

## **Abstracts**

### **Review of Progress in Quantitative NDE**

Bowdoin College

Brunswick, Maine

July 31-August 5, 2005

#### **Organized by:**

Center for Nondestructive Evaluation  
Iowa State University

#### **In cooperation with:**

Air Force Research Laboratories

American Society for Nondestructive Testing

Ames Laboratory - U.S. Department of Energy

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National Aeronautics and Space Administration - LaRC

National Science Foundation

Industry/University Cooperative Research Centers



# ***MONDAY***

Plenary Session 1 – Safety and Reliability .....	1
Plenary Session 2 – Materials Issues .....	1
Session 3 – Signal Processing .....	5
Session 4 –NDE for Composites I .....	11
Session 5 – NDE for Concrete Structures .....	15
Session 6 – Thermal Techniques .....	21

# *Plenary Sessions 1 and 2*

# **REVIEW OF PROGRESS IN QUANTITATIVE NDE**

Bowdoin College  
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## **PROGRAM**

Monday, August 1, 2005

### **PLENARY SESSION 1 SAFETY AND RELIABILITY R. B. Thompson, Chairperson Morrell Gymnasium**

- 9:00 AM**            *Opening Remarks*
- 9:15 AM**            **The National Aeronautics and Space Administration Nondestructive Evaluation Program for Safe and Reliable Operations**  
---**E. Generazio**, Engineering and Safety Center, NASA Langley Research Center, Mail Stop 213, Hampton, VA 23681-0001
- 10:10 AM**            *Coffee Break*

### **PLENARY SESSION 2 MATERIALS ISSUES D. E. Chimenti, Chairperson Morrell Gymnasium**

- 10:30 AM**            **Opportunities and Challenges for Nondestructive Residual Stress Assessment**  
---**P. B. Nagy**, Department of Aerospace Engineering and Engineering Mechanics, University of Cincinnati, Cincinnati, OH 45221-0070
- 11:20 AM**            **Hidden Corrosion and Corrosion Damage: What Should be Measured to Improve Emerging 'Anticipate and Manage' Strategies**  
---**J. R. Scully**, University of Virginia, Department of Materials Science and Engineering, 116 Engineer's Way, P. O. Box 400745, Charlottesville, VA 22904-0745
- 12:10 PM**            *Lunch*

***Please Note: The bolded authors throughout this program indicate the presenting author.***

**The National Aeronautics and Space Administration Nondestructive Evaluation Program for Safe and Reliable Operations**

---**Ed Generazio**, Engineering and Safety Center, NASA Langley Research Center, Mail Stop 213, Hampton, VA 23681-0001

---The National Aeronautics and Space Administration (NASA) Nondestructive Evaluation (NDE) Program will be presented. As a result of the loss of seven astronauts and the Space Shuttle Columbia on February 1, 2003, NASA has undergone many changes in its organization. NDE is one of the key areas that is recognized by the Columbia Accident Investigation Board (CAIB) that needed to be strengthened by warranting NDE as a discipline with Independent Technical Authority (ITA). The current NASA NDE system and activities are presented including the latest developments in inspection technologies being applied to the Space Transportation System (STS). The unfolding trends and directions of NDE of the future are discussed as they apply to assuring safe and reliable operations.

**Opportunities and Challenges for Nondestructive Residual Stress Assessment**

---**Peter B. Nagy**, Department of Aerospace Engineering and Engineering Mechanics,  
University of Cincinnati, Cincinnati, OH 45221-0070

---For a long time, nondestructive residual stress assessment has been one of the great opportunities as well as one of the greatest challenges for the NDE community, and probably it will remain so in the foreseeable future. The most critical issue associated with nondestructive residual stress assessment seems to be that of selectivity. Numerous NDE methods have been found to be sufficiently sensitive to the presence of residual stress, but unfortunately also rather sensitive to other spurious variations that usually accompany residual stresses, such as anisotropic texture, microstructural inhomogeneity, plastic deformation, etc., which could interfere with, or even overshadow, the elastic strain caused by the sought residual stress. The only sufficiently selective NDE method that is more or less immune from these spurious effects is X-ray diffraction measurement, which however does not have the required penetration depth in most applications unless high-energy neutron radiation is used. It is timely for the community to sit back and ask where we are in this important area. This talk will present a broad overview of the various techniques that have been used to measure stress in the past. It will be shown that traditional techniques have a number of limitations, which have spurred several recent research programs. Some of the new techniques that are presently being examined in the NDE community will be also reviewed and the current status of these research efforts will be assessed.

**Hidden Corrosion and Corrosion Damage: What Should be Measured to Improve Emerging 'Anticipate and Manage' Strategies**

---**John R. Scully**, University of Virginia, Department of Materials Science and Engineering, 116 Engineer's Way, P. O. Box 400745, Charlottesville, VA 22904-0745

---The terms 'health management', 'prognosis' and 'condition-based maintenance' are used commonly in many engineering fields. Concerning corrosion damage evolution, there is growing recognition that traditionally utilized 'time-based maintenance,' 'lessons learned' and 'find-it/fix-it' strategies could be improved by introduction of 'anticipate and manage' type strategies. There is also the need to understand how service history, operational environment, new materials and processes as well as green corrosion prevention and control methods might affect corrosive damage evolution and inadvertently degrade the performance, availability, and or increase the life cycle costs of equipment in the DOD and elsewhere. However, corrosion damage, hidden or otherwise, must be detected, quantified, evaluated and factored into models that anticipate the effects of corrosion on structural integrity, etc., in order to move towards effective implementation of 'anticipate and manage' strategies. In this talk, some examples of the challenges in characterizing and accounting for the evolution of corrosion damage of interest in selected emerging models are given. In the case of the effects of corrosion on the transition to fatigue and stress corrosion cracking, the corrosion damage micro-topography that is important to fatigue life and hence 'needs to be measured' is reviewed. Moreover, mechanisms of paint and coating failure by corrosion are briefly reviewed. Comments are then given on what parameters 'seem to be important' and 'need to be characterized' in order to predict and/or recognize loss of coating function and onset of under-paint corrosion.

# *Session 3*

Monday, August 1, 2005

**SESSION 3**  
**SIGNAL PROCESSING**  
**Moulton Union Main Lounge**

- 1:30 PM**      **Sensitivity of Time-Frequency Representations in the Presence of Noise in Guided Waves NDE**  
---**S. Ramaswamy**, M. K. KM, and V. Kommareddy, Industrial Imaging and Modeling Lab, GE Global Research, Bangalore, India
- 1:50 PM**      **Analysis of Time Domain Reflectometry Signals for Wiring Flaw Detection via Wavelet Thumbprints**  
---**M. K. Hinders** and K. E. Rudd, College of William and Mary, Applied Science Department, Williamsburg, VA 23187-8795; K. R. Leonard, Solers, Inc., 3811 N. Fairfax Drive, Suite 950, Arlington, VA 22203; R. Jones, ASRC Aerospace Corporation, P. O. Box 183, Williamsburg, VA 23187-0183
- 2:10 PM**      **Pulsed Eddy Current Measurement of Lift-Off**  
---**J. H. V. Lefebvre**, National Defence Headquarters, Air Vehicles Research Section, Ottawa, Ontario, K1A 0K2, Canada; C. Mandache, NRC/Institute of Aerospace Research, 1200 Montreal Road, Building M14, Ottawa, Ontario, K1A 0R6, Canada
- 2:30 PM**      **Static Load Estimation for Magnetic Alloy Strips by Using Neural Networks**  
---P. Chen, **I. N. Tansel**, and A. Yenilmez, Mechanical Engineering Department, Florida International University, Miami, FL 33174
- 2:50 PM**      **Evaluation and Tuning of Magnetostrictive Sensors by Using S-Transformation**  
---A. Yenilmez, P. Chen, **I. N. Tansel**, and J. Wu, Mechanical Engineering Department, Florida International University, Miami, FL 33174
- 3:10 PM**      **Coffee Break**
- 3:30 PM**      **Application of Hilbert-Huang Transform for the Analysis of Impact-Echo Signals**  
---**D. Algernon** and H. Wiggerhauser, Federal Institute for Materials Research and Testing (BAM), Berlin, Germany
- 3:50 PM**      **Bayesian Defect Signal Analysis**  
---**A. Dogandzic** and B. Zhang, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011
- 4:10 PM**      **Methodology Using Inverse Methods for Pit Characterization in Multilayer Structures**  
---**J. C. Aldrin**<sup>1</sup>, H. A. Sabbagh<sup>2</sup>, E. H. Sabbagh<sup>2</sup>, R. K. Murphy<sup>2</sup>, M. Concordia<sup>3</sup>, D. R. Judd<sup>3</sup>, E. Lindgren<sup>3</sup>, and J. Knopp<sup>4</sup>, <sup>1</sup>Computational Tools, Gurnee, IL, <sup>2</sup>Victor Technologies LLC, Bloomington, IN, <sup>3</sup>SAIC Ultra Image Int., New London, CT, <sup>4</sup>NDE Branch, Materials and Manufacturing Directorate, U.S. Air Force Research Laboratory, Wright-Patterson AFB, OH 45433
- 4:30 PM**      **Advances of Simulation and Expertise Capabilities in Civa Platform**  
---**L. Le Ber**, P. Calmon, T. Sollier, S. Mahaut, and P. Benoist, CEA Saclay, DRT/DETECS/SYSSC/LMUS, Bat. 611, 91191 Gif-sur-Yvette, France
- 4:50 PM**      **A Flexible Digital Signal Processing Platform for Very High Signal-to-Noise Ratio Enhancement of Weak Eddy Current and Ultrasonic Signals Routinely Encountered in NDE**  
---**P. Gaydecki**, G. Miller, R. Mijarez, B. Fernandes, M. Zaid, and H. Hussin, The University of Manchester, School of Electrical and Electronic Engineering, P. O. Box 88, Manchester, M60 1QD, United Kingdom

**Sensitivity of Time-Frequency Representations in the Presence of Noise in Guided Waves NDE**

---**Sivaramanivas Ramaswamy**, Manoj Kumar KM, and Vamshi Kommareddy, Industrial Imaging and Modeling Lab, GE Global Research, Bangalore, India

---Time frequency representation of ultrasonic signals plays an important role in describing the propagation and dispersive effects in thin walled structures. In this paper, a study on the performance of time-frequency representations in the presence of strong colored noise is presented. Generalized time-frequency representations viz. the Wigner-Ville distribution (WVD), Choi-William distribution (CWD) and Short-time Fourier transform (STFT) are discussed in the context of mode analysis of plate waves. The main characteristic of representations like WVD and CWD is that they are bilinear functions of the signals. Due to this structure they generate cross-terms for the multi component signals. The presence of cross-terms obscures the auto-terms, leading to poor localization of the signal and misleading interference terms. A comparison of estimation of various plate wave modes and the obscuring interference terms is presented using the above three methods, from experimental data on aluminum plates. The effect of reassignment method on the time - frequency localization is discussed. The results on the estimation of local time-frequency of the first few symmetric modes corrupted with colored noise are presented.

**Analysis of Time Domain Reflectometry Signals for Wiring Flaw Detection via Wavelet Thumbprints**

---**Mark K. Hinders** and Kevin E. Rudd, College of William and Mary, Applied Science Department, Williamsburg, VA 23187-8795; Kevin R. Leonard, Solers, Inc. 3811 N. Fairfax Drive, Suite 950, Arlington, VA 22203; Robert Jones, ASRC Aerospace Corp., P. O. Box 183, Williamsburg, VA 23187-0183

---We describe a signal processing technique for enhanced time-domain reflectometry (TDR) detection of flaws in wiring. In TDR, a step voltage pulse is transmitted down the wire, and reflected voltage signals are recorded as a function of time, so that time delay indicates very accurately the locations of the wire features that caused each reflection. For subtle wiring flaws (i.e. something less than a complete short or open, which cause complete reflection) the backscattered voltage pulses are often too slight to be identified by standard amplitude-based peak-detection methods or other time-domain processing algorithms. In our work a wavelet transform is used to convert the 1D time traces into 2D binary "thumbprint" images. Flaws are then identified according to their unique 2D time-scale patterns in these wavelet thumbprints. An interactive method for identifying flaw-features in thumbprints is demonstrated here for RG58 coaxial cables with varying amounts of damage to the shielding. Extension of this work to other wiring systems (i.e. twisted pair) as well as branching networks will also be discussed.

**Pulsed Eddy Current Measurement of Lift-off**

---**J. H. V. Lefebvre**, National Defence Headquarters, Air Vehicles Research Section, Ottawa, Ontario, K1A 0K2, Canada; C. Mandache, NRC/Institute of Aerospace Research, 1200 Montreal Road, Building M14, Ottawa, Ontario, K1A 0R6, Canada

---Pulsed eddy current signal responses vary with the test material condition (thickness, conductivity, etc), inspection probe characteristics, and lift-off. The lift-off point of intersection (LOI) is a key feature of the pulsed eddy current signal, enabling measurements independent of lift-off variation. It has been successfully used for corrosion and crack detection in multi-layered material inspection. In this study, it is observed that the slope of pulsed eddy current signals at the LOI point depends strongly on the lift-off. The behavior of the slope at the LOI point is studied under varying test conditions. To obtain the LOI slope measurements, the signal response is curve-fitted to a circuit equivalent non-linear model using the Levenberg-Marquardt algorithm. The slope at the LOI point is computed using the curve-fitted parameters. This study demonstrates that the slope at the LOI point can be used to accurately measure the non-conductive layer thickness (e.g. paint, coatings, etc.) on a conductive substrate.

**Static Load Estimation for Magnetic Alloy Strips by Using Neural Networks**

---**P. Chen, I. N. Tansel**, and A. Yenilmez, Mechanical Engineering Department, Florida International University, Miami, FL 33174

---The dynamic response characteristics of a magnetic alloy strip such as Metglas 2826MB and a coil vary according to the applied strain to the strip. Since the peak frequency of the amplitude is above 100kHz in the typical applications, it is difficult to acquire the data at least the twice of the highest frequency of the signal with low cost microprocessors with built in A/D pins. In this paper, backpropagation type neural networks were proposed for estimation of the load by evaluating the magnetic response characteristics of the system. In the experiments Metglas 2826MB magnetic alloy strip was located in a coil. Both of them were installed in a Helmholtz coil. A sweep sine wave was applied to the Helmholtz coil between 200 kHz and 380 kHz. The signal of the small coil was sampled by using a Nicolet digital oscilloscope. The envelope of the signal was found by selecting the highest point of each period. The envelope was divided into 10 segments and their averages were presented to a backpropagation type neural network. The output of the neural network was the estimation of the load on the strip. 9 cases obtained with different loads were used to train the backpropagation type neural network. Trained network was tested on the envelopes of 4 cases obtained with different loads. The estimation accuracy of the training and test cases were less than 0.01% and 2.5% respectively. The study verified that when the length, thickness and width of a magnetic strip change with applied strain and these changes influence the magnetic properties of the strip-coil system. Even if the sampling rate is not fast enough to avoid aliasing, the envelope of the response of the system to a sweep sine wave could be used to estimate the strain or the load on the strip. BP type NN was found a good choice to estimate the strain or load from the amplitude plot of the magnetic response characteristics of the system.

**Evaluation and Tuning of Magnetostrictive Sensors by Using S-Transformation**

---A. Yenilmez, P. Chen, **I. N. Tansel**, and J. Wu, Mechanical Engineering Department, Florida International University, Miami, FL 33174

---Recently, many researchers have developed sensors by using magnetostrictive materials for very different applications from displacement measurement to health monitoring of composites. Use of s-transformation is proposed for evaluation of the characteristics of the signals and tuning of the sensors according to applications. The proposed method was used to evaluate the response of a Terfenol-D rod to impulses. A coil, magnetic head and laser vibrometer were used to monitor the magnetic and volumetric variations. In the experiments impulses were applied with a PCB 086C80 Miniature Instrument Hammer to a 100mm long Terfenol-D rod with 12mm diameter. The coil had 20mm diameter and 360 windings (magnet wire of 0.4mm diameter). Magnetic head was a NORTRONICS WP-B1HY7K R/P. Force transducer of hammer, laser vibrometer, magnetic head and coil were connected to a Nicolet Integra Series Model 10 digital storage oscilloscope. A Helmholtz coil was used in some experiments to compensate the earth's magnetic field. The appearances of the signals of the coil and laser vibrometer were very similar in the time domain. The head had high frequency components. The s-transformation analysis showed that at the low frequency contents of the coil and the magnetic head were similar. However, the magnetic head was sensitive at high frequencies. On the other hand the coil was more sensitive at low frequencies and it continued the pickup of the magnetic variations after the signal of the magnetic head vanished. S-transformation was found an excellent tool for evaluation and tuning of the magnetostrictive sensors according to the application.

