of design philosophy and depict the follow up research trends that could drive in 5-7 years the methodologies and technologies to adequate readiness level for SHM implementation in next future aircrafts.

9438-58, Session 12B

Heat induced damage detection in composite materials by terahertz radiation

Maciej Radzienski, Magdalena Mieloszyk, The Szewalski Institute of Fluid-Flow Machinery (Poland); Ehsan Kabiri Rahani, Tribikram Kundu, The Univ. of Arizona (United States); Wieslaw M. Ostachowicz, The Szewalski Institute of Fluid-Flow Machinery (Poland)

In recent years electromagnetic Terahertz (THz) radiation or T-ray has been increasingly used for nondestructive evaluation of various materials such as polymer composites and porous foam tiles in which ultrasonic waves cannot penetrate but T-ray can. Most of these investigations have been limited to mechanical damage detection like inclusions, cracks, delaminations etc. So far only a few investigations have been reported on heat induced damage detection. Unlike mechanical damages the heat induced damage does not have a clear interface between the damaged part and the surrounding intact material from which electromagnetic waves can be reflected back. Difficulties associated with the heat induced damage detection in composite materials using T-ray are discussed in detail in this paper. T-ray measurements are compared for different levels of heat exposure of composite specimens. It is observed that sometimes T-ray can detect heat induced damage but some other times it fails to do so. Signal processing techniques that are useful for heat induced damage detection are also discussed in the paper.

9438-59, Session 13A

Monitoring of hidden fatigue crack growth in multi-layer aircraft structures using high frequency guided waves

Henry Chan, Univ. College London (United Kingdom); Bernard Masserey, Univ. of Applied Sciences of Fribourg (Switzerland); Paul Fromme, Univ. College London (United Kingdom)

Varying loading conditions of aircraft structures result in stress concentration at fastener holes, where multi-layered components are connected, potentially leading to the development of hidden fatigue cracks in inaccessible layers. High frequency guided waves propagating along the structure allow for the structural health monitoring (SHM) of such components, e.g., aircraft wings. Experimentally the required guided wave modes can be easily excited using standard ultrasonic wedge transducers. However, the sensitivity for the detection of small, potentially hidden, fatigue cracks has to be ascertained. The type of multi-layered model structure investigated consists of two adhesively bonded aluminium plate-strips with a sealant layer. Fatigue experiments were carried out and the growth of fatigue cracks at the fastener hole in one of the metallic layers was monitored optically during cyclic loading. The influence of the fatigue cracks of increasing size on the scattered guided wave field was evaluated. The sensitivity and repeatability of the high frequency guided wave modes to detect and monitor the fatigue crack growth was investigated, using both standard pulse-echo equipment and a laser interferometer. The potential for hidden fatigue crack growth monitoring at critical and difficult to access fastener locations from a stand-off distance was ascertained. The robustness of the methodology for practical in-situ ultrasonic monitoring of fatigue crack growth was discussed.

9438-60, Session 13A

On propagation of shock waves generated under hypervelocity impact (HVI) and application to characterizing orbital debris-induced damage in space vehicles

Menglong Liu, Zhongqing Su, The Hong Kong Polytechnic Univ. (Hong Kong, China)

The propagation characteristics of shock waves generated under hypervelocity impact (HVI) (an impact velocity leading to the case that inertial stresses outweigh the material strength, usually on the order over 1 km/s) and guided by plate-like structures were interrogated. A numerical modeling approach, based on the Smoothed-Particle Hydrodynamics (SPH) algorithm, was developed, to scrutinize HVI scenarios in which a series of aluminum plates, 1.5-mm, 3-mm and 5-mm in thickness, was considered to be impacted by an aluminum sphere, 3.2-mm in diameter, at an initial velocity of 2490 m/s, 3050 m/s and 3100 m/s, respectively. The meshless nature of SPH algorithm circumvented the inefficiency and inaccuracy in simulating large structural distortion associated with HVI when traditional finite element methods used. The particle density was particularly intensified in order to acquire wave components of higher frequencies. With the developed modeling approach, shock waves generated under concerned HVI scenarios were captured at representative gauging points, and the signals were examined in both time and frequency domains. The simulation results resembled those from earlier experiment, demonstrating a capability of the developed modeling approach in canvassing shock waves under HVI. It has been concluded that in the regions near the impact point, the shock waves propagate with higher velocities than bulk waves; as propagation distance increases, the waves slow down and can be described as fundamental and higher-order symmetric and anti-symmetric plate-guided wave modes, propagating at distinct velocities in different frequency bands. The results will facilitate detection of orbital debris-induced damage in space vehicles.

9438-61, Session 13A

Data fusion for compensation of temperature variations in Lamb-wave based SHM systems

Ziemowit Dworakowski, Lukasz Ambrozinski, Tadeusz Stepinski, AGH Univ. of Science and Technology (Poland)

Temperature variations affect Lamb waves propagation and, therefore, can severely limit their application as baseline for SHM systems. The methods used to handle this problem can be roughly divided into two groups: data driven, e.g. optimal baseline selection (OBS) or signal-driven, e.g. baseline signal stretch (BSS). The OBS techniques use baselines acquired in various ambient conditions and therefore they require a large amount of data storage space. On the other hand, the data-driven methods apply advanced signal processing and need accurate models to compensate for the influence of temperature on signal.

In this paper a new signal-driven method for compensation of these effects will be presented. The approach is based on a fact, that damage affects structures locally while temperature influences it globally. Observation of signal behavior in distinct points of a structure thus allows distinguishing damage from ambient changes. The proposed method will be compared to other signal-driven techniques, e.g. instantaneous-phase-based methods, local-time coherence and data-driven OBS method. Since principle of operation of presented solutions is different, data fusion algorithm may be used to merge all methods into one with increased efficiency.

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9438-62, Session 13A

A distance-domain based localization techniques for acoustic emission sources: a comparative study

Pawel Packo, Krzysztof Grabowski, Mateusz Gawronski, Wieslaw J. Staszewski, Tadeusz Uhl, AGH Univ. of Science and Technology (Poland); Ireneusz Baran, Cracow Univ. of Technology (Poland); Wojciech L. Spychalski, Warsaw Univ. of Technology (Poland); Tribikram Kundu, The Univ. of Arizona (United States)

Acoustic Emission phenomenon is of great importance for analyzing and monitoring health status of critical structural components. In acoustic emission, elastic waves generated by sources propagate through the structure and are acquired by networks of sensors. Ability to accurately locate the event strongly depends on the type of medium (e.g. geometrical features) and material properties, that result in wave signals distortion. These effects manifest themselves particularly in plate structures due to intrinsic dispersive character of Lamb waves.

In this paper there are compared two techniques for acoustic emission source localization in elastic plates – one based on time-domain distance transform and, second – a two-step hybrid technique. A time-distance domain transform approach, transforms the time-domain waveforms into the distance domain by using wavenumber-frequency mapping. The transform reconstructs the source signal removing the distortions resulting from dispersion effects. The method requires an input of approximate material properties and geometrical features of the structure that are relatively easy to estimate prior to measurement. Hence the method is of high practical interest. Subsequently, a two-step hybrid technique, which does not require a priori knowledge of any material parameters, is employed. The method is based on a predefined three-sensors setup, allowing to localize Lamb wave source by calculating angle at which the AE source hits the array. Through comparison of signal strength for a given event, two-step hybrid technique allows for estimation of distance between the source and each sensor. The methods are compared for simulated and experimental signals.

9438-63, Session 13B

Non-classical dissipative model of nonlinear crack-wave interactions used for damage detection

Piotr Kijanka, Pawel Packo, Wieslaw J. Staszewski, Kajetan Dziejach, AGH Univ. of Science and Technology (Poland)

The last few decades have seen a significant increase in research interest related to nonlinearities in micro-cracked and cracked solids. As a result, a number of different nonlinear acoustic methods have been developed for damage detection. The paper investigates nonlinear crack-wave interactions used for damage detection in plate-like structures. Semi-analytical modelling is used to investigate wave propagation in the vicinity of the crack. The focus is on non-classical dissipative crack model leading to wave modulations. Various physical phenomena and numerical discrepancies associated with these modulations are investigated. The work presented can be used for better understanding of nonlinear crack-wave interactions that are used for damage detection in structural health monitoring applications.

9438-64, Session 13B

Perturbation approach to dispersion curves calculation for nonlinear Lamb waves

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Analysis of elastic wave propagation in nonlinear media has gained recent research attention due to the recognition of their amplitude-dependent wave behavior. This creates opportunities for increased accuracy of damage detection and localization, development of new structural monitoring strategies, and design of new structures with desirable acoustic behavior (e.g., amplitude-dependent frequency bandgaps, wave beaming, and filtering). This differs from more traditional nonlinear analysis approaches which target the prediction of higher harmonic growth. Of particular interest in this work is the analysis of amplitude-dependent shifts in Lamb wave dispersion curves. Typically, dispersion curves are calculated for nominal linear material parameters and geometrical features of a waveguide, even when the constitutive law is nonlinear. Instead, this work employs a Lindstedt-Poincaré perturbation approach to calculate amplitude-dependent dispersion curves, and shifts thereof, for nonlinearly-elastic plates. As a result, a set of first order corrections to frequency (or equivalently wavenumber) are calculated. These corrections yield significant amplitude dependence in the spectral characteristics of the calculated waves, especially for high frequency waves, which differs fundamentally from linear analyses. Numerical simulations confirm the analytical shifts predicted. Recognition of this amplitude-dependence in Lamb wave dispersion may suggest, among other things, that the analysis of guided wave propagation phenomena within a fully nonlinear framework needs to revisit mode-mode energy flux and higher harmonics generation conditions.