**Application of Hilbert-Huang Transform for the Analysis of Impact-Echo Signals**

---**Daniel Algernon** and Herbert Wiggerhauser, Federal Institute for Materials Research and Testing (BAM), Berlin, Germany

---Impact-echo as a method for non-destructive testing in civil engineering is based on the use of multiple reflections of stress waves generated by an elastic impact. Normally, for analysis the signal is transformed into the frequency domain using Fast Fourier Transform (FFT) making multiple reflections appear as distinctive peaks. FFT only gives the frequency content of the whole signal without revealing its relation to time. For the identification of short signals within the data, the application of analysis methods giving a time-frequency representation of the amplitude of the signal seems practicable. Well known are the Short-Time-Fourier-Transform and the Continuous Wavelet Transform. This contribution shows the use of the Hilbert-Huang Transform as a refined method. It extends the common Hilbert spectral analysis, which gives the instantaneous frequency and the amplitude in relation to time. The signal is pre-processed by a decomposing algorithm generating the Intrinsic Mode Functions (IMFs), thus highly increasing the range of application of the method. Examples of on-site measurements are given, in which HHT succeeds in identifying signals within a short time span, whereas FFT fails. IMF-decomposition is also shown to be useful even without the following Hilbert spectral analysis, since it also acts as a signal filter.

### **Bayesian Defect Signal Analysis**

---**Aleksandar Dogandzic** and Benhong Zhang,  
Center for NDE, Iowa State University, 1915  
Scholl Road, Ames, IA 50011

---We develop a Bayesian framework for detecting and estimating NDE defect signals from noisy measurements. The defect signal is assumed to be random with unknown mean and variance and a parametric model is proposed for the shape of the potential defect region. We derive a Markov Chain Monte Carlo (MCMC) algorithm for estimating the posterior distributions of the defect signal and shape parameters. We then utilize the obtained posterior distributions of the parameters of interest to detect and localize the potential defect regions. The proposed framework is demonstrated using a Gaussian noise model and an elliptical defect shape model. We apply the proposed methods to simulated and experimental data and demonstrate their performance. We will also consider extensions to more realistic noise and defect shape models. ---This work was supported by the NSF Industry-University Cooperative Research Program, Center for Nondestructive Evaluation (CNDE), Iowa State University.

### **Methodology Using Inverse Methods for Pit Characterization in Multilayer Structures**

---**John C. Aldrin**<sup>(1)</sup>, Harold A. Sabbagh<sup>(2)</sup>, Elias H. Sabbagh<sup>(2)</sup>, R. Kim Murphy<sup>(2)</sup>, Michael Concordia<sup>(3)</sup>, David R. Judd<sup>(3)</sup>, Eric Lindgren<sup>(3)</sup>, and Jeremy Knopp<sup>(4)</sup>, <sup>(1)</sup> Computational Tools, Gurnee, IL, <sup>(2)</sup> Victor Technologies LLC, Bloomington, IN, <sup>(3)</sup> SAIC Ultra Image Int., New London, CT, <sup>(4)</sup> NDE Branch, Materials and Manufacturing Directorate, U.S. Air Force Research Laboratory, Wright-Patterson AFB, OH

---There is a need for improved nondestructive evaluation (NDE) capability to characterize the surface topology of corrosion at faying surfaces in multi-layered aircraft structures to better support fleet management decisions and minimize cost and aircraft disassembly. In particular, characterizing corrosion pits in both first and second layers is a challenge for conventional NDE methods. Model-based inverse methods have been investigated for flaw characterization; however, the ill-posed character of such problems, long model solution times, and the presence of background noise can hinder their application. This paper presents a methodology incorporating ultrasonic and eddy current data and NDE models to characterize pits in first and second layers. Ultrasonic data is used to provide data on first layer corrosion to simplify the second layer eddy current inversion problem. Equivalent pit dimensions and simplified probe models, evaluated through a calibration procedure, can aid in reducing model complexity and minimizing solution time. A novel clutter removal algorithm was also developed that assesses the background response using a model-based evaluation approach with a higher-order polynomial fit incorporating nonlinear least squares estimation (NLSE) to best match the background clutter. Excellent results have been achieved through validation of the methodology with artificial and real pitting corrosion samples.

**Advances of Simulation and Expertise Capabilities in Civa Platform**

---**Laurent Le Ber**, Pierre Calmon, Thierry Sollier, Steve Mahaut, and Philippe Benoist, CEA Saclay, DRT/DETECS/SYSSC/LMUS, Bat 611, 91191 Gif Sur Yvette, France

---Simulation is more and more widely used by the different actors of industrial NDT. The applications are numerous and show a great variety: help for diagnosis, data reconstruction, performance demonstration of existing techniques, probe design and inspection parameters setting, virtual testing etc... The French Atomic Energy Commission (CEA) launched the development of an expertise software for NDT named CIVA. With successive versions of CIVA, the results of latest modeling research have been integrated into the software. At the beginning limited to ultrasonic applications and models issued from CEA laboratories, CIVA now includes Eddy current simulation tools while work is in progress in order to facilitate the integration of algorithms and models developed by different laboratories and to include X-ray modeling. In this communication we give an overview of the existing CIVA capabilities and describe its evolution towards an integration platform.

**A Flexible Digital Signal Processing Platform for Very High Signal-to-Noise Ratio Enhancement of Weak Eddy Current and Ultrasonic Signals Routinely Encountered in NDE**

---**Patrick Gaydecki**, Graham Miller, Rito Mijarez, Bosco Fernandes, Muhammad Zaid, and Haitham Hussin, The University of Manchester, School of Electrical and Electronic Engineering, P. O. Box 88, Manchester, M60 1QD, United Kingdom

---The design, programming and application of a novel and cost effective digital signal processing (DSP) platform is described, whose speed, large dynamic range and stability renders it suitable for NDE applications that mandate the extraction and identification of very weak signals embedded in noise. Thus far, the system has been deployed both for the isolation of weak eddy currents propagated through a ferrous steel boundary, and in the recovery of ultrasonic signals transmitted through seawater and severely attenuated by divergence losses associated with the use of non-optimal transducers. In particular, the system may function as a high-gain, super-narrowband filter, with a bandwidth isolation of 1 Hz within a 48 kHz range and a gain of 90 dB. In recent laboratory and field trials, we have successfully detected magnetic flux densities in the picotesla range using simple search coil configurations, and minute ultrasonic signals associated with a nano-volt range response of the piezo-based receiving transducer.

# *Session 4*

Monday, August 1, 2005

**SESSION 4**  
**NDE FOR COMPOSITES I**  
**S. Rokhlin, Chairperson**  
**Druckenmiller Hall 016**

- 1:30 PM**      **Aerospace Applications of Composite Materials**  
---**J. H. Gosse**, Phantom Works, The Boeing Company, Seattle, WA 98124-2499
- 2:10 PM**      **NDE Developments for Composite Structures**  
---**R. H. Bossi**, Phantom Works, The Boeing Company, Seattle, WA 98124-2499
- 2:50 PM**      **Inspecting Composites with Airborne Ultrasound: Through Thick and Thin**  
---**D. K. Hsu** and D. J. Barnard, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011
- 3:10 PM**      **Coffee Break**
- 3:30 PM**      **Development of Practical NDE Methods for Composite Structures on Aircraft**  
---**D. J. Barnard** and D. K. Hsu, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011
- 3:50 PM**      **Overview of Ultrasonic NDE Problematic for Composites: Material Point of View, Current State of Art and Future Directions**  
---**B. Hosten**, Laboratoire de Mécanique Physique, Université Bordeaux 1, UMR C.N.R.S. 5469 351 Cours de la Libération 33405, Talence Cedex, France
- 4:30 PM**      **Damage Progression in Ceramic Composites**  
---**R. J. Kerans** and G. E. Fair, Air Force Research Laboratory/Materials and Manufacturing Directorate, Wright-Patterson Air Force Base, OH 45433-7817; T. A. Parthasarathy, UES Inc., Dayton, OH 45433

**Aerospace Applications of Composite Materials**

---**Jonathan H. Gosse**, Phantom Works, The Boeing Company, Seattle, WA 98124-2499

---The analysis of the irreversible behavior of composite materials and structures is a complex task of increasing importance in the utilization of these material systems in advanced aerospace structures. The irreversible behavior of composite materials and structures includes damage instability, damage propagation, ultimate failure, damage tolerance and durability. Boeing Phantom Works (PW) has developed sophisticated theories, methodologies and tools specifically designed to address these issues. In this paper a high-level review of these efforts will be presented along with some discussion regarding future directions and the role of NDE as a complimentary technology to these procedures.

**NDE Developments for Composite Structures**

---**Richard H. Bossi**, Phantom Works, The Boeing Company, Seattle, WA 98124-2499

---Graphite-epoxy composite materials are attractive for advanced structural applications because of their excellent strength to weight ratios, high toughness, controlled anisotropy and ability to be fabricated any desired shape. But the utilization of composite structures has been limited to a large degree by their affordability. Significant improvements in composite affordability can realized through improved processing techniques, unitized structure designs and bonding. These activities are challenging NDE development in a number of areas. The most fundamental area is the correlation between NDE measurements and the structural performance characteristics. In the past, composite acceptability has been based to a large part on the ability to make a composite component to simple ultrasonic standard specifications. With larger, more complex composite structures a criterion better suited to the application is needed. As more automated technology is employed for graphite epoxy composite fabrication, automated on-line NDE is being sought. The unitized structure design concepts are creating configurations with considerable geometric complexity. NDE solutions that are simple, but can handle the geometry effects are needed. Finally, bonding offers one of the greatest challenges. Quality assurance of the bonding process and acceptance of the completed bond that will assure bond strength are key elements to composite structure applications.

**Inspecting Composites with Airborne Ultrasound: Through Thick and Thin**

---**David K. Hsu** and Daniel J. Barnard, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011

---Inspection of composite materials and structures with air-coupled ultrasound has the obvious advantage that it is non-contact, non-contaminating, and free from couplants. However, the transmission efficiency from air to solid is very low due to the large impedance difference. Development of more efficient airborne ultrasound transducers over the years has made it possible, and even practical, to inspect composites with airborne ultrasound. It is now possible to drive newer, more efficient transducers with a portable ultrasonic flaw detector to inspect 2-inch thick solid CFRP in air. In this overview we describe our experience in applying air-coupled ultrasound to the inspection of a variety of composite structures, from honeycomb with thin composite facesheet to very thick solid laminates. General considerations for making airborne ultrasonic measurement in composite are given, and mechanism of transmission through honeycomb core, and resonance effects in transmitting through thick laminates will be described. NDE results of defects and damage in various composite structures will be presented.---This material is based upon work supported by the NSF IUCRC at Iowa State University, and by the FAA under Contract #DTFA03-98-D00008, Delivery Order IA047, performed at CNDE as part of the CASR program; technical monitor was Paul Swindell.

**Development of Practical NDE Methods for Composite Structures on Aircraft**

---**D. J. Barnard** and D. K. Hsu, Iowa State University, Center for NDE, Ames, IA 50011

---With each new model, designers are specifying more composites for use in aircraft structures. Composites are alternatives to metallic alloys because of their higher specific stiffness or strength, which translates to lower weight and higher fuel efficiency. However, the increased attenuation and anisotropy of composite materials brings about an increased difficulty of in-service inspections, quantifying damage and evaluating repairs. Here, we will describe several methods developed by the Center for NDE and tested at various airline maintenance and repair facilities. The methods all make use of C-scan type outputs, making interpretation of the soundness of the part simpler, particularly with respect to differentiating defects from internal structure. We will demonstrate how lessons learned from applying these methods and by gauging the acceptance by inspectors can identify future directions for methods development.---This material is based upon work supported by the Federal Aviation Administration under Contract #DTFA03-98-D00008, Delivery Orders IA016, IA047 and 0038, and performed at Iowa State University's Center for NDE as part of the Center for Aviation Systems Reliability program; technical monitor is Paul Swindell.

**Overview of Ultrasonic NDE Problematic for Composites: Material Point of View, Current State of Art and Future Directions**

---**Bernard Hosten**, Laboratoire de Mécanique Physique, Université Bordeaux 1, UMR C.N.R.S. 5469 351, Cours de la Libération 33405 - TALENCE Cedex, France

---In the aerospace industry, it is now foreseen to use massively the composite materials. One restriction to their use was for many years, the lack of reliable NDE technique to follow their integrity. Indeed, contrary to metallic materials, the mechanical behavior of composites is far more complicated and the knowledge of the acoustic propagation mechanism needs to introduce many new features mainly as anisotropic stiffnesses, anisotropic attenuations, heterogeneities and weak interfaces. For instance the evaluation of industrial composite mechanical properties needs 7 (even 9) complex numbers to be evaluated, instead of 2 real numbers for metallic materials. The anisotropic attenuation was not very often taking into account; meanwhile it is fundamental to introduce it in the codes for predicting the propagation and the diffraction of waves by defects. Since composite materials are often made of layered plies, the heterogeneities in composite materials are initially due to the fabrication processes. These heterogeneities are well defined and can be introduced in the analytic or numeric models. Depending of the NDE purpose, these heterogeneities can be eliminate by introducing the homogenized properties or taking into account when one wants to see the effects of localized defects, weak interfaces, delimitations, etc ... Unfortunately, some other heterogeneities are randomly introduced by the fabrication process and produce space variations in the attenuation. For these composites, the large uncertainty on their properties implies the impossibility to detect the defects. This presentation will focus on the various methods and difficulties to evaluate the composites viscoelastic characteristics and their use in Finite Element codes for realistic predictions of the propagation of waves and their interaction with defects. This should permits to write reliable codes for predicting the "controllability" of complex structures made with composites.

**Damage Progression in Ceramic Composites**

---**Ronald J. Kerans** and Geoff E. Fair, Air Force Research Laboratory/Materials and Manufacturing Directorate AFRL/MLLN, Wright-Patterson AFB, OH 45433-7817; Triplicane A. Parthasarathy, UES Inc., Dayton, OH 45433

---Interest in ceramic composites is a consequence of their potential for dramatically improved damage tolerance as compared to monolithic ceramics while delivering similar high temperature properties. The remarkable toughening effect resulting from proper combination of three brittle phases in the form of fiber, coating and matrix is a consequence of a particular sequence in the development of damage. Successful design of composites requires the management of the progression of such damage, and successful application requires component designs that are in concert with the evolution of damage. Significant issues to be better understood include: the property compromises made to gain the desired toughness, development of properties as damage accumulates during use, and how those evolving properties affect design of components, or at least learning a design strategy to accommodate them. Because an evolving damage state is an inherent functional feature of ceramic composites, distinguishing significant damage from benign background damage is a significant problem. Moreover, the degradation level constituting a reasonable choice of end-of-life will be component dependent and is mostly unknown as yet. Issues associated with the design, behavior and identification of significant damage in ceramic composites will be discussed.

# *Session 5*

Monday, August 1, 2005

**SESSION 5**  
**NDE FOR CONCRETE STRUCTURES**  
**Moulton Union Lower Level**

- 1:30 PM**      **The Application of Magneto Inductive Sensors for Nondestructive Testing of Steel Reinforcing Bars Embedded Within Pre-Stressed and Reinforced Concrete**  
---**D. Benitez**, Q. Sung, P. Gaydecki, V. Torres, and B. Fernandes, The University of Manchester, School of Electrical and Electronic Engineering, P. O. Box 88, Manchester, M60 1QD, United Kingdom
- 1:50 PM**      **A Method for Imaging Steel Bars Behind a Ferrous Steel Boundary**  
---**B. Fernandes**, G. Miller, H. Hussin, M. Zaid, and P. Gaydecki, The University of Manchester, School of Electrical and Electronic Engineering, P. O. Box 88, Manchester, M60 1QD, United Kingdom
- 2:10 PM**      **Studies on Geometries for Inducing Homogeneous Magnetic Field in the Application of Real Time Imaging of Steel Reinforcing Bars Embedded Within Pre-Stressed and Reinforced Concrete**  
---**S. Quek**, D. Benitez, P. Gaydecki, and V. Torres, The University of Manchester, School of Electrical and Electronic Engineering, P. O. Box 88, Manchester, M60 1QD, United Kingdom
- 2:30 PM**      **Assessment of Corrosion Activity in Reinforcing Steel Bars Embedded Within Concrete Using the Inductive Scanning Technique**  
---**F. El-Madaani**, M. Zaid, P. Gaydecki, H. Hussin, and G. Miller, The University of Manchester, School of Electrical and Electronic Engineering, P. O. Box 88, Manchester, M60 1QD, United Kingdom
- 2:50 PM**      **Automatic Corrosion Classification and Quantification of Steel Reinforcing Bars Within Concrete Using Image Data Generated by an Inductive Sensor**  
---**M. Zaid**, F. El-Madaani, P. Gaydecki, and G. Miller, The University of Manchester, School of Electrical and Electronic Engineering, P. O. Box 88, Manchester, M60 1QD, United Kingdom
- 3:10 PM**      **Coffee Break**
- 3:30 PM**      **Finite-Element Analysis for Imaging Steel Bars Placed Under a Mild Steel Boundary Using Eddy Current Techniques**  
---**H. Hussin**, M. Zaid, P. Gaydecki, F. El-Madaani, and B. Fernandes, The University of Manchester, School of Electrical and Electronic Engineering, P. O. Box 88, Manchester, M60 1QD, United Kingdom
- 3:50 PM**      **Entrained Air Void Counting Using Inverse Scattering Method**  
---**W. Punurai**, L. J. Jacobs, and K. E. Kurtis, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA 30332; J. Qu and J. Jarzynski, G. W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332
- 4:10 PM**      **Novel TDR Cable Sensors for Crack Detection**  
---**G. Chen**, Department of Civil, Architectural, and Environmental Engineering, University of MO-Rolla, Rolla, MO 65409-0030
- 4:30 PM**      **Detecting Flaws in Concrete Slabs Using Air-Coupled Impact-Echo Method**  
---**J. Zhu** and J. S. Popovics, University of Illinois, Department of Civil and Environmental Engineering, 2152 Newmark Lab, 205 N. Mathews Avenue, Urbana, IL 61801
- 4:50 PM**      **Perturbations in the Core-Drilling Method Caused by Steel Reinforcement**  
---**M. J. McGinnis** and S. Pessiki, Department of Civil and Environmental Engineering, Lehigh University, Bethlehem, PA 18015

**The Application of Magneto Inductive Sensors for Nondestructive Testing of Steel Reinforcing Bars Embedded within Pre-stressed and Reinforced Concrete**

---**Diego Benitez**, Quek Sung, Patrick Gaydecki, Vladimir Torres, and Bosco Fernandes, The University of Manchester, School of Electrical and Electronic Engineering, P. O. Box 88, Manchester, M60 1QD, United Kingdom

---This paper demonstrates the feasibility of using solid-state magneto-inductive probes for detecting and imaging steel reinforcing bars embedded within pre-stressed and reinforced concrete. Changes in the inductance of the sensor material are directly proportional to the strength of the measured magnetic field parallel to the sensor. Important advantages such as high resolution, small size, rapid response, high sensitivity to a well defined axis, noise immunity, temperature stability, low power consumption and repeatability make it suitable for robust detection system design. Experimental results obtained by scanning different probes over steel bar specimens are presented. General performance characteristics and sensor output limitations are investigated by using different orientations, sensing distances, excitation intensities, bar sizes and geometries.

**A Method for Imaging Steel Bars Behind a Ferrous Steel Boundary**

---**Bosco Fernandes**, Graham Miller, Haitham Hussin, Muhammad Zaid, and Patrick Gaydecki, University of Manchester, School of Electrical and Electronic Engineering, P. O. Box 88, Manchester, M60 1QD, United Kingdom

---This paper describes the development of a new system for detecting and imaging steel objects on the distal side of a ferrous steel boundary up to 2 mm thick, using a three-coil system. Typically, it may be applied for the detection and imaging of steel reinforcing bars embedded within concrete, which includes a sheet steel layer located between the bars and the upper surface of the concrete. A transmitter, receiver and a dummy coil are placed on the upper surface of the specimen and moved along it. The dummy coil is used to cancel the cross-talk between the transmitter and receiver thereby enhancing the signal emanating from the steel bars. By exciting the transmitter with a signal at 125 Hz, it is possible to generate a magnetic field that is not severely attenuated by the sheet. This causes sufficient eddy currents to be induced in the steel bar making it detectable. Successful results have been obtained with a 2 mm thick mild steel sheet and 16 mm diameter mild steel bars.

**Studies on Geometries for Inducing Homogeneous Magnetic Field in the Application of Real Time Imaging of Steel Reinforcing Bars Embedded within Pre-stressed and Reinforced Concrete**

---**Sung Quek**, Diego Benitez, Patrick Gaydecki, and Vladimir Torres, The University of Manchester, School of Electrical and Electronic Engineering, P. O. Box 88, Manchester, M60 1QD, United Kingdom

---This paper addresses fundamental issues associated with the development of a real time inductive scanning system for non-destructive testing of pre-stressed and reinforced concrete. These include the coil dimension and the corresponding image depth, the effects of the coil's configuration on the principal components of the emanating magnetic flux density, the determination of AC (and the corresponding excitation frequency) or DC excitation for a given application, the optimum spatial location for positioning magnetic sensor array and the interactions between the primary field and the secondary field radiated by the metal target. Simulated results, based on a boundary element method for time-harmonic electromagnetic problems, has indicated that given a coil dimension of 300 x e 300 x e 40 mm, 10 mm rebars can be imaged down to a depth of 100 mm. Studies also indicate that the vertical component of the induced magnetic field is most favorable as it can be readily reconstructed to yield geometry and dimensional information pertaining to the rebar structure. In addition, studies also reveal that AC excitation would be a preferable option as it results in a signal strength two to three times stronger than that of DC excitation.

**Assessment of Corrosion Activity in Reinforcing Steel Bars Embedded within Concrete Using the Inductive Scanning Technique**

---**Fawzi El-Madaani**, Mohamed Zaid, Patrick Gaydecki, Haitham Hussin, and Graham Miller, The University of Manchester, School of Electrical and Electronic Engineering, P. O. Box 88, Manchester, M60 1QD, United Kingdom

---Concrete structures normally create highly alkaline environments due to the reaction of cement with water (the hydration process). The high alkalinity provides excellent corrosion protection for reinforcing steel due to the formation of a thin passive oxide film on the surface of the steel. Under high alkalinity (Ph>13) steel remains passivated. In the presence of chloride ions at the steel/concrete interface, the passive film breaks down and corrosion initiates, progresses at a steady rate on the steel reinforcing bars. As a result, corrosion products will build up with time causing cracking and delaminating of concrete structures. From a safety aspect as well as economic reasons, it is necessary to monitor concrete structures to detect corrosion at its early stages utilizing non-destructive testing techniques. In this paper, a new monitoring technique using inductive scanning technology is presented. The method generates a vector of voltage values of the reinforced concrete samples scanned in the laboratory at a spatial interval of 1.1mm. These voltage vectors are then compared to the potential mapping (measuring half-cell potentials at the concrete surface) data for the same concrete samples. Results obtained using the inductive scanning technique provide a more detailed view of the corrosion generated on the concrete samples. The advantages and limitations of both techniques are discussed.

**Automatic Corrosion Classification and Quantification of Steel Reinforcing Bars within Concrete Using Image Data Generated by an Inductive Sensor**

---**Muhammad Zaid**, Fawzi El-Madaani, Patrick Gaydecki, and Graham Miller, The University of Manchester, School of Electrical and Electronic Engineering, P. O. Box 88, Manchester, M60 1QD, United Kingdom

---Inductive imaging is a non-destructive testing technology that exploits the phenomenon of eddy current induction and detection for imaging steel reinforcing bars embedded within concrete. Over the last several years, significant progress has been achieved in aspects such as bar dimensional information extraction and scanning time reduction. However, the technology still lacks a proper system that would automatically classify and also quantify corrosion on the various images that are obtained using the inductive sensor. This paper presents a complete methodology that is able to segregate the corroded and non-corroded parts in the images generated by the inductive sensor and to automatically distinguish and quantify the corrosion on the corroded parts. The methodology comprises three stages: image generation using the inductive sensor, image segmentation and feature extraction and neural network object classification. The corroded bar samples are generated using an accelerated test at different currents. Preliminary results of applying the methodology on the images of the obtained samples have shown that the methodology has correctly classified all the corroded parts on the tested samples and has estimated the corrosion rate correctly on 65 % of the tested samples.

**Finite-Element Analysis for Imaging Steel Bars Placed Under a Mild Steel Boundary Using Eddy Current Techniques**

---**Haitham Hussin**, Muhammad Zaid, Patrick Gaydecki, Fawzi El-Madaani, and Bosco Fernandes, The University of Manchester, School of Electrical and Electronic Engineering, P. O. Box 88, Manchester, M60 1QD, United Kingdom

---This paper reports on recent results obtained using finite-element analysis for imaging steel bars placed under mild steel boundaries at different operating frequencies. Two eddy current techniques - inductive scanning and remote field eddy currents - have been used to model three different configurations. Firstly, using signal frequencies ranging between 4.5 kHz and 13 kHz, we have succeeded in modelling the magnetic field penetrating a 2 mm steel boundary. Based on this, the presence of a 16 mm bar under a 0.5 mm and a 1 mm steel boundary has been modelled at signal frequencies ranging between 325 Hz and 1.325 kHz. To penetrate thicker steel boundaries and increase the depth penetration, a different configuration based on remote field eddy currents (RFEC) has been attempted. Modelling results show that using this method it is possible to image steel wires wrapped around the mild steel pipe. This paper contains the details and results of all the above described models.

**Entrained Air Void Counting Using Inverse Scattering Method**

---**Wonsiri Punurai**, Laurence J. Jacobs, and Kimberly E. Kurtis, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA 30332; Jianmin Qu and Jacek Jarzynski, G.W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332

---A technique based on the attenuation of ultrasonic waves is developed for measurement of the average size and volume fraction of entrained air bubbles in hardened cement paste. These measurements are desired to ensure the safety design strength of a cement paste mixture as well as maintaining the ability to achieve the necessary resistance to freeze-thaw damage in cement-based materials. To obtain this information, ultrasonic attenuation coefficients of pulse-burst signals are determined for the frequency range of 500kHz-5MHz. From these parameters, the average size and the volume fraction of the entrained air bubbles can be determined using a combination of an ultrasonic scattering model and an inversion algorithm. Experiments are performed on specimens with and without entrained air. Good agreement between the model prediction and the experiments are found in the systems that contained low volume fraction of entrained air bubbles (< 10%). These results are validated independently using an optical microscopy technique.

**Novel TDR Cable Sensors For Crack Detection**

---**Genda Chen**, Department of Civil, Architectural, and Environmental Engineering, University of Missouri-Rolla, Rolla, MO 65409-0030

---In this paper, the recent development and validation of a fundamentally new, topology-based cable sensor design concept is reviewed for crack detection in reinforced concrete (RC) structures. The sensitivity, spatial resolution, and signal loss of sensors are investigated both numerically and experimentally. Two sensors were fabricated and validated with small- and large-scale laboratory tests under different loads. Both were proven sensitive to crack of various sizes from visually undetectable to excessive, giving the location and severity of damage simultaneously. One sensor has been installed on a three-span bridge for its long-term monitoring. It has a unique memory feature, capable of recording damage that has occurred during a recent event.

**Detecting Flaws in Concrete Slabs Using Air-Coupled Impact-Echo Method**

---**Jinying Zhu** and John S. Popovics, University of Illinois, Department of Civil and Environmental Engineering, 2152 Newmark Lab, 205 N. Mathews Avenue, Urbana, IL 61801

---In previous research, the non-contact NDT technique using air-coupled sensors has been developed and successfully detected surface wave propagation in concrete. In this study, the air-coupled sensor is used to determine the thickness of concrete slabs with impact-echo approach. Test results show that the air-coupled sensor works as effectively as the contact impact-echo sensors when proper impactors are used. No sound insulation is needed to eliminate direct acoustic waves. The air-coupled impact-echo test are then performed on a slab containing several artificial delaminations and voids. Evaluation of the degree of delaminations can be successfully conducted using the air-coupled sensors.

**Perturbations in the Core-Drilling Method Caused by Steel Reinforcement**

---**Michael J. McGinnis** and Stephen Pessiki, Department of Civil and Environmental Engineering, Lehigh University, Bethlehem, PA 18015

---The Core-Drilling Method is an emerging technique for measuring in-situ stress in concrete structures. A small hole is drilled into the structure, and the deformations in the vicinity of the hole are measured and related via elasticity theory to the stress. The method is similar to the ASTM hole-drilling strain-gauge method excepting that displacements rather than strains are the measured quantities. The technique may be considered non-destructive since the ability of the structure to perform its function is unaffected, and the hole is easily repaired. Measurements in the current work are performed using 3D digital image correlation and industrial photogrammetry. The theoretical basis for the method involves a material that is linear-elastic, isotropic and homogeneous, among other assumptions. Factors such as differential shrinkage, swelling induced during wet drilling, and the presence of reinforcement and aggregate violate some of these assumptions and require further review. The current paper addresses perturbations in the method caused by steel reinforcement within the concrete. The steel is significantly stiffer than the surrounding concrete, altering the expected displacement field. A numerical investigation performed indicates an under-prediction of stress by as much as 25% in some instances, although the effect is significantly smaller for most scenarios.

# *Session 6*

Monday, August 1, 2005

**SESSION 6**  
**THERMAL TECHNIQUES**  
**X. Han, Chairperson**  
**Cleveland Hall 151**

- 1:30 PM**      **Thermal Imaging at General Electric**  
---**H. I. Ringermacher**, D. R. Howard, and B. Knight, GE Global Research Center, P. O. Box 8, Schenectady, NY 12301
- 1:50 PM**      **Advances in Thermal Time-of-Flight Imaging with Flash Quenching**  
---**B. Knight**, D. R. Howard, and H. I. Ringermacher, GE Global Research Center, P. O. Box 8, Schenectady, NY 12301
- 2:10 PM**      **Comparison of Thermography Methods for Defect Depth Prediction**  
---**J. G. Sun** and J. Benz, Energy Technology Division, Argonne National Laboratory, Argonne, IL 60439
- 2:30 PM**      **The Potential of Sonic IR to Inspect Aircraft Components Traditionally Inspected with Fluorescent Penetrant and/or Magnetic Particle Inspection in the Field**  
---**X. Han**, L. D. Favro, J. Lu, Z. Zeng, W. Li, G. M. Newaz, and R. L. Thomas, Wayne State University, Physics Department, Detroit, MI; **J. DiMambro** and M. Ashbaugh, Sandia National Laboratories, NDI Validation Center (AANC), 3260 University Boulevard SE, Spirit Drive, Albuquerque, NM 87106
- 2:50 PM**      **Simulation of Sonic IR Imaging of Cracks in Metals with Finite-Element Models**  
---**X. Han** and M. S. Islam, Wayne State University, Department of Electrical and Computer Engineering, 5050 Anthony Wayne Drive, #3140, Detroit, MI 48202; G. Newaz, Wayne State University, Department of Mechanical Engineering, Detroit, MI 48202; L. D. Favro, Wayne State University, Institute for Manufacturing Research, Detroit, MI 48202; R. L. Thomas, Wayne State University, Department of Physics and Astronomy, Detroit, MI 48202
- 3:10 PM**      **Coffee Break**
- 3:30 PM**      **Quantitative Analysis of Flash Thermography Sequence Data**  
---**S. M. Shepard**, Y. Hou, J. R. Lhota, and T. Ahmed, Thermal Wave Imaging, Inc., 845 Livernois, Ferndale, MI 48220
- 3:50 PM**      **Thermographic Characterization of Reinforced Carbon-Carbon Composites**  
---**W. P. Winfree**, K. E. Cramer, J. N. Zalameda, and P. A. Howell, NASA Langley Research Center, MS 231, Hampton, VA 23681; K. L. Hodges, Lockheed Martin, Hampton, VA 23681; A. R. Roberts, Swales Aerospace
- 4:10 PM**      **Advances in Thermosonics for Detecting Impact Damage in CFRP Composites**  
---**T. J. Barden** and D. P. Almond, Research Centre for NDE, Department of Mechanical Engineering, University of Bath, Bath, BA2 7AY, United Kingdom; M. Morbidini and P. Cawley, Research Centre for NDE, Mechanical Engineering Department, Imperial College London, South Kensington Campus, London, SW7 2AZ, United Kingdom
- 4:30 PM**      **A New Approach for the Prediction of the Thermosonic Signal from Vibration Records**  
---**M. Morbidini** and P. Cawley, Imperial College, Department of Mechanical Engineering, Room 564, Exhibition Road, London, SW7 2AZ, United Kingdom; P. Duffour, University College London, Department of Civil and Environmental Engineering, United Kingdom; T. Barden and D. Almond, University of Bath, Department of Mechanical Engineering, United Kingdom
- 4:50 PM**      **Study of the Heat Generation Mechanism in Acoustic Thermography**  
---C. Homma, **M. Rothenfusser**, and J. Baumann, Siemens AG Corporate Technology, Otto-Hahn-Ring 6, Munich, D-81730, Germany

**Thermal Imaging at General Electric**

---**H. I. Ringermacher**, D. R. Howard, B. Knight,  
GE Global Research Center, P. O. Box 8,  
Schenectady, NY 12301

---We will describe advances in and current applications of Thermal Imaging at General Electric. Time-of-Flight methods are in use at several GE facilities. This approach is sufficiently robust to be used in production. Examples presented include evaluation of metal airfoils and ceramic materials.

**Advances in Thermal Time-of-Flight Imaging with Flash Quenching**

---**B. Knight**, D. R. Howard, H. I. Ringermacher,  
GE Global Research Center, P. O. Box 8,  
Schenectady, NY 12301

---Flash quenching, that is, cutting off the tail of the exponentially decaying light flash, permits great strides in realizing the ideal analysis of high resolution IR data. We will describe some current applications of Quenched Thermal Time-of-flight Imaging to high resolution evaluation of metals and fast materials.