9438-65, Session 13B

Detection of structural micro-cracks from macro-scale response: a validation on 3D printed parts

Sonjoy Das, Sourish Chakravarty, Chi Zhou, Univ. at Buffalo (United States)

Micro-cracks (length ~10-100 microns) are difficult to detect in macro-scale structures (length ~10-100 m) by visual inspection. Such micro-cracks, if left undetected, can potentially coalesce into macro-cracks under fatigue loading and eventually result in catastrophic failures. In a recent work by Das & Chakravarty (also presented in SPIE NDE 2014), a probabilistic multi-scale computational scheme has been proposed to identify micro-cracks and the associated weakened (due to the presence of micro-cracks) macro-scale constitutive properties. The core concept is an inverse analysis that heavily relies on preprocessed statistics from stochastic analyses and matrix-valued bounds on macro-scale constitutive properties determined from micromechanical analyses. In the current work, we validate this damage detection scheme. For validation, it is vital to engineer the micro-cracks of desired shape, size and location within a representative macro-scale body. This challenging task is achieved by fabricating ASTM test samples from cured resin using 3D printing, which allows us to introduce micro-cracks at some locations in the macro-scale sample (gage length ~30 mm). The locations of these micro-cracks will be unknown to the damage detection scheme. Only the experimental measurements of displacements and strains (at the macro-scale) on this test specimen will be input to the inverse analysis scheme referred above. Preliminary tests on healthy specimens indicate a nonlinear elastic constitutive relationship, which is additionally accounted for in our damage detection scheme. We extend our previous linear elasticity based detection scheme to account for nonlinear elasticity with finite deformation and finally validate the scheme with experimental

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observations on 3d printed parts. The core outcome of this work is relevant in structural health monitoring of a broad range of materials.

9438-66, Session 13B

Ultrasonic structural health monitoring of brass

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Methods developed for monitoring of the mechanical properties including the relation between stress and strain by ultrasonic waves are presented. Applications to brass are demonstrated. The feasibility, limitations and advantages of the developed methods are discussed. Details of the involved coupling mechanisms including the theoretical background and underlying basic physics are presented including results of modeling and established theoretical schemes.

9438-68, Session 14A

Lamb wave propagation in vibrating structures for effective health monitoring

Xubin Lu, Chee Kiong Soh, Panduranga Vittal Avvari, Nanyang Technological Univ. (Singapore)

Lamb wave based Structural Health Monitoring (SHM) has received much attention during the past decades for its broad coverage and high sensitivity to damage. Lamb waves can be used to locate and quantify damage in static structures successfully. Nonetheless, structures are usually subjected to various external vibrations or oscillations. Not many studies are reported in the literature concerning the damage detecting ability of Lamb wave in oscillating structures which turns out to be a pivotal issue in the practical application of the SHM technique. For this reason, the propagating capability of Lamb waves in a vibrating thin aluminum plate is examined experimentally in this study. Two circular shaped piezoelectric wafer active transducers are surface-bonded on the aluminum plate where one acted as an actuator and another as a sensor. An arbitrary waveform generator is connected to the actuator for the generation of a windowed tone burst on the aluminum plate. An oscilloscope is connected to the sensor for receiving the traveled waves. An external shaker is used to generate out-of-plane external vibration on the plate structure. Time of flight (TOF) is a crucial parameter in most Lamb wave based SHM studies, which measures wave traveling time from the actuator to sensor. In the present study the influence of the external vibrations on the TOF is investigated. Experiments are performed under different boundary conditions of the plate, such as free-free, simply supported and fixed by gluing. The effects of external vibrations in the frequency range between 10 Hz to 1000 Hz are analyzed. Comparisons are carried out between the resulting Lamb wave signals from the vibrating plate for different boundary conditions. Experimental results show that the external vibration effects should not be neglected when applying Lamb wave based SHM.

9438-69, Session 14A

Semi-analytical modelling of piezoelectric excitation of guided waves

Michal K. Kalkowski, Emiliano Rustighi, Timothy P. Waters, Univ. of Southampton (United Kingdom)

Piezoelectric actuators and sensors are a key component of modern structural health monitoring systems and play a significant role in many other areas involving dynamic interaction with the structure such as energy harvesting, active control, or removal of surface accretions using structural waves. In this paper we present a wave-based technique for modelling waveguides equipped with piezo actuators in which there is no need for

common simplifications regarding their dynamic behaviour. The proposed approach is based the semi-analytical finite element (SAFE) method. We developed a new piezoelectric element and employed the analytical wave approach to model the distributed electric excitation and scattering of the waves at discontinuities. The methodology is capable of representing the high frequency behaviour and unlike other approaches is not bound by the assumptions on the deformation and dynamics of the actuator, the interaction with the waveguide or the bonding conditions. Moreover, thanks to the generality of the SAFE formulation it enables simulating the piezo-actuation in waveguides of an arbitrary cross-section. In the paper we present the derivation of the piezoelectric SAFE element and the mathematical outlines for calculation of the response to a distributed voltage excitation. We assemble an illustrative model in the wave domain using the so called analytical wave approach. Finally, we validate the model against an experiment on a beam-like waveguide with emulated anechoic terminations.

9438-70, Session 14A

A haptic approach for structural health monitoring decision-making

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Haptics is the field at the interface of human touch and classification, whereby tactile feedback is used to train and inform a decision-making process. In structural health monitoring (SHM) applications, haptic devices have been introduced and applied in a simplified laboratory scale scenario, in which nonlinearity, representing the presence of damage, was encoded into a vibratory manual interface. In this paper, the "spirit" of haptics is adopted, but here ultrasonic guided wave scattering information is transformed into audio (rather than tactile) range signals. After sufficient training, the structural damage condition, including occurrence and location, can be identified through the encoded audio waveforms. Different algorithms are employed in this paper to generate the transformed audio signals and the performance of each encoding algorithms is compared, and also compared with standard machine learning classifiers. In the long run, the haptic decision-making is aiming to detect and classify structural damages in a more rigorous environment, and approaching a baseline-free fashion with embedded temperature compensation.

9438-71, Session 14A

Development of vibro haptic interface for assessing structural impacts and damage

Hwee Kwon Jung, Gyuhae Park, Myung Jun Lee, Chonnam National Univ. (Korea, Republic of); Chan Yik Park, Agency for Defense Development (Korea, Republic of)

This paper presents development of haptic interface for detecting structural impacts and assessing subsequent damage with application to aerospace structures. The goal of this research is that, with the use of a vibro-haptic interface, human pilots are able to "feel" wings' structural responses (impact, shape changes, damage) and eventually determining the operational and health conditions of airplane wings as if they are extensions of pilot's own body. Both hardware and software components are being developed for the haptic interface. First, L-shape piezoelectric sensor arrays are deployed to measure the acoustic emission data caused by impacts to a wing. Unique haptic signals are then generated after processing the measured acoustic emission data, which are wirelessly transmitted to human arm, and create appropriate vibration to capitalize on the sense of touch of human beings. Our experimental results demonstrate that human could detect and localize impact event by using only haptic interface. Several important aspects of this study, including development of haptic interfaces, design of optimal human training strategies, and extension of the haptic capability into structural damage detection are summarized in this paper.

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9438-82, Session 14A

Assessment of accumulated fatigue damage and remaining life prediction using acoustic emission fiber-optic sensors

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Acoustic emission is a popular technique for monitoring fatigue damage. Piezoelectric sensors are typically used to acquire acoustic emission waveforms. Although piezoelectric sensors enjoy considerable sensitivity and broad bandwidth, they are relatively bulky and require involved wiring when used in large numbers. In this work, we focus on use of fiber-optic sensors to collect acoustic emission data. Advantages of utilizing fiber-optic sensors include low profile and mass of sensors, multiple sensors on a single wire, electro-magnetic immunity and ability to simultaneously acquire temperature data. We demonstrate application of the fiber-optic sensors for assessment of fatigue damage in aluminum alloy specimen subjected to harmonic load. Experimental efforts are coupled with theoretical development of a damage accumulative model that quantifies structural damage and predicts remaining useful life based on parameters of elastic waves.