**Comparison of Thermography Methods for Defect Depth Prediction**

---**J. G. Sun** and J. Benz, Energy Technology Division, Argonne National Laboratory, Argonne, IL 60439

---Pulsed thermography has been widely used as a nondestructive evaluation tool to detect defects such as delaminations within composite materials. In the literature, at least three methods have been developed and demonstrated to be capable of determining defect depth. They are the peak temperature-contrast slope method, the peak second-derivative method, and the least-square fitting method. Despite apparent differences in data processing algorithms, a recent study showed that all these methods are based on an analytical solution for one-dimensional heat conduction under ideal pulsed thermography conditions. Therefore, all methods should converge to the same analytical solution and result in accurate depth prediction under ideal conditions. The performance of these methods has been evaluated and compared with pulsed thermography data taken from a flat ceramic-composite sample with machined flat-bottom holes of different sizes and depths. Detailed temperature-time curves were examined for each method to illustrate the different characteristics that should be considered in data reduction algorithms. The effects of flash duration and three-dimensional heat conduction are discussed based on the experimental data.

**The Potential of Sonic IR to Inspect Aircraft Components Traditionally Inspected with Fluorescent Penetrant and/or Magnetic Particle Inspection in the Field**

---X. Han, L. D. Favro, Jianping Lu, Zhi Zeng, Wei Li, Golam M. Newaz, and R. L. Thomas, Wayne State University, Physics Department, Detroit, MI; **Joseph DiMambro** and Michael Ashbaugh, Sandia National Laboratories, NDI Validation Center (AANC), 3260 University Boulevard SE, Spirit Drive, Albuquerque, NM 87106

---As part of the Federal Aviation Administration (FAA) Sonic Infrared Technology Transfer Program, Sandia National Laboratories, Airworthiness Assurance Nondestructive Inspection Validation Center (AANC) and Wayne State University (WSU) are working together to implement Sonic IR in the field. The technique developed at WSU uses high-power ultrasonic excitation as a heat source and infrared technology to detect defects in a variety of materials. AANC has provided assistance in the form of characterized test specimens for research and development purposes. The inspection of these specimens combined with industry interest has us focused on two specific applications. The potential of Sonic IR to inspect aircraft components that are traditionally inspected with fluorescent penetrant inspection (FPI) and magnetic particle inspection (MPI) in the field is of interest. In addition, applying this technology to the inspection of composite materials is also being investigated. This paper will highlight current activities such as the Sonic IR inspection results of defective aircraft components supplied by airlines.

**Simulation of Sonic IR Imaging of Cracks in Metals with Finite-Element Models**

---**Xiaoyan Han** and Md. Sarwar Islam, Wayne State University, Department of Electrical and Computer Engineering, 5050 Anthony Wayne Dr., #3140, Detroit, MI 48202; Golam Newaz, Wayne State University, Department of Mechanical Engineering, Detroit, MI 48202; Lawrence D. Favro, Wayne State University, Institute for Manufacturing Research, Detroit, MI 48202; Robert L. Thomas, Wayne State University, Department of Physics and Astronomy, Detroit, MI 48202

---We will describe realistic finite-element models that simulate the heating of cracks in metals by both chaotic and non-chaotic sound. These models allow for both friction and plastic deformation as sources of heating. We will describe calculations of the relative efficiencies of the two kinds of sound for producing thermal contrast in images. We also will present both qualitative and quantitative comparisons of calculated temperature distributions with experimental images.

**Quantitative Analysis of Flash Thermography Sequence Data**

---**Steven M. Shepard**, Yulin Hou, James R. Lhota, and Tasdiq Ahmed, Thermal Wave Imaging, Inc., 845 Livernois, Ferndale, MI 48220

---Until recently, analysis of flash thermography cooling sequences has been limited to visual interpretation of surface temperature images, in which hot spots that appear in the image are associated with subsurface discontinuities in the sample that obstruct the flow of heat. This type of approach is limited in that subsurface features are identified in terms of their contrast with respect to a defect-free background, which may not exist at all, or may reside outside of the field of view. The Thermographic Signal Reconstruction (TSR) method provides an alternate approach to analysis that does not require visual identification of the target-background temperature contrast. Instead, TSR treats each pixel as a separate entity, and analyzes its logarithmic temperature-time history. The TSR derivatives, calculated with respect to the natural logarithm of time, offer an extremely useful means of evaluating the state of the sample on a pixel-by-pixel basis. Derivative results are readily predicted for intact monolithic samples, laminates, and general defect cases. The characteristic times associated with the derivative peaks can be used to measure depth, thickness or thermal diffusivity, and the shape of the peaks can be used to infer the properties of the buried feature or layer. Measurements have been confirmed using 1 and 2-dimensional modeling, as well as experimentally, in a variety of metals and composites.

**Thermographic Characterization of Reinforced Carbon-Carbon Composites**

---**William P. Winfree**, K. Elliott Cramer, Joseph N. Zalameda, and Patricia A. Howell, NASA Langley Research Center, MS 231, Hampton, VA 23681; Kenneth L. Hodges, Lockheed Martin, Hampton, VA 23681; Allison R. Roberts, Swales Aerospace

---Thermographic inspection is a viable technique for detecting in-service damage in reinforced carbon-carbon (RCC) composites representative of the RCC used as thermal protection in the leading edge of the shuttle orbiter. A significant advantage of thermography is the potential for a rapid, noncontacting, full field imaging, single-sided inspection that can be performed between flights without removing the RCC panels from the orbiter. This paper presents an assessment of the thermographic technique for detection of near surface and deep flaws in the RCC composites structures. Near surface flaws 0.3 cm in diameter or greater are shown to be easily detected in the thermographic images. Deeper flaws, 1.3 cm in diameter are detectable by processing the thermographic images to enhance the contrast between flawed and unflawed material. In particular, a principle component analysis technique is shown to be a very capable technique for rapid detection of deep flaws. Results are presented on several specimens with a collection of different size programmed flaws at different depths from the front surface. From the results on these specimens, a relationship between detectability and flaw size and depth has been determined.

**Advances in Thermosonics for Detecting Impact Damage in CFRP Composites**

---**Tim J. Barden** and Darryl P. Almond, Research Centre for NDE, Department of Mechanical Engineering, University of Bath, Bath, BA2 7AY, United Kingdom; Marco Morbidini and Peter Cawley, Research Centre for NDE, Mechanical Engineering Department, Imperial College London, South Kensington Campus, London, SW7 2AZ, United Kingdom

---Thermosonics or ultrasound stimulated thermography has been shown to reveal structural defects such as impact damage in CFRP that are not detectable by conventional optically stimulated thermography. However, there are concerns that the large amounts of ultrasonic excitation energy employed to make thermosonic inspections may cause damage, particularly by heating at the attachment point of the exciter. The objectives of this study were to investigate methods of reducing the electrical power required to detect defects and thus to reduce surface damage during testing. The magnitude of the heating at the surface over ultrasonically excited defects was modelled, to determine the heating requirements for different materials. Thermosonic images were collected whilst measuring test piece vibrations, using strain gauges and laser vibrometry. A long pulse, low power excitation method has been found to produce satisfactory impact damage images whilst eliminating damage to the test piece caused, in other methods, by heating of the ultrasonic excitation horn. Images of impact damage in 4mm and 8mm CFRP plates have been obtained using only 1watt of electrical power applied to an ultrasonic excitation horn.

**A New Approach for the Prediction of the Thermosonic Signal from Vibration Records**

---**Marco Morbidini** and Peter Cawley, Imperial College, Department of Mechanical Engineering, Room 564, Exhibition Road, London SW7 2AZ, United Kingdom; Philippe Duffour, University College London, Department of Civil and Environmental Engineering, United Kingdom; Tim Barden and Darryl Almond, University of Bath, Department of Mechanical Engineering, United Kingdom

---Thermosonics is a viable NDT method for the detection of contacting interface type defects such as fatigue cracks in metals and delaminations in composites. A high power acoustic horn is typically used to excite a complex vibration field which causes the defect interfaces to rub and dissipate energy as heat. The resulting local increase in temperature at one of the specimen surfaces can then be measured by an infrared camera. In this study a set of steel beams with fatigue cracks of different depth and variable partial crack opening was tested. Each beam was instrumented with strain gages across the crack and at the back face for the measurement of both the "breathing" behavior of the cracks and the excited vibration. The heat released at the crack was predicted from the measured vibration and an experimental estimate of the additional damping introduced in the specimens by each crack. These calculations were then used to predict the surface temperature rise as a function of time during the excitation and the results compared with the infrared camera measurements. The efficiency of the dissipation mechanisms was shown to be a function of the crack morphology. The general threshold level of vibration which allows reliable crack detection was also discussed for the purpose of the design of new, controlled excitation methods.

**Study of the Heat Generation Mechanism in Acoustic Thermography**

---Christian Homma, **Max Rothenfusser**, and Joachim Baumann, Siemens AG Corporate Technology, Otto-Hahn-Ring 6, Munich, D-81730, Germany

---Acoustic Thermography is a new imaging NDE technique for defect detection in various materials. Due to the induced vibration defects like cracks heat up which can be detected by infrared cameras. The technique can be applied to arbitrarily shaped objects. Also the size of the objects may vary within some orders of magnitude, e.g. from semiconductor components to large rotor discs of gas or steam turbines. While the vibrational behaviour of the objects has been studied in detail with optical methods like laser vibrometry the mechanism of heat generation is not well understood. We will report the results of recent investigations which reveal several different mechanisms contributing to the overall thermal signal. Besides frictional effects at crack faces also thermoplastic heating occurs at crack tips. In materials with high sound attenuation the bulk material itself heats up. In this case the detected infrared signal corresponds to local stress fields of the induced vibration. Moreover, the consequences of resonant excitation and the influence of local crack vibration modes will be discussed.

# ***TUESDAY***

Session 7 – UT Modeling and Simulation.....	27
Session 8 – NDE For Composites II.....	33
Session 9 – Microwave NDE.....	39
Session 10 – New Techniques.....	44
Session 11 – Posters: Student Poster Competition, Sensors and Techniques, Image and Signal Processing, Civil Materials and Structures, and Ultrasonics.....	50
Session 12 – Improved and New Techniques.....	76
Session 13 – Infrastructure NDE.....	79
Session 14 – Signal Analysis Techniques.....	83
Session 15 – Residual Stress I.....	87

# *Session 7*

Tuesday, August 2, 2005

**SESSION 7**  
**UT MODELING AND SIMULATION**  
**Druckenmiller Hall 016**

- 8:30 AM**      **Modeling of Ultrasonic Signals from a Side-Drilled Hole Using a Rectangular Transducer**  
---**H.-J. Kim** and S.-J. Song, Sungkyunkwan University, School of Mechanical Engineering, 300 Chunchun-dong, Jangan-gu, Suwon 440-746, Korea; L. W. Schmerr, Jr., Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011
- 8:50 AM**      **Modeling of 2D SH Wave Scattering by a Crack**  
---**T. Zagbai** and A. Bostrom, Chalmers University of Technology, Department of Applied Mechanics, SE-412 96 Goteborg, Sweden
- 9:10 AM**      **2D Wave Analysis Near the Interface Between Fluid and Anisotropic Solid**  
---**S. Hirose** and R. Kamitsuji, Department of Mechanical and Environmental Informatics, Tokyo Institute of Technology, Meguro-ku, Tokyo, Japan; C.-Y. Wang, Mathematics and Modeling Department, Schlumberger-Doll Research, Ridgefield, CT
- 9:30 AM**      **Use of a Mass-Spring Lattice Model for Simulating Ultrasonic Waves in an Anisotropic Elastic Solid**  
---**E. Baek** and H. Yim, Hongik University, Mechanical Engineering, 72-1 Sangsoo Dong, Mapo Ku, Seoul, 121-791, Korea
- 9:50 AM**      **Analysis of Wave Propagation for TOFD Methods with Finite Element Method**  
---**S. Lin**, H. Fukutomi, and T. Ogata, Materials Science Research Laboratory, Central Research Institute of Electric Power Industry, 2-11-1, Iwoda Kita, Komae-shi, Tokyo 201-8511, Japan
- 10:10 AM**      **Coffee Break**
- 10:30 AM**      **Diffraction Effects on Ultrasonic Guided Waves Radiated or Received by Transducers Mounted on the Section of the Guide**  
---K. Jezzine and **A. Lhémy**, LIST, Commissariat a l'Energie Atomique, Gif-sur-Yvette, France
- 10:50 AM**      **Guided Ultrasonic Wave Inspection of Corrosion at Ship Hull Structures**  
---**P. Fromme**, Department of Mechanical Engineering, University College London, United Kingdom
- 11:10 AM**      **Simulation of Ultrasonic Wave Propagation Using Spectral Element Method**  
---G. Baskaran and R. C. Lakshmana, Department of Applied Mechanics, Indian Institute of Technology Madras, Chennai 600036, Tamil Nadu, India; **K. Balasubramaniam** and C. V. Krishnamurthy, Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036, Tamil Nadu, India
- 11:30 AM**      **Finite Element Modeling of Guided Wave Propagation in Plates**  
---**M. K. KM**, S. Ramaswamy, and V. Kommareddy, Industrial Imaging and Modeling Lab, GE Global Research, Bangalore, India
- 11:50 PM**      **Lunch**

**Modeling of Ultrasonic Signals from a Side-drilled Hole Using a Rectangular Transducer**

---**Hak-Joon Kim** and Sung-Jin Song, Sungkyunkwan University, School of Mechanical Engineering, 300 Chunchun-dong, Jangan-gu, Suwon 440-746, Korea; Lester W. Schmerr, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011

---In ultrasonic nondestructive testing an angle beam transducer with a rectangular piezoelectric element is often adopted in practice to detect flaws. And, a side-drilled hole (SDH) is very widely used as a standard reflector in ultrasonic testing. For proper interpretation of the measurement results of a SDH using a rectangular transducer, it is very helpful to have a complete ultrasonic measurement model including ultrasonic beam model of the rectangular transducer, a scattering model of the SDH, and a ultrasonic system model. Recently, a highly efficient ultrasonic beam model of the rectangular transducer and an accurate scattering model of the SDH have been proposed. Thus, in this study, by integrating a system efficiency factor for a rectangular transducer, we will develop a complete ultrasonic measurement model to predict ultrasonic signals from a SDH. Based on the model to be developed, we will calculate the ultrasonic responses from a SDH at different transducer orientations to investigate the dependency of the response according to the transducer orientation. The predicted results will be compared to the experiments.

**Modelling of 2D SH Wave Scattering by a Crack**

---**Theo Zagbai** and Anders Bostrom, Chalmers University of Technology, Department of Applied Mechanics, SE-412 96 Goteborg, Sweden

---An analytical model of a 2D SH wave scattering by a crack in a cladding is developed in this paper. Two plates of different anisotropic materials in welded contact constitute the media of wave propagation. The upper plate is referred to as the base material supporting a probe while the lower one is regarded as the cladding that contains an open crack. The interface of contact is assumed to be wavy (as is the case in practice for common welded claddings). Anisotropy is restricted so that all planes perpendicular to the crack are planes of elastic symmetry. This constraint hence allows a decoupling of 2D SH from 2D in-plane waves. A hyper singular integral equation technique based on Fourier representations for the total field and crack boundary conditions lead to an integral equation for the crack opening displacement (COD). This equation is solved by expanding the COD in the modified Chebyshev functions. The reason for this expansion is that, these functions, alike the displacement fields, have square root behavior at the crack edges. This important property is therefore used to project the integral equations on the Chebyshev functions. The result is a linear system of equations where the expansion coefficients are the unknowns. The probe, acting here as both transmitter and receiver, is modelled upon the assumption that the traction is zero everywhere except on the plate-probe interface. An expression for the probe signal response is determined and numerical values are obtained from computer simulation and presented in the space (or time) domain.

**2-D Wave Analysis Near the Interface Between Fluid and Anisotropic Solid**

---**S. Hirose** and R. Kamitsuji, Department of Mechanical and Environmental Informatics, Tokyo Institute of Technology, Meguro-ku, Tokyo, Japan; C.-Y. Wang, Mathematics and Modeling Department, Schlumberger-Doll Research, Ridgefield, CT

---Acoustic wave propagation near the fluid-solid interface is affected by the properties of the solid. More specifically, exciting modes and dispersion curves of acoustic waves propagating in a fluid along the interface depend to some extent on anisotropic and inhomogeneous properties of the solid. In this paper, a time domain boundary element method is developed to determine acoustic wave field in a 2D fluid-solid layered medium. The solid is a general anisotropic medium so that inplane motions are not separated from antiplane motions even in a 2D problem. The incident pressure wave is generated by a type of acoustic sources such as monopole and dipole, and refracted waves by the fluid-solid interface are calculated at points in a fluid. Time-domain waveforms of refracted waves at several points are transformed into the frequency-wavenumber spectra, and the effect of source types and anisotropic properties of solids on dispersive properties of refracted waves will be discussed.

**Use of a Mass-Spring Lattice Model for Simulating Ultrasonic Waves in an Anisotropic Elastic Solid**

---**Eunsol Baek** and Hyunjune Yim, Hongik University, Mechanical Engineering, 72-1 Sangsoo Dong, Mapo Ku, Seoul, 121-791, Korea

---Anisotropic media such as austenitic welds have been known difficult to inspect using the ultrasonic nondestructive testing (NDT) method because of the complex wave behaviors therein. Several previous studies have demonstrated a great potential, in simulating ultrasonic NDT in isotropic elastic media, of the mass-spring lattice model (MSLM). MSLM is a numerical model of an elastic solid in view of the dynamic behaviors of mass-points interconnected via linear springs. In the present work, a modified MSLM, called the rectangular mass-spring lattice model (RMSLM), is introduced which better models transversely isotropic media. Using the RMSLM, various wave phenomena such as point-source radiation, propagation, and reflection in a transversely isotropic medium have been simulated. The numerical results such as the displacement polarization, magnitude and direction of the group velocity, and reflection angles are shown to agree very well with the analytically found values. Thus, it may be concluded that the RMSLM may serve as a useful numerical tool for simulating ultrasonic NDT in anisotropic media such as austenitic welds.

**Analysis of Wave Propagation for TOFD Methods with Finite Element Method**

---**Shan Lin**, Hiroyuki Fukutomi, and Takashi Ogata, Materials Science Research Laboratory, Central Research Institute of Electric Power Industry, 2-11-1, Iwoda Kita, Komae-shi, Tokyo 201-8511, Japan

---TOFD techniques are applicable to detection and sizing of flaws in power plant components and much attention is being paid to the techniques in these years. However TOFD techniques have more complicated wave propagation than conventional angle beam techniques. Precise understanding of their wave propagation will help us to apply the techniques more effectively. FEM analysis of wave propagation of the techniques is performed under plane strain assumption. FEM analysis of wave propagation of the techniques is performed under plane strain assumption. Lumped mass matrix approximation and a unique data structure of stiffness matrix are introduced. Analyzed domain is a rectangle with length and height of 110mm and 25mm, respectively. Triangular elements are applied to subdivide the domain. Mesh size and time step are 0.05mm and 2ns. The frequency of incident wave is 7.5MHz and refract angle is 60 degrees. An experiment is also performed in a specimen with a normal notch open to the opposite surface of transducers. Experimental received signals are in good agreement with numerical ones. Numerical results show that the error of flaw depth due to the deviation of 5mm of lateral position is smaller than 0.3mm. Finally, wave propagation behavior is also analyzed in a model with inclined notches and the effect of the incline on sizing accuracy is investigated at well.

**Diffraction Effects on Ultrasonic Guided Waves Radiated or Received by Transducers Mounted on the Section of the Guide**

---Karim Jezzine and **Alain Lhémery**, LIST, Commissariat à l'Energie Atomique, Gif-sur-Yvette, France

---Ultrasonic guided waves (GW) propagate over long distances in guiding structures such as plates, rods, tubes etc. Various models to predict them are well established. Dispersion curves can be calculated depicting the behavior of propagating modes as functions of the frequency. Predicting the amplitude of all propagating modes as they are radiated by an actual transducer is somewhat more difficult. GW are commonly radiated from the guiding surface: one of the two planes of a plate, cylindrical surface of a rod, outer (or inner) cylindrical surface of a tube etc. The semi-analytic finite element (SAFE) method allows such predictions. It is sometimes more convenient to radiate (and receive) GW from the guide section. To deal with such testing configurations, a modified form of the SAFE method is proposed. It allows to predict very efficiently (the 3D problem being transformed into a 2D one) amplitudes and time-dependent waveforms (by Fourier synthesis) of both propagating, inhomogeneous and evanescent modes. The proposed formulation is specifically used to study transducer diffraction effects in such configurations (e.g. influence of transducer aperture or bandwidth). For illustration, numerical examples concern mode radiation and reception in cylindrical guides. Practical implications to ultrasonic testing by guided waves are discussed.

**Guided Ultrasonic Wave Inspection of Corrosion at Ship Hull Structures**

---**Paul Fromme**, Department of Mechanical Engineering, University College London, United Kingdom

---Many technical structures, e.g., ships, are subject to corrosion and fatigue damage during their service life. Corrosion damage often results in severe thickness reduction close to structural features of the hull, e.g., frames, stiffeners, and welds. This poses a significant inspection problem in modern double-hull ships, where access for conventional inspection techniques is very limited. Guided ultrasonic waves can propagate over large distances in thin structures like the hull plates of a ship and allow for efficient nondestructive testing of such structures with limited access. The sensitivity of guided ultrasonic waves for damage detection close to structural features, e.g., stiffeners, in plate-like structures, has been investigated. The combined interaction of the guided ultrasonic waves with defects and structural features in large structures has been modeled numerically to predict and improve the sensitivity and reliability of damage detection. The results have been compared to experimental results at laboratory size specimens and good agreement was found.

**Simulation of Ultrasonic Wave Propagation Using Spectral Element Method**

---G. Baskaran and Rao C. Lakshmana, Department of Applied Mechanics, Indian Institute of Technology Madras, Chennai 600036, Tamil Nadu, India; **Krishnan Balasubramaniam** and C. V. Krishnamurthy, Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036, Tamil Nadu, India

---Numerical simulation of ultrasonic wave propagation using methods such as Finite Element or Finite Difference, is computationally expensive particularly when (a) structural dimensions are high, (b) inspection at higher frequencies (due to short wavelengths), and (c) in complex materials that are not isotropic. This paper discusses a numerical technique which is similar to FEM, but works in frequency domain and has advantage of more accurate results in quick computational time called the Spectral Element Method (SEM). When the second order partial differential wave equation transformed to frequency domain by Continuous Fourier Transform, the wave equation transforms to ordinary differential equation (ODE) that has exact solution. This paper discusses simulation of Lamb wave modes and Time of Flight Diffraction Technique in isotropic plates.

**Finite Element Modeling of Guided Wave Propagation in Plates**

---**Manoj Kumar KM**, Sivaramanivas Ramaswamy, and Vamshi Kommareddy, Industrial Imaging and Modeling Lab, GE Global Research, Bangalore, India

---This paper aims at developing a numerical model for guided wave propagation in plates and the interaction of modes with defects using Finite Element Modeling (FEM). Guided waves propagate as extensional, flexural and torsional waves. Theoretically, these modes are infinite in number, but only some of these propagate and the others are attenuated. The dispersion curves for a structure reveal the plausibility of these modes. In this paper, FEM is used to examine interaction of first few symmetric and anti-symmetric modes independently with the cracks of various sizes in a plate. A comparison of pure mode sensitivity with crack size is discussed and the obtained data is validated with experiments. A time-frequency representation of the acquired guided wave mode signals will be discussed to show the mode sensitivity with crack size.

# *Session 8*

Tuesday, August 2, 2005

**SESSION 8**  
**NDE FOR COMPOSITES II**  
**Cleveland Hall 151**

- 8:30 AM**      **Ultrasonic Characterization of Composites: Capabilities and Limitations**  
---**S. I. Rokhlin**, Nondestructive Evaluation Program, The Ohio State University, Edison Joining Technology Center, 248 Arthur E. Adams Drive, Columbus, OH 43221
- 9:10 AM**      **Thermal History Sensor: Towards Smart Components**  
---**G. E. Fair** and R. J. Kerans, Air Force Research Laboratory/Materials and Manufacturing Directorate, AFRL/MLLN, Wright-Patterson, AFB, OH 45433-7817; T. A. Parthasarathy, UES Inc., Dayton, OH 45433
- 9:30 AM**      **The Effect of Composite Material Anisotropy on Ultrasonic Guided Wave Tomography**  
---**E. T. Hauck**, F. Yan, H. Gao, and J. L. Rose, Department of Engineering Science and Mechanics, The Pennsylvania State University, University Park, PA 16802
- 9:50 AM**      **Modeling of the Ultrasonic Propagation into Carbon-Fiber-Reinforced Epoxy Composites, Using a Ray Theory Based Homogenization Method**  
---**S. Deydier**, P. Calmon, and N. Leymarie, Commissariat a l'Energie Atomique, LIST, CEA-Saclay, Bat. 611, 91191 Gif-sur-Yvette, Cedex, France; V. Mengeling, EADS/CCR, BP 76, 12 rue Pasteur, 92152 Suresnes, Cedex, France
- 10:10 AM**      **Coffee Break**
- 10:30 AM**      **Using SAFT for Signal Improvement in Composites**  
---**C. Engstrand** and R. A. Kline, San Diego Center for Materials Research, Department of Mechanical Engineering, San Diego State University, San Diego, CA 92182
- 10:50 AM**      **An Ultrasonic Nondestructive Method for Evaluating Carbon/Carbon Composites**  
---**K.-H. Im**, Department of Automotive Engineering, Woosuk University, 490, Hujung-ri, Samrae-up, Wanju-kun, Chonbuk, 565-701, Korea; D. K. Hsu, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011; S.-J. Song and H. Cho, School of Mechanical Engineering, Sungkyunkwan University, Kyonggi-do, 440-746, Korea; J.-W. Park, Dept. of Naval Architecture and Ocean Eng., Chosun University, 375 Seosuk-dong, Dong-gu, Kwangju 501-759, Korea; I.-Y. Yang, School of Mechanical Engineering, Chosun University, 375 Seosuk-dong, Dong-gu, Kwangju 501-759, Korea
- 11:10 AM**      **Nondestructive Evaluation Using HTS SQUID Magnetometer to Detect Impact Damage in Carbon Fiber Reinforced Polymers with Different Fiber Orientation**  
---**C. Bonavolontà**, Department of Materials and Production Engineering, University of Naples, Federico II, Naples, Italy; M. Valentino, G. P. Pepe, and G. Peluso, Department of Physical Science, University of Naples, Federico II, Naples, Italy; CRS Coherentia National Institute of Matter Physics (INFM), Naples, Italy
- 11:30 AM**      **Material Characterization in Flexibility Supported Shear Deformable Laminated Composite Plates**  
---C. M. Chen and **T. Y. Kam**, Mechanical Engineering Department, National Chiao Tung University, Hsin Chu, Taiwan, Republic of China
- 11:50 AM**      **Fundamentals of Wave Propagation in Cellular Structures**  
---**M. Ruzzene** and S. Gonella, Georgia Institute of Technology, School of Aerospace Engineering, Atlanta, GA 30332; M. Klein, T. Sienicki, and J. Eichenberger, Lasson Technologies, Culver City, CA 90230; Z. Shi and J. Smith, Corning Incorporated, Advanced Engineering Systems, MCSI, Corning, NY 14831
- 12:10 PM**      **Lunch**

**Ultrasonic Characterization of Composites: Capabilities and Limitations**

---**S.I. Rokhlin**, Nondestructive Evaluation Program, The Ohio State University Edison Joining Technology Center, 248 Arthur E. Adams Drive, Columbus, OH 43221

---Composites are enjoying widespread application in primary and secondary structures in both military and civilian aircraft. Polymer and ceramic matrix composites for jet engines are beginning to find application. Composites are extremely nonhomogeneous and anisotropic compared to metals and have different modes of damage in service which may require different practical ways to address their inspection needs. This creates new challenges for quantitative evaluation and inspection of composites, not only after manufacturing but also in service. In this paper recent advances in ultrasonic characterization of composites and distributed composite damage are addressed. Both experimental and modeling methods are considered. Difficulties and unresolved ultrasonic NDE issues are also discussed.

**Thermal History Sensor: Towards Smart Components**

---**Geoff E. Fair** and Ronald J. Kerans, Air Force Research Laboratory/Materials and Manufacturing Directorate AFRL/MLLN, Wright-Patterson AFB, OH 45433-7817; Triplicane A. Parthasarathy, UES Inc., Dayton, OH 45433

---The degradation of mechanical properties of materials during service is strongly dependent on the history of thermal exposure resulting from thermally-activated microstructural processes. This degradation can lead to catastrophic failure of engineering components; consequently, knowledge of the thermal history of a component is crucial to predicting the degradation of properties and anticipating/preventing failures. In this work, a thermal history sensor capable of operating in severe environments has been developed which functions as much more than a thermal fuse, but less than a computer monitored thermocouple. The sensor utilizes the thermally activated crystallization of glass-ceramics to record a thermal history fingerprint in an array of glass-ceramic substrates. Computer modeling as well as experimental results are presented as proof of concept for the sensor. Degradation state sensing as well as the potential limitations on use of the sensor will also be discussed. The end product will employ a pattern-matching algorithm to characterize instantly the thermal exposure by comparing to a database of thermal history fingerprint. The thermal history sensor is expected to be useful in a variety of high temperature, severe environment applications.

**The Effect of Composite Material Anisotropy on Ultrasonic Guided Wave Tomography**

---Eric T. Hauck, Fei Yan, Huidong Gao, and Joseph L. Rose, Department of Engineering Science and Mechanics, The Pennsylvania State University, University Park, PA 16802

---Ultrasonic guided wave tomography has great potential for nondestructive destructive evaluation and structural health monitoring. In this paper, the effect of anisotropy and inhomogeneity in a cross-ply carbon fiber composite plate is compared with an isotropic aluminum plate when using Lamb wave tomography. An impact delamination in the composite plate is compared with a simulated corrosion defect in the aluminum plate of equal size. The reconstruction algorithm of the ultrasonic guided wave tomography is modified by taking into account the effect of the anisotropy based on wave velocity and skew angle. The enhanced tomogram will use features such as amplitude, wave velocity, and comparison of signals before and after damage.

**Modeling of the Ultrasonic Propagation Into Carbon-Fiber-Reinforced Epoxy Composites, Using A Ray Theory Based Homogenization Method**

---Sébastien Deydier, Pierre Calmon, and Nicolas Leymarie, Commissariat à l'énergie Atomique, LIST, CEA-Saclay, Bât. 611, 91191 Gif-sur-Yvette cedex, France; Vanessa Mengeling, EADS/CCR, BP 76, 12 rue Pasteur, 92152 Suresnes cedex, France

---Simulation of ultrasonic testing is of great interest for the aircraft industry to improve measurement analysis and optimize configurations. This paper describes a study dedicated to the modeling of the ultrasonic propagation in parts made of carbon-fiber-reinforced epoxy composites (CFRP), whose thickness and shape complexity tend to increase in current industrial use. In a previous communication, we proposed to compute the field radiated into such parts by means of a ray theory based homogenization method, coupled to the pencil model implemented in CIVA simulation platform. This homogenization is based on the follow-up of the energy ray path inside each ply of a repeated pattern, which gives access to an average energy direction. A set of calculated energy directions allows us to construct the overall slowness surfaces, and an appropriate inverse method is then applied to obtain the associated effective stiffness tensor. Therefore, an effective anisotropic homogeneous medium is described, characterizing the whole composite. In this paper, an improvement is developed, which consists in fully taking into account the inner refraction phenomenon. The benefits of this procedure are shown through comparisons of measured and simulated fields transmitted through parts of continuously varying thickness.

### **Using SAFT for Signal Improvement in Composites**

---**Cody Engstrand** and Ronald A. Kline, San Diego Center for Materials Research, Department of Mechanical Engineering, San Diego State University, San Diego, CA 92182

---Ultrasonic inspection of layered composites is an important area of NDE. Testing of layered composite parts is difficult, due to their anisotropy and highly attenuative nature. Synthetic aperture focusing technique (SAFT) can increase both signal-to-noise ratio and lateral resolution in these tests. When applying SAFT to anisotropic media, directionally dependent velocities and beam skew phenomena must be taken into account. In this paper we present a full three dimensional synthetic aperture focusing algorithm for layered anisotropic media that works for any number of layers and ply orientations. Tests have been performed on composites of varying ply orientations with flat bottom holes.