9438-72, Session 14B

Dual-frequency super harmonic imaging piezoelectric transducers for transrectal ultrasound

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Contrast-enhanced ultrasound imaging has shown its potential in prostate cancer assessment, since it can efficiently detect micro-vessel (vasa vasorum) density change around the growing tumor. However, the main challenge of this imaging method to date has been the lack of available dual-frequency transducers for transrectal ultrasound application. In this paper, a 2/14 MHz dual frequency transducer was developed as a prostate scanner. The 1-3 piezoelectric composite was used as an active material of both transmitter and receiver due to its low acoustic impedance and high coupling factor. The sandwich structure of dual-frequency transducers was designed using Krimholtz-Leedom-Matthaei (KLM) model and finite element analysis (FEA). The low transmitting frequency was designed as 2 MHz considering the resonant frequency of microbubbles and their distribution. The high receiving frequency was designated as 14 MHz, which is 7th harmonic of the transmitting frequency. The peak-negative pressure and bubble response were tested, and contrast imaging was conducted in vitro using a tissue-mimicking phantom made of graphite-gelatin. The prototype dual frequency transducer showed the -6 dB bandwidth of 61 % for the transmitter, and 45 % for the receiver. The peak negative pressure at the far field was about -1.6 MPa, which is high enough to excite microbubbles for nonlinear responses with 300 Vpp, 2-cycle 2 MHz bursts. The 7th harmonic responses from microbubbles were successfully detected in the phantom imaging test. The developed dual-frequency transducer is promising for super-harmonic contrast enhanced transrectal imaging.

9438-73, Session 14B

Characterization of fungal pathogenesis using quantitative acoustic contrast tomography

Sourav Banerjee, Subir Patra, Anindya Chanda, Univ. of South Carolina (United States)

Due to change in climates, increased number of hurricanes caused increased number of flooded buildings across the coastal region of USA. In turn they have become the breathing ground of wild type marine fungi that produce detrimental toxins. Fungal growth on damp building materials leads to spore contamination of indoor air causing several fatal respiratory and neurological illnesses in immunocompromised patients, children and the elderly. United States experiences approximately 5 million cases of asthma that occurs due to dampness and mold problems in buildings leading to a total healthcare cost of approximately \$3.5 billion. Mycotoxins, which is a group of natural toxin (secondary metabolites) synthesized by few pathogenic fungi, is a critical health and economic challenge in the US and in rest of the world. The mycotoxin management cost in US agriculture is in the range of \$1.3 to 2.5 billion annually. It is estimated that children in the rural areas of southern US ingest ~40µg aflatoxin (a carcinogenic mycotoxin) through contaminated food every day that can lead to a significant rise in aflatoxin-induced liver cancer cases. However, there is no method to quickly characterize the fungi to find if they are the potentially harmful pathogens. It is hypothesized that pathogenesis is correlated with the mechanochemical landscaping and the structural configuration of the fungi. Here in this paper we present quantitative acoustic contrast tomography (QACT) specially for characterizing fungi to quantify the pathogenesis.

9438-74, Session 14B

Thermography in the investigation of the inflammation inside the human muscle

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Unaccustomed eccentric exercise is associated with muscle damage, which is evidenced by a number of events that are manifested for several days after the initial muscle injury. Inflammation occurs due to eccentric exercise and plays a critical role in the degeneration and regeneration of the damaged muscle by triggering the acute phase response of the immune system and the removal of the damaged muscle tissue. The aim of this work was to investigate the potential of imprinting the intensity of the produced inflammation inside the muscle using infrared thermography. For this reason, both males and females (20-30 year old) participated in the study. Thermographic images of the rectus femoris muscle were taken before, as well as 24, 48 and 72 hours immediately after an acute bout of eccentric exercise (5 sets of 15 maximum repetitions). Eccentric exercise was performed with the one lower extremity, whereas the other lower extremity served as control.

9438-75, Session 14B

Application of structural health monitoring technologies to biosystems: current status and path forward

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This article aims to share a vision on potential future applications of smart

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materials in the fields of bio-mechanics and bio-medicine. It reviews the current status of the ongoing research and presents an overview of the potential future applications of the smart materials and related technologies to bio-medical systems and bio-mechanical processes. Over the last two and half decades, smart materials such as piezoelectric transducers, shape memory alloys and fibre optic sensors have found numerous applications in the fields of infrastructure and mechanical systems monitoring, popularly called the field of structural health monitoring (SHM). Now, they are being increasingly researched (and in some cases already applied) for bio-medical and related applications, such as opening blocked arteries, foot pressure monitoring, healing of bone after fracture, pulse monitoring and several other related processes. These have huge potential benefits for people suffering from ailments such as heart disease, osteoporosis and diabetes. This field of research is highly interdisciplinary and has attracted researchers from across disciplines such as electronics, medicine and engineering. Possible potential applications include energy harvesting from walking and heart beat, monitoring of muscular processes and monitoring functioning of organs. The recent developments in the area of microelectronics and inter digital transducers are likely to accelerate the ongoing research. This paper envisions potential future applications of these materials in this interdisciplinary area of research and possible pros and cons of the technology.

9438-76, Session 14B

On the repeatability of the EMI technique for the health monitoring of bonded elements

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Pervincenzo Rizzo, Univ. of Pittsburgh (United States);
Alberto Milazzo, Univ. degli Studi di Palermo (Italy)

We study the feasibility and the repeatability of the electromechanical impedance (EMI) method for the health monitoring of lightweight bonded joints. The EMI technique exploits the coupling between the displacement field and the potential field of a piezoelectric material, by attaching or embedding a piezoelectric transducer to the structure to be monitored. The sensor is excited by an external voltage and the electrical admittance which is the ratio between the electric current and the applied voltage is measured as it depends on the mechanical coupling between the transducer and the host structure. Owing to this interaction, the admittance may represent a signature for the health of the host structure. In this study the EMI method is applied to aluminum joints adhesively bonded. We investigate the repeatability of the proposed method by monitoring the same aluminum components bonded many times using the same adhesive mix, and then by monitoring the same two components bonded several times by means of different adhesive qualities. The results demonstrate that the EMI is repeatable and variations in the admittance signatures are related to the quality (health) of the bond.

Conference 9439: Smart Materials and Nondestructive Evaluation for Energy Systems

Monday - Tuesday 9 -10 March 2015

Part of Proceedings of SPIE Vol. 9439 Smart Materials and Nondestructive Evaluation for Energy Systems 2015

9439-1, Session Key

Needs and opportunities: nondestructive evaluation for energy systems (*Keynote Presentation*)

Leonard J. Bond, Iowa State Univ. (United States)

Advanced manufacturing and new energy systems are presenting new challenges for nondestructive testing and evaluation (NDT/NDE). This talk will discuss the state of the art, needs and opportunities for NDE to provide reliable, effective and economic inspection and monitoring for energy systems. Examples to be discussed will include wind turbine blades and systems for structural health monitoring (SHM), NDE for advanced nuclear, where inspection needs to be performed at high temperatures and in harsh environments (i.e. ~ 250C, gamma radiation and operating in liquid sodium), and parts fabricated using additive manufacturing and powder metals.

9439-2, Session 1

Investigation of UT inspection approach for primary piping welds of Chinese evolutionary pressurized reactor nuclear power plant

Weiqiang Wang, Huaidong Chen, Guanbing Ma, Maocheng Hong, Ming Li, Jinhong Liu, CGNPC Inspection Technology Co. Ltd. (China); Norbert G. Meyendorf, Fraunhofer IKTS-MD (Germany)

Abstract?The three main barriers in a pressurized water reactor to prevent nuclear leakage accident are the fuel cladding, the primary coolant boundary and the concrete containment building. The main coolant line (MCL) is one of the most important parts of the primary coolant boundary and it is the key factor for the reactor safety. The main coolant lines of Chinese Evolutionary Pressurized Reactor (CEPR) are made from forged austenitic stainless steel, and automatic narrow gap TIG welding is used in the welding process of 44 MCL welds. Maintaining the structural integrity of the MCL welds is essential to the safe operation of a CEPR plant. Ultrasonic testing (UT) is used for implementing volumetric inspections of the MCL according to the RSE-M 2010 code. The difficulties in examining are mainly caused by austenitic coarse grain structure and limited access space. This paper discusses developments and results of automatic inspection system for detection the MCL welds with different geometries and diameters.

9439-3, Session 1

Phased array ultrasonic testing of dissimilar metal welds using geometric based referencing delay law technique

Tae Young Han, Norbert G. Meyendorf, Kyoung Hee Kim, Frank Schubert, Martin Barth, Andreas Brusinsky, Fraunhofer IKTS-MD (Germany)

Phased array ultrasonic testing (PAUT) techniques are widely used for the non-destructive testing (NDT) of austenitic welds to find defects like cracks. However, the propagation of ultrasound waves through the austenitic material is intricate due to its inhomogeneous and anisotropic nature. Such

a characteristic leads beam path distorted which causes the signal to be misinterpreted. By employing a reference block which is cutout from the mockup of which the structure is a dissimilar metal weld (DMW), a new method of PAUT named as Referencing Delay Law Technique (RDLT) is introduced. With the RDLT, full matrix capture (FMC) was used for data acquisition. To reconstruct the images, total focusing method (TFM) was used. After the focal laws were calculated, PAUT was then performed. As a result, the flaws are more precisely positioned with significantly increased signal-to-noise ratio (SNR).

9439-4, Session 2

Nondestructive evaluation of thick concrete structures

Dwight A. Clayton, Oak Ridge National Lab. (United States)

Materials issues are a key concern for the existing nuclear reactor fleet as material degradation can lead to increased maintenance, increased downtime, and increased risk. Extending reactor life to 60 years and beyond will likely increase susceptibility and severity of known forms of degradation. New mechanisms of materials degradation are also possible. A multitude of concrete-based structures are typically part of a light water reactor (LWR) plant to provide foundation, support, shielding, and containment functions. Concrete has been used in the construction of nuclear power plants (NPPs) due to three primary properties; its low cost, structural strength, and ability to shield radiation. Examples of concrete structures important to the safety of LWR plants include the containment building, spent fuel pool, and cooling towers. Use in these structures has made concrete's long-term performance crucial for the safe operation of commercial NPPs. This creates the need to be able to nondestructively evaluate the current subsurface concrete condition of aging concrete material in NPP containment structures.

The size and complexity of NPP containment structures and heterogeneity of Portland cement concrete make characterization of the degradation extent a difficult task. Unlike most metallic materials, reinforced concrete is a composite with a relatively low density matrix, a mixture of Portland cement, fine aggregate or sand, aggregate, water, admixtures, and a high density reinforcement (typically 5 percent in NPP containment structures), made up of steel rebar or tendons. NPPs have been typically built with local cement and aggregate fulfilling the design specifications regarding strength, workability, and durability, but as a consequence each plant's concrete composition is unique and complex.

Specially designed and fabricated test specimens can provide realistic flaws that are similar to actual flaws in terms of how they interact with a particular nondestructive evaluation (NDE) technique. Artificial test blocks allow the isolation of certain testing problems as well as the variation of certain parameters. Due to the controlled conditions in the laboratory, the number of unknown variables can be decreased, making it possible to focus on specific aspects, investigate them in detail, and gain further information on the capabilities and limitations of the methods. To minimize artifacts caused by boundary effects, the dimensions of the specimens should not be too compact. Representative large heavily reinforced concrete specimens would allow for comparative testing to evaluate the state-of-the-art in NDE in this area and to identify additional developments necessary to address the challenges potentially found in NPPs. This paper describes the design and fabrication of such; a thick specimen that is representative of structures in NPPs. Preliminary ultrasonic linear array NDE results are also presented.

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9439-5, Session 2

Impact damage assessment of high pressure cylindrical composite structures by energy based acoustic emission analysis

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Acoustic emission technology (AET) have been used for the structural health monitoring of large structures such as pressure vessel, civil structures, and aerospace structures. Especially, comparing to other nondestructive testing technology, it is one of the most powerful techniques being able to detect damages and to identify damage location during operations. In this study, in order to assess the location and the degree of damage by external impact in the high pressure cylindrical composite structures, we have used a new source location algorithm which is based on the acoustic emission energy contour map. This measurement of energy distribution in the composite materials is much better than conventional time arrival difference method in its detectability point of view. It was found that acoustic emission signal energy was much affected by its type of source and its path of wave propagation. This kind of database for signal energy provides valuable information for assessing the degree of damages of tested specimen. This study describes the new concept of source location and damage assessment, and discusses how they can be verified for the exact source location and for the degree of impact damage of cylindrical composite structures. That is, the location and the degree of damages were obtained by measuring the distance between source and sensor as well as its signal energy. From experimental results, the proposed new energy based AE analysis is verified for assessing the impact damage in cylindrical CFRP composite structure.

9439-6, Session 2

Effect of spatial frequency components of surface roughness on ultrasonic reflection

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Ultrasonic NDE is widely used for inspection in power generation industries. For this technique, understanding the elastic wave reflections from cracks is one of the fundamental building blocks with which one can detect the existence of cracks and locate them. When a crack surface is rough, it is known that its detectability decreases in the specular direction and increases in the other directions, since the incident wave is scattered more widely at the crack surface than it is at a smoother surface. However, the nature of the reflections from rough surfaces is still difficult to investigate compared with the case of a smooth crack, due to experimental and computational limitations. In this paper, the relation between the spatial frequency range of a rough surface and ultrasonic reflection is investigated. Rough surfaces are created with different surface-generation methods, and ultrasonic propagation and reflections are simulated using finite element procedure. The characteristics of the reflected waves are discussed in relation with the spatial frequency ranges of the rough surfaces.

9439-7, Session 2

The investigation about the ultrasonic inspection of RPV safe end dissimilar metal weld

Tianming Lv, Ming Li, Jinhong Liu, Huaidong Chen, Zhe

Yu, Chenxu Hu, CGNPC Inspection Technology Co. Ltd. (China); Norbert G. Meyendorf, Fraunhofer IKTS-MD (Germany)

Abstract: Ultrasonic inspection of reactor pressure vessel (RPV) safe end dissimilar metal welds is an challenging task because of the exist of cladding and austenitic coarse grain and complicated geometry of dissimilar metal welds. In order to improve the reliability and efficiency of ultrasonic inspection of safe end dissimilar metal welds, the conventional dual elements longitudinal wave (TRL) inspection technology and phased array (PA) inspection technology has been investigated. The results of examination indicated that TRL and PA inspection technology could detect the defects of dissimilar metal welds effectively, and the precision of defects sizing met the requirements of related rules. Thereinto, TRL inspection technology has been applied to the pre-service and in-service inspection of nuclear power plant; the accuracy of defect sizing and efficiency of PA inspection technology was better than that of TRL inspection technology.

9439-8, Session 2

Residual stresses evaluation in the inner and outer surface of a dissimilar welded pipe by using finite element and ultrasonic method

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This study investigates ultrasonic-stress-measurement in a dissimilar welded pipe made from TP-304 stainless steel and A106 carbon steel. The welding residual stresses are evaluated in the inner and outer surfaces of the pipe by using ultrasonic-stress-measurement, which is based on the acoustoelasticity law. Longitudinal critically refracted (LCR) waves, ultrasonic waves capable of propagating parallel the material surface in a predetermined penetration depth, are employed for stress measurement. By employing four different series of the ultrasonic probes (1 MHz, 2 MHz, 4 MHz and 5 MHz), penetrating in four different depths of the pipe would be practical leading to evaluation of sub-surface residual stresses from the outer to the inner surface of the pipe. A finite element (FE) model of the welding process is also used to verify the ultrasonic-stress-measurement results. By combination of the FE and the LCR method (known as the FELCR method), a comprehensive distribution of the welding residual stress is achieved. It has been concluded that the residual stresses could be accurately evaluated by the FELCR method in the inner and outer surface of a dissimilar welded pipe.

9439-9, Session 3

MEMS inertial sensors for load monitoring of wind turbine blades

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Structural load monitoring of wind turbines is becoming increasingly important due to two current trends in the wind industry: offshore deployment and increasing turbine size. Rotor blades are a key component for structural monitoring. Wind turbine blades experience substantial deflections during operation due to their length and relatively flexible structure. Continuous monitoring of the blade deformation can reduce the risk of damage and unanticipated failures. Precise knowledge of the blade deformation can be used in variety of ways. Modal analysis can be applied to the deformation shapes to detect damage to the blades, and information about the maximum deflection can be fed back into the design process. Furthermore, the deflection may be used to determine strain and loads on the blades for operational load monitoring and control.

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The method investigated here for monitoring blade deformation utilizes a multi-sensor approach based on micro-electromechanical systems (MEMS). A complete sensor package includes triaxial accelerometers, gyroscopes and magnetometers, as well as a temperature sensor, all incorporated into a single unit with dimensions of approximately 35 × 35 × 15 mm and a weight of 10 grams. MEMS can be installed as wireless sensors or using wired connections. The small size, light weight and comparatively low cost of MEMS devices allows for the installation of a network of sensors within each blade. Compared to bulk devices, however, MEMS inertial sensors suffer from higher levels of noise and bias and offer lower precision. To address these shortcomings, a filtering algorithm has been applied to the MEMS sensors using the extended Kalman filter and combining the output of magnetometers, accelerometers and gyroscopes into a single value. Sensor orientations are represented using quaternions, which enables more efficient computation and avoids the singularities associated with Euler angles. Fusion of the inertial and magnetic sensor outputs provides more accurate estimation of the sensor orientation than would be achieved using a single measurement. Orientations detected by several distributed sensors are input to a finite element model in order to estimate stress and strain throughout the monitored structure.

The platform used to demonstrate this approach is a cantilever beam instrumented with 5 MEMS sensors and 4 foil strain gauges, which is subjected to an axial bending load. The individual MEMS sensor orientations are fitted to a spline curve to determine the total deformation of the beam. Euler-Bernoulli beam theory and the maximum deflection are used to verify the estimated beam shape. The deformation measured by the MEMS is input to a finite element model of the beam. The finite element model provides a complete estimate of the strain throughout the beam, which is validated by comparison with the strain gauge measurements. Future work will include applying this methodology to a small wind turbine blade under static and dynamic flapwise bending loads.