### **An Ultrasonic Nondestructive Method For Evaluating Carbon/Carbon Composites**

---**Kwang-Hee Im**, Department of Automotive Eng., Woosuk University, 490, Hujung-ri, Samrae-up, Wanju-kun, Chonbuk, 565-701, Korea; David K. Hsu, Center for NDE, Iowa State University, 1910 Scholl Road, Ames, IA 50011; Sung-Jin Song and Hyeon Cho, School of Mechanical Engineering, Sungkyunkwan University, Kyonggi-do, 440-746, Korea; Je-Woong Park, Dept. of Naval Architecture and Ocean Eng., Chosun University, 375 Seosuk-dong, Dong-gu, Kwangju 501-759, Korea; In-Young Yang, School of Mechanical Engineering, Chosun University, 375 Seosuk-dong, Dong-gu, Kwangju 501-759, Korea

---Advanced materials are required to have specific functions associated with extremely environments. Especially carbon/carbon (C/C) composites are one of the few materials that are suitable for structural applications at high temperature environments. Characterization and integrity of carbon/carbon(C/C) composite materials should be evaluated because of its inhomogeneity and composite. A nondestructive evaluation (NDE) technique would be very beneficial to assess material properties and part homogeneity because manufacturing of C/C composites requires complicated and costly processes. In this work, a C/C composite material was nondestructively characterized and a technique was developed to measure ultrasonic velocity in C/C composites using automated data acquisition software. We have proposed a peak-delay measurement method based on the pulse overlap measurement method. Also through transmission mode was performed to compare ultrasonic velocity with the above peak-delay measurement method in an immersion tank. The variation of ultrasonic velocity was measured and found to be consistent with those in a large C/C composite manufactured by chemical vapor infiltration (CVI) method. These results were compared with that obtained by dry-coupling ultrasonics. Through-transmission scan method was performed based on both amplitude and time-of-flight of the ultrasonic pulse for mapping out the material property inhomogeneity. A peak-delay measurement method well corresponded to ultrasonic velocities of the pulse overlap method of through-transmission mode and C-scan image variation based on peak-to-peak and time-of-flight amplitude.

**Nondestructive Evaluation Using HTS SQUID Magnetometer to Detect Impact Damage in Carbon Fiber Reinforced Polymers With Different Fiber Orientation**

---**C. Bonavolontà**, Department of Materials and Production Engineering, University of Naples "Federico II", Naples, Italy; M. Valentino, G. P. Pepe, and G. Peluso, Department of Physical Science, University of Naples "Federico II", Naples, Italy; CRS "Coherentia" National Institute of Matter Physics (INFM), Naples, Italy

---In this work the detection of damage, due to impact loading, on CFRPs using eddy current technique based on HTS dc-SQUID (Superconductive QUantum Interference Device) magnetometer is presented. The main advantage of HTS SQUID magnetometer in NDE applications is represented by its unrivalled magnetic flux sensitivity down to very low frequencies, which allows the detection of weak magnetic fields variations due to defects also in materials characterized by a very low electrical conductivity. The variation of the magnetic flux measured by the SQUID sensor during the scan allow to obtain an imaging of the damaged area of sample. The SQUID spatial magnetic flux distribution gives information about the position of the defect and the tensile strength of fiber orientations. The imaging obtained by means of the magnetic flux variations could be an useful technique for an easier interpretation of SQUID magnetic responses get along without post-processing algorithm.

**Material Characterization of Flexibly Supported Shear Deformable Laminated Composite Plates**

---Ching Rong Lee and **Tai Yan Kam**, Mechanical Engineering Department, National Chiao Tung University, Hsin Chu, Taiwan, Republic of China

---A nondestructive evaluation method is presented for material characterization of elastically restrained shear deformable laminated composite plates using impulse vibration test data. The theoretical natural frequencies of the elastically restrained laminated composite plate are determined in the Rayleigh-Ritz method using trial material properties of the plate system. A number of natural frequencies are extracted from the vibration data of the elastically restrained plate. An error function is established to measure the differences between the experimentally and theoretically predicted natural frequencies of the elastically restrained plate. The material characterization of the plate is then formulated as a constrained minimization problem in which the mechanical properties of the plate and elastic supports are determined by making the error function a global minimum. The feasibility and accuracy of the proposed method are studied via both theoretical and experimental approaches. It has been shown that only six measured natural frequencies are needed in the proposed method to produce good estimates of the material properties of the plate system. The excellent results obtained in this study have validated the applicability of the proposed method.

**Fundamentals of Wave Propagation in Cellular Structures**

---**M. Ruzzene** and S. Gonella, Georgia Institute of Technology, School of Aerospace Engineering, Atlanta, GA 30332; M. Klein, T. Sienicki, and J. Eichenberger, Lasson Technologies, Culver City, CA 90230; Z. Shi and J. Smith, Corning Incorporated, Advanced Engineering Systems, MCSI, Corning, NY 14831

---Cellular composites and ceramics are becoming preferred structural elements for critical applications. Cellular structures have great mechanical strength, vibration resistance and are very durable. Furthermore, cellular configurations greatly increase surface area and reduce weight. Honeycomb structures allow for the production of various cell shapes and sizes. Thus, cellular structures can be designed to present an ideal geometric structure for applications that require slight margins of safety. This flexibility in the geometric structure presents a considerable challenge to acoustic inspection techniques. The propagation of waves in three-dimensional structures with periodic cells is not well understood. Periodic structures have unique wave propagation characteristics that allow mechanical waves in specific frequency bands to propagate, while mechanical waves in the frequency "band gap" region are attenuated. A numerical model of a three dimensional cellular structure will be developed and experimentally verified using laser ultrasonics. The fundamental knowledge gained from this research is expected to provide insight into wave propagation in complex structures.

# *Session 9*

Tuesday, August 2, 2005

**SESSION 9**  
**MICROWAVE NDE**  
**N. Bowler, Chairperson**  
**Moulton Union Main Lounge**

- 8:30 AM**      **Overview of Microwave and Millimeter Wave Testing Activities for the Inspection of the Space Shuttle SOFI and Heat Tiles**  
---**R. Zoughi**, University of MO-Rolla, Applied Microwave NDT Laboratory, Electrical and Computer Engineering Department, EECH 224, Rolla, MO 65409
- 9:10 AM**      **The Effect of Probe Lift-Off on Crack Detection Sensitivity by the Open-Ended Waveguide Technique**  
---A. M. Yadegari, F. Mazlumi, **S. H. H. Sadeghi**, and R. Moini, Amirkabir University of Technology, Electrical Engineering Department, 424 Hafez Avenue, Tehran 15914, Iran
- 9:30 AM**      **Millimeter Wave Imaging of Corrosion Under Paint in Aluminum Structures**  
---**M. T. Ghasr**, S. Kharkovsky, and R. Zoughi, Applied Microwave NDT Laboratory, Electrical and Computer Engineering Department, University of MO-Rolla, Rolla, MO 65409; M. O'Keefe, Materials Science and Engineering Department, University of MO-Rolla, Rolla, MO 65409; D. Palmer, The Boeing Company, St. Louis, MO 63166-0516
- 9:50 AM**      **Hybrid Numerical Model for Microwave NDE of Civil Structures**  
---**K. Arunachalam**, V. R. Melapudi, L. Udpa, and S. S. Udpa, Michigan State University, Electrical and Computer Engineering, E. Lansing, MI 48824-1226
- 10:10 AM**      **Coffee Break**
- 10:30 AM**      **Local Probe Microwave Imaging Techniques and Their Applications in NTD of Cu/Si, Magnetic Materials and Structural Health Monitoring**  
---**M. Tabib-Azar**, Case Western Reserve University, 10900 Euclid Avenue, Cleveland, OH 44106
- 11:10 AM**      **Characterization of Dielectric and Magnetic Properties of Powdered Materials Such as Powdered Coal**  
---**R. J. Weber**, Iowa State University, Department of Electrical and Computer Engineering, Ames, IA 50011
- 11:30 AM**      **Monitoring the Effect of Relative Humidity During Curing on Dielectric Properties of Composites at Microwave Frequencies**  
---**N. Bowler** and E. R. Abram, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011
- 11:50 AM**      **A Formula for Dielectric Mixtures**  
---**E. Tuncer**, Oak Ridge National Laboratory, Applied Superconductivity Group, High Voltage and Dielectrics, Oak Ridge, TN 37831
- 12:10 PM**      **Lunch**

**Overview of Microwave and Millimeter Wave Testing Activities for the Inspection of the Space Shuttle SOFI and Heat Tiles**

---**Reza Zoughi**, University of Missouri-Rolla, Applied Microwave NDT Laboratory, Electrical and Computer Engineering Department, EECH 224, Rolla, MO 65409

---Microwave and millimeter wave nondestructive testing and evaluation methods, have shown great potential for inspecting the Space Shuttle's external tank spray on foam insulation (SOFI) and acreage heat tiles. These methods are capable of producing high-resolution images of the interior of these structures. To this end, several different microwave and millimeter wave nondestructive testing methods have been investigated for this purpose. These methods have included near-field as well as focused approaches ranging in frequency from 10 GHz to beyond 100 GHz. Additionally, synthetic aperture focusing methods have also been developed in this regime for obtaining high-resolution images of the interior of these critical structures. These methods possess the potential for producing 3D images of these structures in a relatively short amount of time. This paper presents a summary of these activities in addition to providing examples of images produced using these diverse methods.

**The Effect of Probe Lift-Off on Crack Detection Sensitivity by the Open-Ended Waveguide Technique**

---Amir M. Yadegari, Farhad Mazlumi, **S. H. Hesam Sadeghi**, and Rouzbeh Moini, Amirkabir University of Technology, Electrical Engineering Department, 424 Hafez Avenue, Tehran 15914, Iran

---There are several nondestructive testing techniques for detecting surface cracks in metals each of which possesses certain limitations and disadvantages. In the last decade, the use of open-ended waveguide technique has shown promising for detection of surface cracks in metals. In this technique, the metal surface is scanned by an excited open-ended waveguide probe while its standing wave characteristics is monitored using a slotted guide and a diode detector. The crack detection and sizing in this technique is done by analyzing the detector signal at different crack positions beneath the open-ended waveguide aperture. In practice, there should be a small lift-off distance between the probe and the metal surface in order to facilitate the probe movement. This paper presents a modeling technique to study the effect of probe lift-off on the sensitivity of crack detection. Several theoretical and experimental results are presented to demonstrate the validity of the proposed modeling technique.

**Millimeter Wave Imaging of Corrosion Under Paint in Aluminum Structures**

---**M. T. Ghasr**, S. Kharkovsky, and R. Zoughi, Applied Microwave NDT Lab., Electrical and Computer Engineering Department, University of Missouri-Rolla, Rolla, MO 65409; M. O'Keefe, Materials Science and Engineering Department, University of Missouri-Rolla, Rolla, MO 65409; D. Palmer, The Boeing Company, St. Louis, MO

---Critical aircraft structures are susceptible to harsh environmental conditions that cause corrosion of these structural components. Early detection of corrosion affects the required effort and cost associated with repair and maintenance of these structures. It is of great importance to detect corrosion under paint particularly in its early stages before it causes blistering of paint and the eventual structural failure. Millimeter wave nondestructive evaluation methods have shown great potential for detecting corrosion under paint and evaluating its properties. However, at the early stages of corrosion process, the perturbation caused by corrosion on the reflected millimeter wave signal may be small and strong clutter may mask this signal. This paper presents and compares the results of using two distinct detection methods; namely a standard single probe and a differential probe that coherently removes the effect of clutter, for imaging several corroded aluminum panels. The panels were corroded in a salt fog chamber, with varying exposure times resulting in progressive increase in the amount of corrosion. These panels were subsequently painted and tested using the two methods mentioned above. The imaging attributes of each method along with a quantitative measure of detection capability of each method will be presented as well.

**Hybrid Numerical Model for Microwave NDE of Civil Structures**

---**Kavitha Arunachalam**, Vikram R. Melapudi, Lalita Udpa, and Satish S. Udpa, Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48824-1226

---Nondestructive assessment of the integrity of civil structures is paramount for the safety of the nation. In concrete imaging, radiography, ground penetrating radar and infrared thermography are the widely used and accomplished techniques for health monitoring. The other emerging technologies that are gaining impetus for location of steel reinforcement bars and flaws include radioactive computed tomography, microwave holography, microwave and acoustic tomography. Good penetration and contrast between rebar and concrete and the non-radioactive nature makes microwaves a promising imaging modality of all the emerging techniques. This paper presents a hybrid numerical model based on FE and BI for investigating the feasibility of using microwave for detecting and characterizing corrosion in reinforced concrete structures. Simulation results and some initial experimental measurements will be presented.

**Local Probe Microwave Imaging Techniques and Their Applications in NTD of Cu/Si, Magnetic Materials and Structural Health Monitoring**

---**M. Tabib-Azar**, Case Western Reserve University, 10900 Euclid Avenue, Cleveland, OH 44106

---A new family of probes that use near-field (also called evanescent) electromagnetic fields to non-destructively study electromagnetic properties of materials at 1-20 GHz will be discussed. These probes are used to perform microwave microscopy and imaging with very high spatial resolution of  $\lambda/1000,000$  where  $\lambda$  is the wavelength of the microwave. Such an unprecedented high spatial resolution with electromagnetic fields having relatively large wavelengths ( $\lambda_{\text{free space}} \approx 1.5\text{-}30$  cm) has been made possible by small spatial decay constants of evanescent fields generated at the terminal end of a microwave resonator near a wire tip. Upon interaction with a sample placed near this tip, the reflection coefficient of the resonator shifts to lower frequencies enabling the characterization of the microwave properties of the sample which are affected by various factors including density, moisture, polymerization, carrier mobility and concentration, impurities, oxidation state, and temperature. The group at Case has used the evanescent microwave probe (EMP) to study a variety of organic and inorganic materials including metals, semiconductors, insulators, composites, ferromagnetic materials, tooth enamel, botanical, and agricultural samples as well as detecting corrosion in metals covered with a layer of paint. The principles of operation of the EMP, parameters affecting its spatial and permittivity/permeability/conductivity resolutions, and examples of its applications in organic and inorganic conductors, semiconductors and insulators will be discussed along with current trends and future work.

**Characterization of Dielectric and Magnetic Properties of Powdered Materials Such as Powdered Coal**

---**Robert J. Weber**, Department of Electrical and Computer Engineering, Iowa State University, Ames, IA 50011

---The microwave dielectric properties of powdered fly ash obtained from power plants have been reported. A more comprehensive consideration of the data from these measurements suggested that density of the samples was a variable that markedly changed the observed dielectric constant as expected. In addition, data related to magnetic material content appeared to be available from the same fixture and measurement. This paper reports on the measurement procedure taken to obtain both electrical and magnetic parameters of materials, in particular an application to powdered materials. Some correlation exists between the various components of coal such as carbon content and water. The amount of magnetic materials such as iron might also be quantifiable with microwave measurements over the microwave and sub-millimeter wavelengths in the same fixture. Dispersion effects related to the changes in dielectric constant of the components, e.g. water, can be detected in a change in phase velocity of the wave through the material.

**Monitoring the Effect of Relative Humidity During Curing on Dielectric Properties of Composites at Microwave Frequencies**

---**Nicola Bowler** and Eric R. Abram, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011

---In the production of composite materials for particular electromagnetic applications, such as for shielding or absorption of electromagnetic radiation, it is important to tightly control the complex permittivity and permeability of the final product. Some commonly-used binder matrix materials are highly moisture-sensitive, and variations in environmental relative humidity affect the way in which the matrix cures. A microwave non-destructive method for measuring permittivity and permeability of the composite during curing can indicate whether or not the fully cured material will have the desired properties. As a precursor to developing a non-destructive method for monitoring this process, permittivity and permeability of curing composites have been measured using a coaxial transmission/reflection method in which composite samples are inserted into a beadless airline sample cell. Broadband measurements of complex permittivity and permeability were made in the frequency range 0.5 to 18 GHz for spherical ferromagnetic particles dispersed in a polyurea/polyurethane matrix. The effect of water uptake on the electromagnetic properties of the composite was examined as a function of time during the curing process, for values of relative humidity in the range 0% to 90%. Water uptake into the matrix manifested itself as an increase in the magnitude of the real permittivity of the material, as a function of increasing relative humidity and time.---This work was performed at the Center for NDE at Iowa State University with funding from the Air Force Research Laboratory through S&K Technologies, Inc. on delivery order number 5007-IOWA-001 of the prime contract F09650-00-D-0018.

**A Formula for Dielectric Mixtures**

---**Enis Tuncer**, Oak Ridge National Laboratory, Applied Superconductivity Group, High Voltage and Dielectrics, Oak Ridge, TN 37831

---Dielectric properties of material mixtures are of importance in diagnostics, characterization and design of systems in various engineering fields. In this presentation, we propose a peculiar dielectric mixture expression, which is based on the dielectric relaxation phenomena and the spectral density representation. The expression is tested on several composite systems and expressions. Results illustrate that the proposed expression can be used to obtain valuable structural information in composites, even for highly filled, bi-percolating, systems, and therefore it has a significant potential for microwave nondestructive evaluation of composite's properties. Lastly, the proposed expression is an alternative to other existing homogenization formulas in the literature.