9439-10, Session 3

Structural damage localization in wind turbine blades based on time series representations

Simon Hoell, Yen-Ting Chen, Piotr Omenzetter, Univ. of Aberdeen (United Kingdom)

The development of large wind turbines that enable to harvest energy more efficiently is a consequence of the increasing demand for renewables in the world. To optimize the potential energy output, light and flexible wind turbine blades (WTBs) are designed. However, the higher flexibilities and lower buckling capacities adversely affect the long-term safety and reliability of WTBs, and thus increasing operation and maintenance costs reduce the expected revenue. Effective structural health monitoring techniques can help to counteract this by limiting inspection efforts and avoid unplanned maintenance actions. Vibration-based methods deserve high attention due to the moderate instrumentation efforts and the applicability for in-service measurements. The present paper proposes the use of cross-correlations (CCs) of acceleration responses between sensors at different locations for structural damage detection and localization (SDDL) in WTBs. CCs were in the past successfully applied for damage detection in numerical and experimental beam structures while utilizing only single lags between the signals. The present approach uses vectors of CC coefficients for multiple lags between measurements of two selected sensors taken from multiple possible combinations of sensors. This is done firstly by statistical hypothesis testing in order to identify the occurrence of damage. Secondly, SDDL is performed with the help of Mahalanobis distances between CC vectors and clustering of the results. The method is applied to realistic numerical simulations of a large WTB with disbanding damage scenarios. Furthermore, experimental validation is performed in the laboratory on a small scale WTB.

9439-11, Session 3

Acoustic emission monitoring of wind turbine blades

Jeremy E. Van Dam, Leonard J. Bond, Iowa State Univ. (United States)

Minimizing operation and maintenance (O&M) costs is important for reducing the overall levelized cost of wind energy. Implementing an online structural health monitoring (OSHM) system can potentially reduce costs by removing the need for physical inspections, increasing efficiency, decreasing downtimes, and converting corrective maintenance to preventative maintenance. One of the causes of failure of wind turbine blades is impact damage. Impact damage has the capability of causing hidden damage that if untreated, can lead to severe and costly failures. Acoustic emission (AE) events are releases of energy within a structure, which often signal defect locations. Passive AE sensing has the capability of detecting impacts and characterizing the severity and evolution of the damage. This paper provides a review of the current OSHM systems (Fiber optics and modal analysis) and the potential use of AE sensing. The two primary benefits of AE detection are its ability to detect different types of defects (crack initiation and propagation, breaking fibers, and matrix cracking and fretting between surfaces at de-bonds or de-laminations) and determine the defect location. Despite the potential benefits of AE sensing, challenges have inhibited its ability for commercial use. AE sensors are sensitive, which allows detection of minor flaws, but also allow for the collection of noise. In order to combat the low signal to noise ratio in field operations, the systems employ thresholds to filter the data. Setting the thresholds correctly is critical to operations, because a low threshold will allow for significant noise/false calls and a high threshold will not allow for more minor or defect detection. Secondly, the paper analyzes the ability of an AE system to detect impact damage and to characterize the acoustic response. The experiments use an AE system with piezoelectric sensors attached to blade segments, which are composed of sheets of glass-fiber reinforced polymer (GFRP) layered in varying directions and glued together using an epoxy resin. The AE system collects the wave energy signals from the impact force and uses wave analysis software to convert the raw data into a recordable and interpretable form. The experimentation reveals different characteristics including distance and modes of travel and frequency range of the energy waveform. The paper will also present a model of the experiment, which shows the method in which the impact energy propagates through the material. Combining experimental data and the physics of the wave contributes to increasing model accuracy. The paper will conclude with a discussion of the results and the correlation between AE waveforms and impact energy leading to tools to estimate the severity of an impact based on the AE data.

9439-12, Session 3

HF eddy current imaging for electrical characterization of solar cells

Henning Heuer, Fraunhofer IKTS-MD (Germany)

Eddy Current imaging with optimized frequency and complex phase rotation is a versatile analysis method that allows inspection of multiple defects located in different layers of mono- and multi-crystalline silicon solar cells. Due to favorable standard penetration depth of doped silicon, Megahertz frequencies assessed quality for electrodes contact and examined defects of bulk and backside. By demonstrating homogeneity of sheet resistance and laser scribing structure, the method also saw the feasibility of new application areas in PV production. Furthermore, the Eddy Current imaging brings up a topic of potential defects which can be eventually breakable during solar cell lifetime. In this connection, reliability testing with the Eddy Current imaging is proposed in order to identify the link between crack development and power degradation.

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9439-13, Session 3

**Pyro-paraelectricity: a new effect in
heterogeneous material architectures**

Huai-An Chin, Princeton Univ. (United States); Sheng Mao, Univ. of Pennsylvania (United States); Bhadrinarayana L. Visweswaran, Princeton Univ. (United States); Kwaku Ohemeng, Department of Chemistry, Princeton Univ. (United States); Sigurd Wagner, Princeton Univ. (United States); Prashant K. Purohit, Univ. of Pennsylvania (United States); Michael C. McAlpine, Princeton Univ. (United States)

Various mechanisms have been studied involving the electrical responses of materials and devices to thermal inputs, including the Seebeck effect and pyroelectricity. However, to our knowledge, methods exploiting heterogeneities in the mechanics of heterostructure materials and systems have not been explored to date as a viable means for investigating thermo-electrical responses. Here, we demonstrate an innovative mechanism which we refer to as "pyro-paraelectricity," for converting thermal power into electricity via such heterogeneous architectures. Specifically, when a metal-insulator-metal (MIM) heterostructure is fabricated with a paraelectric layer as the insulator, high temperature processing and variations in thermal expansion coefficients among the layers lead to a slight bending curvature. This results in induction of bound charges in the paraelectric layer via flexoelectricity, leading to a polarization. The permittivity of the insulating layer, and thus the polarization, change with temperature. Thus, when the MIM heterostructure is subject to a thermal input, changes in permittivity lead to a generated electrical response. Here, we demonstrate this concept of "pyro-paraelectricity" by employing a MIM heterostructure with a high-permittivity (relative permittivity ~ 200) sputtered barium strontium titanate (BST) film as the insulating layer in a platinum sandwich. Paraelectricity in the BST was confirmed from permittivity-temperature and hysteresis measurements. To demonstrate "pyro-paraelectricity," the MIM heterostructure was subjected to a thermal input. Intriguingly, current was generated which was highly correlated to the thermal input. Low-permittivity SiO₂ (relative permittivity ~ 5) was used as a control, which showed a comparatively negligible response. These results provide a proof of concept investigation into this new effect.

9439-35, Session 3

**Electrospinning of strontium titanate
incorporated with nickel oxide
nanoparticles for improved photocatalytic
performances**

Abulaziz Alharbi, Ibrahim M. Alarifi, Waseem S. Khan, Ramazan Asmatulu, Wichita State Univ. (United States)

The sources of fossil fuels in the world are limited, and will deplete very soon because of the huge demand on the energy and growing economies worldwide. Thus, many research activities have been focused on the non-fossil fuel based energy sources, and this will continue next few decades. Water splitting using photocatalysts is one of the major alternative energy technologies to produce hydrogen directly from water using photon energy of the sun. Numerous solid photocatalysts have been used by researchers for water splitting. In the present study, nickel oxide and strontium titanate were chosen as photocatalyst for water splitting. Poly(vinylpyrrolidone) (PVP) was incorporated with nickel oxide [Ni₂O₃] (co-catalyst), while poly (vinyl acetate) (PVAc) was mixed with titanium (IV) isopropoxide [C₁₂H₂₈O₄Ti] and strontium nitrate [Sr(NO₃)₂]. Then, two solutions were electrospun using coaxial electrospinning technique to generate nanoscale fibers incorporated with NiOx nanoparticles. The fibers were then heat treated at elevated temperature for 2hr in order to transform the strontium titanate and nickel oxide in crystalline form for better photocatalytic efficiency. The morphology of fibers was characterized via scanning electron

microscopy (SEM), while the structure of the nanofibers was verified by XRD analysis. The UV spectrophotometer was also used to determine the band gap energy values of the nanofibers. The test results may be useful for many energy companies producing hydrogen and other alternative energies.

9439-14, Session Key

**Advanced ceramics for energy for energy
systems (Keynote Presentation)**

Alexander Michaelis, Fraunhofer-IKTS CMD (Germany)

Advanced ceramic materials offer enormous potential for innovations in the fields of efficient energy conversion and storage as well as environmental technology. The joint application of structural and functional ceramic technology allows for unique combination of electronic, ionic (electrochemical) and mechanical properties enabling the development of new, highly integrated systems. We present specific examples for Fuel Cell, Li-Ion and high temperature Na-metal batteries as well as ceramic membrane systems development.

As a first example, high temperature fuel cell systems development for both mobile and stationary applications are presented. In the power range from 1 W to several 10 kW we use SOFC (solid oxide fuel cell) technology, for the high power range up to several MW we prefer MCFC (molten carbonate fuel cell) technology. Both fuel cell types use conventional hydrocarbon fuels and are currently being commercialized.

Using related ceramic technology platforms we also develop energy storage systems in different power ranges. Examples for fabrication of Li-Ion batteries as well as high temperature NaNiCl batteries are presented. The production of both, power generation and storage systems require new approaches for non-destructive in line testing methods which are discussed as well.

For illustration of the potential of advanced ceramic materials in environmental technology, ceramic membrane systems are discussed. Ceramic membranes can be used for micro-, ultra- or nano- filtration of liquids. Further innovations require an improved control and reduction of pore size. This allows for new applications in gas separation and pervaporation systems. For this, pores sizes below 1 nm have to be generated using specific structural features of selected materials. Several new methods for preparation and non destructive testing of such membranes are presented.

9439-15, Session 4

**High-performance porous carbon/CeO₂
nanoparticles hybrid super-capacitors for
energy storage**

Mohammad Arif I. Shuvo, Hasanul Karim, Gerardo Rodriguez, The Univ. of Texas at El Paso (United States); Manjula I. Nandasiri, Ashleigh M. Schwarz, Arun Devraj, Pacific Northwest National Lab. (United States); Yirong Lin, The Univ. of Texas at El Paso (United States); Murugesan Vijayakumar, Pacific Northwest National Lab. (United States); Md T Islam, University of Texas at El Paso (United States) and Univ of Texas at El Paso (United States); Juan C Noveron, University of Texas at El Paso (United States)

Increasing demand for energy storage devices has propelled researchers for developing efficient super-capacitors (SC) with long cycle life and ultrahigh energy density. Carbon-based materials are commonly used as electrode materials for SC. Herein we report a new approach to improve the SC performance utilizing porous carbon (PC)/CeO₂ nanoparticles (NPs) hybrid as electrode material synthesized via low temperature hydrothermal method and a new type of ionic liquid as electrolyte. Through this approach,

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charges can be stored not only via electrochemical double layer capacitance (EDLC) from PC but also through pseudo-capacitive effect from CeO₂ NPs. The excellent electrode-electrolyte interaction due to the electrochemical properties of the ionic electrolyte provides a better voltage window for the SC. Transmission Electron Microscopy (TEM), X-Ray Diffraction (XRD) and X-ray Photoelectron Spectroscopy (XPS) measurements were used for the initial characterization of this PC/CeO₂ NPs hybrid material system. Electrochemical measurements of SCs will be performed using a potentiogalvanostat.

9439-16, Session 4

Porous carbon/CeO₂ composites for Li-ion battery application

Hasanul Karim, Mohammad Arif I. Shuvo, Gerardo Rodriguez, Yirong Lin, The Univ. of Texas at El Paso (United States); Manjula I. Nandasiri, Ashleigh M. Schwarz, Arun Devaraj, Murugesan Vijayakumar, Pacific Northwest National Lab. (United States); Md Tariqul Islam, Juan C Noveron, Armando Sandoval, University of Texas at El Paso (United States)

Development of new materials hold the key to the fundamental progress in energy storage systems such as Li-ion battery, which is widely used in modern technologies because of their high energy density and extended cycle life. Among these materials, porous carbon is of particular interest because it provides high lithiation and excellent cycling capability by shortening the transport length for Li⁺ ions with large electrode/electrolyte interface. It has also been demonstrated that transition metal oxide nanoparticle can enhance surface electrochemical reactivity and increase the capacity retention capability for higher number of cycles. Here we investigate porous carbon/ceria (CeO₂) nanoparticles composites as an anode material. The high redox potential of ceria is expected to provide a higher potential window as well as increase the specific capacity and energy density of the system. Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD) and X-Ray Photoelectron Spectroscopy (XPS) will be used for material characterization; while battery analyzer and potentiogalvanostat will be used for measuring the electrical performance of the battery.

9439-17, Session 4

Applications of nano and smart materials in renewable energy production and storage devices

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

This paper presents development of renewable energy production and storage devices employing nanomaterials and smart materials. The use of carbon nanotubes (CNTs) and graphene nanosheets (GNS) to improve the performance and durability of wind turbine and wave rotor blades will be explained. While GNS are primary used for the performance enhancement of the resin system [1-2] called nanoresin, CNT nanoforests and nanofilms [3-6] are used to improve the performance of fiber systems in high-performance composites. In addition, the use of CNTs and piezo-nanofibers will be explained as the health monitoring and smart systems within the composites. A self-healing mechanism will also be explained within the composites using these materials. Next the use of CNTs as gas diffusion layers and CNTs combined with in-situ generated platinum nanoparticles as catalyst layers will be explained to improve the performance, efficiency, and durability of proton exchange membrane fuel cells while reducing their costs, weight, and size [7-8]. In addition, the use of CNTs and GNSs to improve the efficiency and performance of polymer solar cells will be explained. Finally, the use of CNTs and GNSs to enhance the performance, efficiency, and durability of batteries and supercapacitors while reducing

their costs, weight, and size will be explained.

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9439-19, Session 5

Using aeroelastic structures with nonlinear switching electronics to increase potential energy yield in airflow: Investigating analog control circuitry for automated peak detection

Alexander Mihalca, Jonathan Drosinos, Malika Grayson, Ephraim Garcia, Cornell Univ. (United States)

Piezoelectric power harvesters continue to be modeled based on specific geometric and material properties for the purpose of performance prediction in a given application. These harvesters have the ability to harness energy from the local environment, especially in untapped wind energy sources such as in the urban environments over civil infrastructure. By employing piezoelectric structures such as a small flapping mechanism, aeroelastically-induced vibrations generated over a range of velocities can be manipulated to extract power from the airflow. Therefore, this study aims to further investigate the increase in potential energy yield in the flow using aeroelastic structures and nonlinear switching devices, particularly Synchronized Switching and Discharging to a Storage Capacitor (SSDCI). Using the piezoelectric composite device as a transducer, the vibration of the flapping mechanism can be converted into storable electrical energy. Non-linear switching circuits are used to enhance the efficiency of the device, maximizing the power extracted from the airflow during aerodynamic oscillations. Given an optimal resistive load, the extracted power is expected to be quadrupled, maximizing the energy transferred across the circuit. Currently, wind tunnel experiments are being conducted over a wide range of wind speeds to measure the flutter vibrations of the flapping mechanism as a function of velocity. Additionally, a combined model using the existing electromechanical models for the aeroelastic system and models for switching electronics are being developed and it is expected that analysis of the data will validate and support the findings presented.

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9439-20, Session 5

Acoustic signatures of different damage modes in plain and repaired marble and granite specimens

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In construction sector marble and granite are widespread because of their unique properties through the centuries. The issue of repair in these materials is crucial in structural integrity and maintenance of the monuments through the world, as well as in modern buildings. In this study fracture experiments on different types of marble and granite specimens are conducted. The goal is to compare the typical acoustic emission (AE) signals from different modes (namely bending and shear) in plain granite and marble specimens as well as repaired in the crack surface with polyester adhesive.

This is an advancement of a recent study focusing on mortar and marble specimens, which shows that AE leads to characterization of the dominant fracture mode using a simple analysis with few AE descriptors. The distinct signature of the cracking modes is reflected on acoustic waveform parameters like the amplitude, rise time and frequency. Conclusions about how the repair affects the mechanical properties as well as the acoustic waveform parameters, are drawn. Results show that AE helps to characterize the shift between dominant fracture modes using a simple analysis of AE descriptors as well as the integrity of the specimen (difference between plain and repaired). This offers the potential for in-situ application mainly in the maintenance of the monuments where the need for continuous and nondestructive monitoring is imperative, but always care should be taken for the distortion of the signal, which increases with the propagation distance and can seriously mask the results in an actual case.

9439-21, Session 5

Ultrasonic thickness structural health monitoring photoelastic visualization and measurement accuracy for internal pipe corrosion

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Oil refinery production of high quality clean fuels is becoming more challenging as a result of the changing world supply of crude oil towards properties of higher density, higher sulfur concentration, and higher acidity. One such production challenge is an increased risk of corrosion from crudes with a high concentration of organic naphthenic acids. The rate of naphthenic acid corrosion is considered to be dependent on metallurgy, acid species, acid concentration, sulfur concentration, process temperature, shear stress, and the extent of a gas phase resulting in a corrosion rate that is difficult to predict. The degradation morphology of naphthenic acid corrosion can vary based on acid concentration, flow rate, and temperature resulting in three damage mechanism surface profiles of uniform corrosion, non-uniform corrosion, and localized pitting at temperatures between 150°C and 400°C; the irregular surface morphology and high surface temperature lead to a challenging in-service monitoring application for precise thickness measurements. Improved corrosion measurement technology is needed to better quantify the integrity risk associated with refining crude oils of higher acid concentration. This paper first identifies and discusses the advantages and disadvantages of potential inspection and structural health monitoring technologies (optic, electromagnetic, radiographic, acoustic, and ultrasonic)

for localized internal corrosion in high temperature steel piping. The paper then describes the specific approach under investigation to apply flexible ultrasonic thin-film piezoelectric transducer arrays fabricated by the sol-gel manufacturing process. Next, a statistical method is presented to quantify thickness measurement accuracy considering the influence of dynamic environmental variables such temperature fluctuations, system degradation, and non-uniform back-wall surface reflections. This method uses a maximum likelihood approach to identify the statistical distribution model (such as a normal distribution, smallest extreme value distribution, largest extreme value distribution, or logistic distribution) as well as the model parameters that best fit a given thickness measurement residual value data set. A 90% confidence measurement accuracy range derived from the best fit distribution model as well as a 90% confidence range derived from the 95% probable fit models are presented analogous to a90 and a90/95 values used within the Probability of Detection inspection community for flaw size detection assessments. Finally, initial experimentation results on steel test pieces of known thickness are presented in an effort to quantify initial measurement accuracy as well as the accuracy influence of various environmental factors over time for multiple time-of-flight thickness calculation algorithm methods such as local maxima method, threshold method, and optimum correlation method in both pulse-echo and pitch-catch sensor configurations. The application of data censoring to account for true thickness uncertainty as well as a few potential sources of outlier thickness data points are also discussed. The final result is an understanding of the expected thickness measurement accuracy in a naphthenic acid corrosion structural health monitoring application for various system design variables and environmental influences.