# *Session 10*

Tuesday, August 2, 2005

**SESSION 10**  
**NEW TECHNIQUES**  
**Moulton Union Lower Level**

- 8:30 AM**      **Electrothermal Defect Detection in Powder Metallurgy Compacts**  
---**S. Benzerrouk** and R. Ludwig, Department of Electrical and Computer Engineering, Worcester Polytechnic Institute, Worcester, MA 01609; D. Apelian, Metal Processing Institute, Worcester Polytechnic Institute, Worcester, MA 01609
- 8:50 AM**      **EMAT and Pulsed Eddy Current Dual Probe for Detecting Surface and Near-Surface Defects**  
---**R. S. Edwards** and S. Dixon, University of Warwick, Department of Physics, Coventry CV4 7AL, United Kingdom
- 9:10 AM**      **Imaging of Flaws in a Composite Plate Using Vibro-Acoustography: A Comparison Between Continuous-Wave and Tone-Burst Imaging Modes**  
---**F. G. Mitri**, J. F. Greenleaf, and M. Fatemi, Mayo Clinic and Foundation, Ultrasound Research Laboratory, Rochester, MN 55905
- 9:30 AM**      **A Parametric Study of Crack Propagation During Sonic IR Inspection**  
---J. Kephart and **J. C. Chen**, Department of Mechanical Engineering, Rowan University, Glassboro, NJ 08028-1701; W. T. Riddell, Department of Civil and Environmental Engineering, Rowan University, Glassboro, NJ 08028
- 9:50 AM**      **Load Measurement in Structural Members Using Guided Acoustic Waves**  
---**F. Chen** and P. D. Wilcox, Department of Mechanical Engineering, University of Bristol, Bristol, United Kingdom
- 10:10 AM**      **Coffee Break**
- 10:30 AM**      **Linear and Nonlinear NDE Using Air-Coupled Lamb Waves**  
---**I. Solodov**, D. Doering, K. Pfeleiderer, and G. Busse, Institute for Polymer Testing and Polymer Science (IKP), Nondestructive Testing (IZFP), Stuttgart University, Stuttgart 70569, Germany
- 10:50 AM**      **Application of Acoustic Wavefield Imaging to Non-Contact Ultrasonic Inspection of Bonded Components**  
---**T. E. Michaels** and J. E. Michaels, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0250
- 11:10 AM**      **Detection of Hidden Corrosion and Cracks Using Dry-Coupled Ultrasonic Probes**  
---**I. N. Komsky**, Northwestern University, Center for QEFP, 2137 Tech Drive, Evanston, IL 60208-3020
- 11:30 AM**      **Remote High Temperature Thermography Using Ultrasonic Guided Waves in Thin Wires**  
---**M. M. Kropf** and B. R. Tittmann, Engineering Science and Mechanics, The Pennsylvania State University, University Park, PA 16802
- 11:50 AM**      **Near-Field Scanning Laser Source Technique and Microfabricated Ultrasound Receiver**  
---**Y. Sohn** and S. Krishnaswamy, Northwestern University, Center for QEFP, 2137 Tech Drive, Evanston, IL 60208-3020
- 12:10 PM**      **Lunch**

**Electrothermal Defect Detection in Powder Metallurgy Compacts**

---**Souheil Benzerrouk** and Reinhold Ludwig, Dept. of Electrical and Computer Eng., Worcester Polytechnic Institute, Worcester, MA 01609; Diran Apelian, Metal Processing Institute, Worcester Polytechnic Institute, Worcester, MA 01609

---Faced with increasing market pressures, metal part manufacturers have turned to new processes and fabrication technologies. One of these processes is powder metallurgy (P/M) which is employed for low-cost, high-volume precision part manufacturing. Despite many advantages, the P/M process has created a number of challenges, including the need for high-speed quality assessment and control, ideally for each compact. Consequently, sophisticated quality assurance is needed to rapidly detect flaws early in the manufacturing cycle and at minimal cost. In this paper we will discuss our progress made in designing and refining an active infrared (IR) detection system for P/M compacts. After discussing the theoretical background in terms of underlying equations and boundary conditions, analytical and numerical solutions are presented that are capable of predicting temperature responses for various defect sizes and orientations of a dynamic IR testing system. Preliminary measurements with controlled and industrial samples have shown that this active IR methodology can successfully be employed to test both green-state and sintered P/M compacts. The developed system can overcome many limitations observed with a standard IR testing methodology such as emissivity, background calibration, and contact resistance.

**EMAT and Pulsed Eddy Current Dual Probe for Detecting Surface and Near-surface Defects**

---**Rachel S. Edwards** and Steve Dixon, University of Warwick, Department of Physics, Coventry CV4 7AL, United Kingdom

---In non-destructive testing (NDT) it is often preferable to test samples using several different techniques, in order to gain a higher probability of detection and a more reliable characterization of each defect. However, this can lead to an increase in testing time and cost. A probe containing several NDT devices will give this accuracy and reliability, with the testing speed of using only one technique. We present initial results using a probe containing a pulsed eddy current (PEC) probe and a pair of electromagnetic acoustic transducers (EMATs) generating ultrasonic surface waves in a pitch-catch manner. These two techniques are complimentary and are sensitive to surface and near surface defects, and no detrimental interference between the two techniques is observed. As both techniques are non-contact there is the possibility of use in hot or moving environments. The results from both can be combined using data fusion to give a higher probability of detection and more reliable sizing. Measurements of aluminum and steel samples containing manufactured and real defects are presented.

**Imaging of Flaws in a Composite Plate Using Vibro-Acoustography: A Comparison Between Continuous-Wave and Tone-Burst Imaging Modes**

---**Farid G. Mitri**, James F. Greenleaf, and Mostafa Fatemi, Mayo Clinic and Foundation, Ultrasound Research Laboratory, Rochester MN 55905

---This paper describes the application of a new imaging technique called vibro-acoustography (V.A.) for the inspection of defects and damages in a composite rectangular plate, reinforced with ceramic fibers. Continuous-wave -C.W.- (mode 1) and tone-burst -T.B.- (mode 2) V.A. experiments were conducted on a flawed plate having the dimensions 100mm x 55mm x 1mm. For both modes, the ultrasound frequency was set at  $f_1 = 3$  MHz and  $f_2 = 3$  MHz +  $\Delta f$ . The plate was placed at the focus of the transducer and scanned point-by-point over an area of 40 mm by 64 mm on its frontal face with an increment step equal to 0.4 mm/pixel, while the resulting acoustic emission amplitude at  $\Delta f$  was recorded. For the C.W. mode, the difference frequency was set at  $\Delta f = 12.9$  kHz. In the T.B. mode, the burst-emitted signal was 100 micro-seconds long at a PRF of 100 Hz corresponding to bursts of 300 cycles at 3 MHz, and the difference frequency was set at  $\Delta f = 44$  kHz. The resulting V.A. images readily show the shape of the flaws. The images also reveal considerable detail of internal substructures such as the fibers used to reinforce the plate. However, the C.W.-V.A. image show an artifact caused by the effect of ultrasound standing waves established between the plate and the concave surface of the transducer, resulting in masking some of the flaws. But the T.B.-V.A. image was free from such artifacts. Despite some advantages of using T.B.-V.A., there are some limitations related to this mode. Advantages and limitations of using the two modes will be discussed.

**A Parametric Study of Crack Propagation During Sonic IR Inspection**

---Jacob Kephart and **John C. Chen**, Department of Mechanical Engineering, Rowan University, Glassboro, NJ 08028-1701; William T. Riddell, Department of Civil and Environmental Engineering, Rowan University, Glassboro, NJ 08028

---We have developed an experiment to study the propagation of synthetic cracks under various controlled conditions during Sonic IR inspection. The experiment provides for good repeatability in testing. The parameters of interest include the initial crack length, load history during crack generation, tightness of the crack, geometry of the crack, material, and also the various conditions involving the ultrasonic source. In addition to describing our findings on crack propagation, we will describe our observation of crack retardation under certain experimental conditions.

**Load Measurement in Structural Members Using Guided Acoustic Waves**

---**Feng Chen** and Paul D. Wilcox, Department of Mechanical Engineering, University of Bristol, Bristol, United Kingdom

---A non-destructive technique to measure load in structures such as rails and bridge cables by using guided acoustic waves is investigated both theoretically and experimentally. It is proposed to exploit the dispersive properties of some guided wave modes whose velocities are functions of the applied tensile or compressive load. Robust Finite Element (FE) models for predicting the effect of load on guided wave propagation are developed and example results are presented for plates and rods. FE results indicate that the presence of stress causes a small but measurable change in the velocity of the transverse mode but not of the longitudinal mode. The experimental set-up is presented, which consists of two PZT transducers, one transmitter and one receiver, and operates in pitch-catch mode. From laboratory observation and data processing in the low-frequency region (<100kHz), reasonably good agreement of experimental results with modeling prediction is obtained. Further FE studies reveal the effect of characteristic dimensions of structures under load on dispersion curves. The application of the FE technique is demonstrated on structures with more complex cross sections.

**Linear and Nonlinear NDE Using Air-Coupled Lamb Waves**

---**Igor Solodov**, Daniel Doering, Klaus Pfleiderer, and Gerhard Busse, Institute for Polymer Testing and Polymer Science (IKP), Nondestructive Testing-(ZFP), Stuttgart University, Stuttgart 70569, Germany

---Air-coupled ultrasound and Lamb waves are two well established acoustic methodologies for NDE and material characterization. Our study is aimed at combining these two approaches to develop an air-coupled Lamb wave tool for non-contact linear and non-linear NDE applications. Such a combination was realized by using a slanted transmission of a focused air-coupled ultrasonic beam through a plate-like specimen. An alternative technique developed includes dynamic visualization of the air-coupled Lamb waves with a laser interferometer. By monitoring a local wave amplitude and in-plane velocity anisotropy the methods enable precise measurements of fibre directions in composites, thickness profilometry of thin coatings, advanced imaging of cracked defects and delaminations. Measurements of local flexural wave velocity as a function of static strain are used to determine second-order nonlinearity parameters and track down material behaviour through a loading cycle. The benefits of non-contact excitation are combined with a high sensitivity of dynamic nonlinear methods in a new air-coupled nonlinear NDE methodology. It demonstrates flexible capabilities of remote scanning and high contrast nonlinear defect-selective imaging with air-coupled Lamb waves.

**Application of Acoustic Wavefield Imaging to Non-Contact Ultrasonic Inspection of Bonded Components**

---**Thomas E. Michaels** and Jennifer E. Michaels, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0250

---Through transmission ultrasonic (TTU) methods are widely used for inspection of critical aerospace structural components because of their simplicity of implementation and high sensitivity to delaminations and bonding defects. TTU inspection requires access to both sides of a component, which is generally not a problem before components are installed into final assemblies. However, limited access to the back side of a component after final assembly precludes using TTU methods without expensive and time-consuming disassembly. Pulse echo (PE) ultrasonic methods must be used when only single sided access is possible, but PE methods have a limited penetration range from the outer surface and do not have the sensitivity of TTU, particularly when the thickness is not constant and surfaces are not parallel. Thus, structures are often disassembled when a thorough ultrasonic inspection is required. The work presented here addresses the need for a field deployable ultrasonic inspection method which has the sensitivity of TTU methods, does not require access to the back side of the part, and is non-contact; i.e., couplant is not required. The approach is based upon attaching a sparse array of ultrasonic transducers to the back side of a component or, alternatively, embedding transducers within the component. These transducers are excited to generate elastic waves which propagate throughout the component. The resulting acoustic wave field is detected by external scanning of a non-contact, air-coupled transducer, and we refer to this ultrasonic imaging method as Acoustic Wavefield Imaging. Results are presented for several aluminum plate samples with bonded attachments on the back surface, and are compared to conventional water-coupled TTU images. The recorded wavefield images clearly show bonding flaws at internal interfaces and compare favorably with TTU images.

**Detection of Hidden Corrosion and Cracks Using Dry-Coupled Ultrasonic Probes**

---**Igor N. Komsky**, Northwestern University, Center for Quality Engineering and Failure Prevention, 2137 Tech Drive, Evanston, IL 60208

---Combination of corrosion and fatigue damage can significantly affect airworthiness of aging aircraft. This action of corrosion and fatigue tends to concentrate on joints in the multi-layered aircraft structures due to high stresses and possible gaps for moisture entrapment. Surface corrosion and cracks can be efficiently detected by visual or other surface inspection techniques. Detection of hidden corrosion and cracks, on the other hand, is still a challenging task. Therefore, it is essential to develop non-destructive methods that can inspect different layers of the aircraft structures for corrosion and cracks before they become a safety concern. Ultrasonic methods can readily provide quantitative information about cracks and corrosion in the internal layers of the multilayered aircraft structures. Novel dry-coupled ultrasonic probes were developed at Northwestern University for rapid inspections of the aircraft structures from the outside without any disassembly. The probes have successfully been tested on the DC-10 horizontal stabilizer (crack detection around fasteners). However, adequate inspection for small pitting corrosion and incipient fatigue cracks may require superior sensitivity and resolution from the applied non-destructive method. Several novel designs and configurations were explored to increase both sensitivity and resolution of the dry-coupled probes for either subsurface or deep internal defects. Special ultrasonic technique was also developed to verify the interlayer sealant quality.---This material is based upon work supported by the Federal Aviation Administration under Contract # DTFA03-98-D-00008, Delivery Order # DTFA03-01-F-IA049 and performed at Northwestern University as part of the Center for Aviation Systems Reliability program through the Airworthiness Center of Excellence.

**Remote High Temperature Thermometry Using Ultrasonic Guided Waves in Thin Wires**

---**Matthew M. Kropf** and Bernhard R. Tittmann, Engineering Science and Mechanics, The Pennsylvania State University, University Park, PA 16802

---An ultrasonic technique to accurately and remotely measure high temperatures has been developed. Using long, thin (~2 mm) refractory metal wires as ultrasonic wave guides, changes in time-of-flight between fixed reflectors are monitored while the temperature of the wire changes. Several physical phenomena contribute to the change in the time of flight as the temperature of the wire increases. The wire thermally expands causing both the physical distance between reflected signals to increase and the density of the wire to decrease. The velocity of sound decreases due to changes in Young's Modulus and density. By relating these effects in terms of guided wave propagation to the precise time-of-flight measurement, temperature can be accurately measured from 20 to over 1000 degrees Celsius.

Measurements have been made on wire waveguides of lengths greater than 20 meters. By using digitally automated signal processing to monitor the changes in time-of-flight, temperature measurements can be made continuously. This method of ultrasonic in-situ thermometry has proven viable in accurately and remotely monitoring high temperatures in harsh environments.

**Near-Field Scanning Laser Source Technique and Microfabricated Ultrasound Receiver**

---**Younghoon Sohn** and Sridhar Krishnaswamy, Center for Quality Engineering and Failure Prevention, Northwestern University, 2137 Tech Dr., Evanston, IL 60208-3020

---The scanning laser source (SLS) technique has been proposed recently as an effective way to investigate small surface-breaking defects. We now propose an extension of the SLS approach to map surface-breaking defects by bringing both the generator and the receiver to the near-field scattering region of the defects. For the purpose of near-field ultrasound measurement, silicon microcantilever probes are fabricated and their acoustical characteristics are investigated. Silicon cantilevers with tip and chip body are fabricated using microfabrication techniques. The fundamental frequency of the microcantilever is measured and compared with analytically calculated fundamental frequency assuming the cross sections of the cantilevers are rectangular. Next, the performance of the fabricated microcantilevers as ultrasound detectors is investigated. The microcantilever is used essentially as a profilometer by contacting it to the specimen surface. Surface and bulk acoustic waves are generated with specific narrowband frequencies and the surface ultrasonic displacements are detected using the microcantilever probe. Next, broadband ultrasound is generated by a laser source and the resulting surface acoustic displacements are monitored using the microcantilever probe in the near-field of the source. Finally, both the laser-generated ultrasonic source and the microcantilever probe are used to monitor near-field scattering by a surface-breaking defect.