9439-22, Session 5

Developing a structural health monitoring system for nuclear dry cask storage canister

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Interim storage of spent nuclear fuel from reactor sites has gained additional importance and urgency for resolving waste-management-related technical issues. In total, there are over 1482 dry cask storage system (DCSS) in use at US plants, storing 57,807 fuel assemblies. Nondestructive material condition monitoring is in urgent need and must be integrated into the fuel cycle to quantify the "state of health", and more importantly, to guarantee the safe operation of radioactive waste storage systems (RWSS) during their extended usage period. A state-of-the-art nuclear structural health monitoring (N-SHM) system based on in-situ sensing technologies that monitor material degradation and aging for nuclear spent fuel DCSS and similar structures is being developed. The N-SHM technology uses permanently installed low-profile piezoelectric wafer sensors to perform long-term health monitoring by strategically using a combined impedance (EMIS), acoustic emission (AE), and guided ultrasonic wave (GUW) approach, called "multi-mode sensing", which is conducted by the same network of installed sensors activated in a variety of ways. The system will detect AE events resulting from crack (case for study in this project) and evaluate the damage evolution; when significant AE is detected, the sensor network will switch to the GUW mode to perform damage localization, and quantification as well as probe "hot spots" that are prone to damage for material degradation evaluation using EMIS approach. The N-SHM is expected to eventually provide a systematic methodology for assessing and monitoring nuclear waste storage systems without incurring human radiation exposure.

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9439-23, Session 5

**Robust ultrasonic waveguide based
distributed temperature sensing**

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This is the novel technique for the distributed temperature measurements, using single robust ultrasonic wire-like waveguides, shaped in the form of special configurations that can cover large area/volume in enclosed regions. Such distributed temperature sensing has low cost applications in the long term monitoring critical enclosures such as containment vessels, flue gas stacks, furnaces, underground storage tanks, buildings for fire, etc. The range of temperatures that can be measured may be from very low (-60 C) to very high (1500 C). The transduction is performed using Piezo-electric crystals that are bonded to one end of the waveguide which both transmitter as well as receivers. The wires will have periodic reflector embodiments (notches, bends, gratings, helical, etc.) that allow reflections of an input ultrasonic wave, in a pulse echo mode, back to the crystal. Using the time-of-flight (TOF) variations at the multiple predefined reflector locations, the temperature are mapped using 3D volume software. The exact geometry of the waveguide configuration will depend on the area/volume that is being monitored. Using either the L(0,1) or the T(0,1) guided waves, either separately or simultaneously, measurements other than temperature may also be included. This paper will describe the demonstration of this technology using a 0.5MHz longitudinal piezo-crystal for transmitting and receiving the L (0, 1) mode through the special form of the Chromel waveguides at various temperatures zones.

9439-24, Session 6

**Performance quantification of
piezoelectric energy harvesting devices**

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States)

The ultimate goal in research of piezoelectric vibration energy harvesting (PVEH) is to realize a powering device that can provide sufficient power for practical applications such that operation of wireless electronics in a self-powered manner is possible. A great deal of the latest research has focused on improving the performance of PVEH devices through exploration of various piezoelectric materials, device configurations, and optimization of circuit designs. In order to find innovative ways to develop devices with enhanced performance at both materials and system (structural) levels, the fundamental and important question is which performance metric should be considered as a figure of merit. Then, it is quite essential to identify and understand the relevant variables and factors that influence the objective output performance of harvesting devices so as to gain insight into the device design guidelines. At present, despite the increasing number of PVEH devices reported in the literature, a full set of key performance metrics for comparing different PVEH devices have not been clearly defined and standardized, presenting a need for better figures of merit of device performance. In this work, harvesting efficiency for a PVEH device is analytically described and thoroughly analyzed to find optimal conditions that maximize harvesting efficiency. Comparison results of different optimal conditions for each performance parameter such as power, voltage, and efficiency are also discussed.

9439-25, Session 6

**Robust design optimization for nonlinear
vibration energy harvesters**

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 County (United States); Chao Hu, Medtronic, Inc. (United
States)

The power output of a vibration energy harvesting device is highly sensitive to uncertainties in materials, manufacturing, and operation conditions. Although the use of a nonlinear spring (e.g., snap-through mechanism) in energy harvesting device has been reported to reduce the sensitivity of power output with respect to the excitation frequency, the nonlinear spring characteristic remains significantly sensitive and it causes unreliable power generation. In this paper, we present a robust design optimization study of nonlinear energy harvesters. Two nonlinear spring designs implemented in the middle of cantilever beam harvester are considered in the study: (i) a curved shell type; and (ii) a suspension type. In the first design the curved section in the center of beam causes bi-stable configuration, while the spring held by a suspension-like structure and linkages realizes bi-stable configuration in the second design. When vibrating, the inertia of the tip mass activates either the curved shell or the nonlinear spring to cause snap-through buckling, which makes the nature of vibration nonlinear. In this study, robust design optimization will be performed to simultaneously maximize the power and minimize its variation while considering uncertainties in material properties, geometry parameters, and excitation conditions. As a result of this robust design optimization, an optimum bi-stable vibration configuration whose power output is insensitive to the uncertainties will be obtained. Experimental tests will be undertaken to verify the power generation capability and robustness of the optimum energy harvester designs.

9439-26, Session 6

**Rotating beam flexural vibrations in
perpendicular directions as a wide-band
piezoelectric energy harvester**

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States)

A piezoelectric energy harvester is a resonant device so that they can only collect energy effectively near a particular resonant frequency. As a result of this limitation, the responsive frequency range of common piezoelectric harvesters is of a narrowband, which prevents them from being used in the case of random or fast-varying frequency excitations. We present here a new design of a wide-band piezoelectric energy harvester. Our system consists of two pairs of cantilever beams with attached PZT (lead zirconate titanate) patches aligned in perpendicular directions. In the experiment, two resonance peaks are observed and by adjusting the rotation angle of these beams, the operational bandwidth has been enlarged for 70%-100%. Therefore, our new piezoelectric energy harvester has the potential to harvest energy in a wider frequency range to address the challenge that the frequency source is variable.

9439-27, Session 6

**An experimentally validated parametrically
excited vibration energy harvester with
time-varying stiffness**

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Vibration energy harvesting is the transformation of vibration energy present in the environment into electrical energy. This has applications on many length scales, though the intended application of this work is to power a wireless sensor network for condition health monitoring. Parametric amplification has been used to tune vibration energy harvesters to maximise energy gains at system superharmonics, often at twice of the first natural frequency. In these systems the harvester is under parametric excitation and it is compared with the direct excitation case.

In this paper a parametrically excited harvester under direct excitation is

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presented, which is a system where the stiffness of the harvester varies with time. The aforementioned system is modelled as a two degree of freedom system with cubic nonlinearity, and the response of the system is calculated analytically using the averaging method. This analytical response is compared with results from an experimental model. This experimental model consists of a cantilever beam representing a structure, and two coil and magnet pairs to generate time-varying stiffness for the harvester. A piezoelectric sensor is attached to the beam with a shunted resistive load in order to measure the average absorbed power.

It is found that more energy is harvested from a parametrically excited harvester with small cubic nonlinearity than the corresponding non-parametric system, despite the power required by the electromagnet system. Furthermore, the cubic nonlinearity of the harvester is presented to determine whether or not broad banding occurs.

9439-28, Session 6

Self-assembled graphene films based self-heating slab and its electro-thermal performance in deicing applications

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In this article, a layered paper-like Graphene Films (GFs) as a emerged heating element was integrated with the graphene-oxide reinforced cement-based composite (GRC) to form a self-heating slab which would supposedly be used for deicing applications. GFs, contributed to the layered-stacked nano-structure with the interlayer distance between graphene nano-sheets about 0.35nm, is synthesized from graphene nano-sheets in a free-standing and self-assembly way, and it is experimentally verified spectacular electro-thermal performance, remarkable mechanical property, excellent electrical conductivity, and durable structural and conductive stability. And GRC, with Graphene Oxide (GO) as a modified component by the wt. of 1%, presents significant improvement of thermal conductivity (3.78 W/(m·K)) compared to the other fillers based cement composites (-1.58 W/(m·K)). Based on promising properties on electro-thermal and thermal conduction, the integrated slab of GFs and GRC is adopted to implement serials of deicing applications under multi-parameters dependent effects (environmental temperature, heat flux density, convection intensity, ice thickness). With a stable heating power, a uniform temperature distribution on the surface of GFs is detected by an infrared camera, and the GFs/GRC slab is verified stable electro-thermal performance and higher efficiency. Eventually, the systematical experiments demonstrate the feasibility of GFs/GRC slab in deicing performance, implying that this material could be employed as a competitive candidate for deicing application with the purpose of operational feasibility, environmental protection, constructive compatibility, higher efficiency and longer workability.

9439-29, Session 6

Experimental investigation of fatigue in a cantilever energy harvesting beam

Panduranga V. Avvari, Yaowen Yang, Chee Kiong Soh, Peiwen Liu, Nanyang Technological Univ. (Singapore)

Over the last decade, cantilever energy harvesters gained immense popularity owing to the simplicity of the design and piezoelectric energy harvesting (PEH) using the cantilever design has undergone considerable evolution. The major drawback of a vibrating cantilever beam is its vulnerability to fatigue over a period of time. This article brings forth an experimental investigation into the phenomenon of fatigue of a PEH cantilever beam. As there has been very little literature reported in this area, an effort has been made to scrutinize the damage due to fatigue in a linear vibrating cantilever PEH beam consisting of an aluminum substrate with a piezoelectric macro-fiber composite (MFC) patch attached near the root of the beam and a tip mass attached to the beam. The beam was subjected to transverse vibrations and the behavior of the open circuit voltage was recorded with passing time. Moreover, electro-mechanical

impedance readings were obtained periodically using the same MFC patch as an impedance sensor to assess the health of the PEH beam. The results show that with passing time the PEH beam underwent fatigue in both the substrate and MFC, which is observed in a complimentary trend in the voltage and impedance readings. The claim is further supported using the variation of root mean square deviation (RMSD) of the real part of impedance (conductance) readings. Thus, this study concludes that the fatigue issue should be addressed in the design of PEH for long term vibration energy harvesting.

9439-30, Session PTues

Ultrasonic assessment of tension shear strength in resistance spot welding

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Ultrasonic non-destructive techniques for evaluation of the mechanical properties of resistance spot welding are presented. The aim of this study is to develop the capability of the ultrasonic techniques as an efficient tool in the assessment of the welding characterization. Previous researches have indicated that the measurements of ultra-sound attenuation are sensitive to grain-size variations in an extensive range of metallic alloys. Other researchers have frequently described grain sizes which are able to have significant effects on the physical characteristics of the material. This research provides a novel method to estimate the tension-shear strengths of the resistance spot welding directly from the ultrasonic attenuation measurements. The effects of spot welding parameters on the ultrasonic waves are further investigated. The results confirm that it is possible to extend this method's applicability to other welding ranges.

The study confirms that there is a relation between the ultrasonic test characters (attenuation coefficient ultrasonic waves and length of ultrasonic wave's pathway) and the tension-shear fracture load; when the attenuation coefficient increases, the tension-shear strength of the spot weld increases as well. It is possible to predict the tension-shear strengths of the spot welds by the ultrasonic attenuation characteristics.

9439-31, Session PTues

Fabrication, microstructure, and high-temperature thermoelectric properties of Ca_{0.8}Y_{0.2-x}DyxMnO_{3-?}

Kyeongsoon Park, J. W. Seo, C. M. Kim, Sejong Univ. (Korea, Republic of)

Thermoelectric materials can be utilized to convert a temperature gradient to electrical energy directly due to the Seebeck effect. Thermoelectric power can potentially be obtained from the waste heat emitted from vehicle applications and manufacturing processes without using moving parts and without producing waste gas or other emissions. Metal oxides have attracted considerable attention as potential thermoelectric materials due to low production cost, high thermal and chemical stability in air at high temperatures, good oxidation resistance, and lack of toxicity. In this study, we fabricated Y- and Dy-doped Ca_{0.8}Y_{0.2-x}DyxMnO_{3-?} by solid-state reaction method. Two kinds of Ca_{0.8}Y_{0.2-x}DyxMnO_{3-?} powders with different particle size and morphology were fabricated using high-energy planetary milling and ball milling processes. The obtained powders were cold-pressed to prepare green pellets. The pellets were sintered at 1300 °C in air. The sintered Ca_{0.8}Y_{0.2-x}DyxMnO_{3-?} had an orthorhombic perovskite-type structure. The doped Y- and Dy did not affect the crystal structure of CaMnO₃. The electrical conductivity for Ca_{0.8}Y_{0.2-x}DyxMnO_{3-?} decreased with increasing temperature, indicating a typical metallic behavior. The sign of the Seebeck coefficient was negative over the measured temperature range (500–800 °C). The absolute value of the Seebeck coefficient increased with an increase in temperature. High-energy planetary milled samples showed much better thermoelectric properties in comparison with

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ball milled samples. The microstructural and thermoelectric properties of the high-energy planetary and ball milled samples will be discussed. It is suggested that the high-energy planetary milled Ca_{0.8}Y_{0.2-x}Dy_xMnO_{3-?} has high potential for thermoelectric energy conversion application.

9439-32, Session PTues

Investigation of eddy current examination on OD fatigue crack for steam generator tubes

Yuying Kong, Boyuan Ding, Ming Li, Jinhong Liu, Huaidong Chen, CGNPC Inspection Technology Co. Ltd. (China); Norbert G. Meyendorf, Fraunhofer IKTS-MD (Germany)

The opening width of fatigue crack was very small, and conventional Bobbin probe was very difficult to detect it in steam generator tubes. Different sizes of 8 fatigue cracks were inspected using Bobbin probe and two other probes, rotating probe and array probe. The analysis results showed that, Bobbin probe was not sensitive for fatigue crack even for small through wall crack mixed with dent signal. On the other hand, the rotating probe and array probe were easily to detect all cracks. Finally, the OD phase to depth curve for fatigue crack using rotating probe was established and the results agreed very well with the true crack size.

9439-33, Session PTues

The eddy current inspection and evaluation for the bottom mounted instrument of reactor pressure vessel

Yayao Bei, Yi He, Ming Li, Tao Song, Ge Lin, Huaidong Chen, Jinhong Liu, CGNPC Inspection Technology Co. Ltd. (China); Norbert G. Meyendorf, Fraunhofer IKTS-MD (Germany)

The bottom mounted instruments (BMIs) of reactor pressure vessel were susceptible to stress corrosion cracking under the environment of high temperature and high pressure boron water. Recently, boron crystallization were found on several BMIs in the nuclear power plants around the worldwide, so it is very important to carry out non-destructive testing to ensure the integrity of the BMIs. Our institute have developed the eddy current inspection technique for the evaluation of BMI inner wall and outer surface of J-weld, the phase array probe and plus point probe were used. It was found that the best sensitivity for the BMI inner wall and outer surface of J-weld were 0.5mm and 1mm respectively during the testing on the mockups. However, the sensitivity for outer surface of J-weld would become worse due to the bad coupling between the probe and the inspection surface, the modification of probe scanner and application of data processed method were made to eliminate this phenomenon. The qualitative and quantitative evaluation of the flaw were discussed. In addition, the growth of axial and circumferential cracks were studied using Scott model in order to estimate the remaining life or time until it was reaching the maximum allowable size.

9439-34, Session PTues

Electrospun TiO₂ nanofibers incorporated with conductive nanoscale inclusions for energy conversion

Ramazan Asmatulu, Manish A. Shinde, James Ho, Wichita State Univ. (United States)

Solar energy has been used in many different ways, including solar water heater for hot water, solar cooking, space heating, and solar electricity by using the sun's heat and the photovoltaic system that uses the photons to convert directly to electricity. One of the major drawbacks of the solar cells include the lower conversion efficiency and higher manufacturing costs. In order to eliminate these obstacles, many studies were focused on the energy efficiencies and cost of the solar cells (particularly dye sensitized solar cells - DSSC and thin film solar cells). In the present study, TiO₂ nanofibers incorporated with graphene nanoflakes (0, 1, 2, 4, and 8wt.%) were produced using electrospinning process. The chemical combinations of the electrospinning process included poly (vinyle acetate), dimethylformamide (DMF), titanium (IV) isopropoxide and acetic acid in the presence and absence of graphene nanoflakes dispersions. The resultant nanofibers were heat treated at 300 °C for 12 hrs in a standard oven to remove all the organic parts of the nanofibers, and then further heated at 500 °C in an argon atmosphere for additional 12 hrs to crystalline the nanofibers. SEM and XRD studies showed that graphene and TiO₂ nanofibers are well integrated in the nanofiber structure. The nanofibers were crashed in a mortar grinder, treated well with appropriate chemicals and used in the DSSC experiments. The general efficiency of the DSSC cell were considerably increased in the presence of graphene into the TiO₂ nanofibers. Overall, the present study may open up new possibilities of using these studies in various other energy systems for improved efficiencies of the solar cells.

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