# *Session 11*

Tuesday, August 2, 2005

**SESSION 11**  
**STUDENT POSTER COMPETITION**  
**Morrell Gymnasium**

**NOTE:** Student posters are to be mounted Monday, August 1<sup>st</sup> from 4:00 to 6:00 PM for Monday evening judging only-*not public display*. During this period, no identification (author names, institutional names etc.) will be shown on the posters in order to preserve anonymity during judging. They will be open for public viewing with author and institutional titles during the regular Poster Session 11 on Tuesday, August 2<sup>nd</sup> from 1:30-3:00 PM

**Ultrasonic Monitoring of Fastener Holes Using Load Modulated Energy Algorithms for Early Detection of Fatigue Cracks**

**Advanced Signal Processing Techniques to Interpret Nonlinear Acoustic Measurement Data**

**Comparison of Simulated and Measured Lamb Waves Using a 2D LISA Model**

**Ultrasonic Shear Wave Reflection Measurements of Curing Epoxy Resins**

**Determination of Microwave Dielectric Properties of Materials Using a Unique Application of Embedded Modulated Scatterer Technique**

**Improved On-Line and Off-Line Non-Contact Ultrasound Time-of-Flight Measurement of Weld Penetration Depth**

**Microwave and Millimeter Wave Imaging of the Space Shuttle External Fuel Tank Spray on Foam Insulation (SOFI) Using Synthetic Aperture Focusing Techniques (SAFT)**

**Review of Synthetically Focused Guided Wave Imaging Techniques with Applications to Defect Sizing**

**Super Resolution Imaging: Performance Studies**

**High Frequency Ultrasonic NDE of Titanium Metal Matrix Composites**

**Ultrasonic Surface Wave Propagation and Interaction with Surface Defects on Rail Track Head**

**Generation and Detection of Higher Harmonics in Rayleigh Waves Using Laser Ultrasound**

**Interaction of the Fundamental Shear Horizontal Mode with a Through Thickness Crack in an Isotropic Plate**

**Efficient Numerical Modeling of Absorbing Regions for Boundaries of Guided Wave Problems**

**Charged Particle Detection Potential Based on Love Wave Acoustic Sensors**

**State Space Feature Extraction Applied to Diffuse Ultrasonic Signals Using Simulated Chaotic Excitations**

**Development of LiNbO<sub>3</sub> Transducer for Nonlinear Ultrasonic Measurement and Phased Array in the MHz Range**

**Quantitative Evaluation of Closed Cracks in Stainless Steel by Using Time-Domain Analysis of Subharmonics and Tail Effect**

**Ultrasonic Evaluation of Concrete Using Nonlinear Methods**

**A Convolution-Based Approach for the Direct Comparison of Eddy-Current Data with Surface Topography**

**Application of Air-Coupled Sensors to Surface Wave Detection in Civil Engineering**

**3:10 PM      *Coffee Break***

### **Ultrasonic Monitoring of Fastener Holes Using Load Modulated Energy Algorithms for Early Detection of Fatigue Cracks**

---Ultrasonic techniques have the potential to provide early detection of fatigue induced cracks originating from fastener holes with the long term goal of structural health monitoring. This project considers energy-based algorithms for analyzing ultrasonic waveforms obtained using fixed angle beam transducers in a through-transmission configuration. The transducers are located on either side of the hole with the sound beam oriented along the loading direction, and waveforms are obtained as a function of applied load. Previous work has shown that the ratio of the ultrasonic signal energy at no load to the energy with the sample under tensile loading is a robust method for determining the presence of cracks. The reason for the effectiveness of this metric is that the energy reduction from the crack opening is accentuated by the applied load. For structural health monitoring applications, the earliest possible detection of cracking is desired, and the total energy ratio method does not utilize the information contained in different time and frequency windows of the transmitted signals. Considered here are energy ratio parameters derived from multiple time and frequency windows in order to optimize the sensitivity of detection to the widest range of crack sizes and geometries. These parameters are considered individually and in combination, and results are compared to those obtained using the total energy ratio method in terms of how much earlier in the fatigue life cracking is detected.---This work was supported by the Defense Advanced Research Projects Agency (DARPA), Defense Sciences Office, "Structural Integrity Prognosis System" Program, contract No. HR0011-04-0003. This abstract is approved for public release, distribution unlimited.

### **Advanced Signal Processing Techniques to Interpret Nonlinear Acoustic Measurement Data**

---An effective way to describe changes in the microstructure of a material or to track fatigue damage is by measuring the acoustic nonlinearity parameter  $\beta$ . Beta depends on the ratio of the amplitudes of the first harmonic of the exciting signal and the second harmonic generated by changes in microstructure. A reliable measurement of the amplitudes of these harmonics is crucial since the amplitude of the higher harmonic is much smaller than the amplitude of the first harmonic. This research applies advanced signal processing techniques to develop a quantitative procedure to remove "external" effects (e.g. reflections in the sample itself) to extract the nonlinearities inherent to the material. A time-frequency based technique is developed to investigate the evolution of the nonlinearity parameter with time. The present technique helps make more accurate evaluation of the acoustic nonlinearity parameter and the prediction of fatigue damage and the remaining life of a sample.

### **Comparison of Simulated and Measured Lamb Waves Using a 2D LISA Model**

---Modeling is useful for better understanding the underlying phenomena behind a physical experiment, and an accurate and efficient model can be a valuable source of simulated data. Modeling is particularly important for developing robust ultrasonics-based damage detection algorithms because of the wide range of physical variables that must be considered. The Local Interaction Simulation Approach (LISA) has been shown to be a computationally efficient algorithm for simulating elastic wave propagation, making it a candidate method to model waves in plate-like structures. In this work, we investigate the accuracy of the 2-dimensional LISA model as an approximation to Lamb waves in thin plates of finite extent. Specifically, we present results from a comparative analysis between the 2-D LISA model and experimental ultrasonic data obtained from piezoelectric transducers bonded to a thin aluminum plate. Experimental waveforms change when damage is introduced in the plate, and these changes are recorded for artificial defects of various type and location with a sparse array of attached transducers. The LISA method is used to simulate scattering from these defects, and the computed waveforms are compared to the corresponding measurements. LISA model parameters for simulating both the defects and the transducer source functions are optimized to best match the experimental data. The result is a practical tool for generating simulated data that can be used to conduct synthetic experiments on a broader range of plate and defect geometries than is possible via experimental methods.

### **Ultrasonic Shear Wave Reflection Measurements of Curing Epoxy Resins**

---Simple modeling shows that a shear wave, traveling in an elastic medium, reflected from an interface with a viscous medium will undergo a phase change, typically of the order of nanoseconds for realistic material properties. It has been shown by previous workers that in the case of reflection from a classic viscous liquid only the phase or the amplitude need be measured in order to return the viscosity of the liquid. This paper explores the more general case for a viscoelastic substance where both amplitude and phase must be measured in order to return the viscosity and elastic modulus. Non-contact ultrasonic transducers, generating wideband shear wave pulses, are used to observe a curing epoxy resin and both viscosity and elasticity are calculated over cure. As expected the accuracy is limited by significant measurement errors in the reflected amplitude.

**Determination of Microwave Dielectric Properties of Materials Using a Unique Application of Embedded Modulated Scatterer Technique**

---Material characterization is an important field of science and application. A relatively new microwave approach involves embedding a small modulated PIN diode-loaded dipole probe in a material whose dielectric properties are sought. In this application of the modulated scatterer technique (MST), the modulated diode results in an alternating high and low impedance load on the dipole, which corresponds to measured high and low reflection coefficients. The dielectric properties of interest can then be determined by utilizing the complex ratio of the reflection coefficients from these two unique states. This complex ratio is independent of system parameters such as the relative orientation of embedded probe to the incident signal polarization, relative distance between the radiator and probe, etc. This paper explores the method in which the complex ratio of the reflection coefficients from two unique states of a loaded dipole probe is utilized to inversely calculate the dielectric properties of interest. The theoretical approach to this model, experimental verification of the results, and the accuracy of the method will be presented.

**Improved On-line and Off-line Non-Contact Ultrasound Time-of-Flight Measurement of Weld Penetration Depth**

---Welding is the primary technique used for joining structural components together. Automated welding is common in industry today. However, weld penetration depth measurement is not done in real-time resulting in open-loop control of weld penetration depth. The major obstacle to on-line weld penetration depth measurement is a lack of accurate and high resolution non-destructive and non-contact sensors, that can operate in high temperatures and harsh environments typical of welding processes. The use of ultrasonic sensors to measure weld penetration depth of butt-welds has focused on using a direct reflection of either a longitudinal or shear wave from the bottom of a weld bead. During laser generation of ultrasound, it was observed that a Rayleigh wave was generated on the bottom of weld samples. This Rayleigh wave traveled to the bottom of the weld bead where it mode converted into a longitudinal and shear wave. The mode converted longitudinal wave traveled to the bottom of the weld sample where it generated a shear (RGLS) and longitudinal (RGLL) wave reflection. Similarly, the mode converted shear wave also generated a shear (RGSS) and longitudinal (RGSL) wave reflection. The development of a new RGLS time of flight (TOF) technique for weld penetration measurements will be presented. Experimental results using the RGLS TOF technique for weld penetration depth measurement has proven to be accurate, precise, and repeatable both off-line after welding and on-line during welding. Additional RGLL, RGSL, and RGSS TOF techniques related to RGLS TOF technique will also be presented. This new technique for measuring weld penetration depth can enable closed loop control of weld penetration depth. Costs associated with scrapping and re-working bad welds will be lowered by using closed loop control. Closed loop control will enable robotic welders to be used for critical welding tasks usually done by human welders. This will reduce workplace injuries or accidents.

**Microwave and Millimeter Wave Imaging of the Space Shuttle External Fuel Tank Spray on Foam Insulation (SOFI) Using Synthetic Aperture Focusing Techniques (SAFT)**

---The Space Shuttle Columbia's catastrophic failure is thought to have been caused by a dislodged piece of external tank SOFI (Spray On Foam Insulation) striking the left wing of the orbiter causing significant damage to some of the reinforced carbon/carbon leading edge wing panels. Microwave and millimeter wave nondestructive evaluation methods, have shown great potential for inspecting the SOFI for the purpose of detecting anomalies such as small voids that may cause separation of the foam from the external tank during the launch. These methods are capable of producing relatively high-resolution images of the interior of SOFI particularly when advanced imaging algorithms are incorporated into the overall system. To this end, synthetic aperture focusing techniques are being developed for this purpose. These techniques produce high-resolution images that are independent of the distance of the imaging probe to the SOFI with spatial resolution in the order of the half size of imaging probe aperture. At microwave and millimeter wave frequencies these apertures are inherently small resulting in high-resolution images. This paper provides the results of this investigation using 2D and 3D SAF based methods and holography. The attributes of these methods and a full discussion of the results will also be provided.

**Review of Synthetically Focused Guided Wave Imaging Techniques with Applications to Defect Sizing**

---Synthetically focused imaging has been used for some time in the NDE community, under the guise of the Synthetic Aperture Focusing Technique (SAFT) either with a scanned pulse-echo transducer or, more recently, a phased array. The techniques have primarily been directed towards imaging using bulk waves. There has recently been use of SAFT using guided waves in plates using a scanned wedge transducer (Sicard et al in Quebec) and a circular array (Wilcox et al in UK) employing compensation for the dispersive nature of guided waves. Here, we review different synthetically focused imaging algorithms with various implementations for a linear array aperture. The resolution of the different techniques is obtained from scalar diffraction theory and then tested against synthetic data and a low frequency (50 kHz) plate experiment. The extension of the results to defect sizing using synthetically focused guided wave imaging is presented and discussed with finite element models and further experimental results on plates.

### **Super Resolution Imaging: Performance Studies**

---In most current defect imaging techniques image resolution is limited by the wavelength  $\lambda$  of the interrogating signal. In this paper a technique whose resolution is not confined by  $\lambda$  is presented and thus it is classified as being a super resolution technique. This technique has emerged from the combination of advanced signal processing methods introduced in radar technology and the physical notion of time reversal. The method has the potential for dramatically improved imaging and sub-wavelength resolution. The method uses an array of  $N$  transducers; signals are collected for each permutation of transmitter and receiver element pairs in the array to create an  $N^2$  matrix. Evaluation of this matrix yields an image, so revealing any defects in the system. An overview of this method will be presented by our poster. In order for an imaging technique to be applicable to real world situations it must be able to cope with noise. This is a key concern for array applications because individual array elements are often weak in comparison to regular monolithic transducers. Noise is difficult to define and model reliably as the noise in any real system will depend on many variables, can be random or coherent, and is often system specific. The data derived from our ideal simulations are randomly corrupted to give the effect of noise, and studies are performed for many cases of noise level, defect location and array geometry. It is found that the method can interpret this data with marked success even in the presence of significant noise. We have confirmed these findings with experimental measurements.

### **High Frequency Ultrasonic NDE of Titanium Metal Matrix Composites**

---The mechanical properties of titanium metal matrix composite (TiMMC) provide high strength, weight reduction and high temperature tolerance to fulfill the demand of turbine components required within aircraft and military peripherals. Pulse-echo wave propagation through a multi-layered TiMMC with a honeycomb-layered structural arrangement was measured experimentally. Embedded in each of the layers are unidirectional, horizontally positioned, parallel oriented silicon carbide fibers cored with tungsten. During the manufacturing process it has been realized that NDE of TiMMC is necessary because fibers are vulnerable to misalignment and breakage resulting in a reduction in mechanical properties. Single-sided immersion testing with the application of high frequency focused transducers ( $>35\text{MHz}$ ) revealed an initial 'doubly transmitted' back wall signal and that the amount of the reflection from lower plies is partly governed by the amount of ultrasound transmission from upper plies. In this paper, results show that the experimental data is in good agreement with finite element simulation and frequency dependence exists within the structure. This paper presents the results of fiber position, waviness and orientation detection in TiMMCs. Influences of step size, transducer frequency, focus and filtering are investigated. Issues relating to the TiMMC structure are also investigated using finite element modeling.

**Ultrasonic Surface Wave Propagation and Interaction with Surface Defects on Rail Track Head**

---Electromagnetic Acoustic Transducers (EMATs) are non-contact ultrasonic transducers capable of generating wide band surface waves on metallic samples. We describe some lab based ultrasonic measurements using EMATs to generate a wide band, low frequency (approximately 50-500kHz) ultrasonic surface wave, with Rayleigh wave-like properties on a rail head. A Michelson interferometer has been used to accurately measure the absolute out-of-plane displacement of the ultrasonic waves generated on the rail head which propagate along the rail head to interact with a simulated surface breaking defect. Some of the energy is reflected from the defect and some propagates under the defect. We describe different approaches that can be used to determine the depth and presence of the crack and present the data as a range of ultrasonic B-scans. The non-contact nature of EMATs and the pitch-catch test geometry that we propose to use for testing make them especially suitable for online detection and gauging of crack depth at high speed.

**Generation and Detection of Higher Harmonics in Rayleigh Waves using Laser Ultrasound**

---This research studies higher harmonics of Rayleigh surface waves propagating in nickel based superalloys. Rayleigh waves are used because they carry most of the energy and travel along the surface of a specimen where fatigue damage is typically initiated. The energy concentration near the free surface leads to stronger nonlinear effects compared to bulk waves. An ultrasonic piezoelectric transducer together with a plastic wedge is used for the experimental generation of the Rayleigh wave. The detection system consists of a laser heterodyne interferometer. Measurements are performed to detect the fundamental wave as well as the second harmonic. The amplitude ratio is related to the nonlinearity parameter beta which is typically used to describe changes in microstructure and investigate fatigue damage.

**Interaction of the Fundamental Shear Horizontal Mode with a Through Thickness Crack in an Isotropic Plate**

---This poster presents work aimed at developing guided wave NDE inspection systems with improved resolution. Guided waves are already well established for use in rapid inspection of large structures. They serve essentially as screening tools and the emphasis is not so much on sensitivity as on coverage. However, there is much interest in improving the resolution of guided wave NDE towards defect sizing for applications where access is difficult. One possibility for instance, presently being studied by our group, is to use fundamental modes in conjunction with array imaging methods. The shear horizontal (SH) modes are attractive for such studies considering that they can be seen either as SH modes in a plate or as the torsional modes ( $T(0,n)$ ) in a pipe. This poster presents a study of the interaction of the cylindrical crested fundamental shear horizontal (SH0) mode with a through thickness crack in an isotropic plate. The study examines the reflection and diffraction of the wave at the crack, in order to gain understanding for the development of imaging procedures. Circular wavefronts are used to imitate the individual elements of a transducer array, which behave as point sources. Finite element (FE) simulations are used to gain an insight into the problem and the relative strengths of the diffraction and reflection fields for various crack lengths and incidence angles are assessed.

**Efficient Numerical Modeling Of Absorbing Regions For Boundaries Of Guided Waves Problems**

---Numerical methods, mainly Finite Elements (FE) and Finite Differences (FD), are widely used in research to make predictions of wave propagation, and have become established as a dependable means of assessing the sensitivity of waves to defects. However the majority of numerical studies so far have addressed only simple geometries. One reason for this is that initial work is bound to focus on the simplest cases. Another reason is that, despite rapid growth in computer power, many of the more complex realistic problems are still beyond the capacity of the models. A particular problem, causing an unnecessary increase of the model size, is unwanted reflections from the boundaries of the models. Larger models are needed to prevent these reflections from obscuring the signals. An alternative is to model absorption of the signal at the boundaries. Non-reflective boundaries have been developed for bulk waves problems but they do not work well for guided waves problems because of the complicated mode shapes of the waves. Solutions using finite absorbing regions show much better potential. The poster will present progress in this approach.

### **Charged Particle Detection Potential Based on Love Wave Acoustic Sensors**

---An investigation of the dependence of film density on group and phase velocities of a Love Wave device shows a potential for acoustic-based charged particle detection (CPD). Exposure of an ion-sensitive photoresist to charged particles causes localized density changes through scission or cross-linking. A theoretical model was developed to study the sensitivity of Love Wave propagation to these effects based on: ion energy, effective density changes, layer thickness, and Love mode selection. The model is based on a Polymethylmethacralate (PMMA) film deposited on a Quartz substrate. The effect of Helium ion fluence on the properties of PMMA have previously been investigated. These guidelines were used as an initial basis for the prediction of helium ion detection in a PMMA layer. Procedures for experimental characterization of ion effects on material properties in PMMA are reviewed. Techniques for experimental validation of the predicted velocity shifts are discussed. A Love Wave Device for CPD could potentially provide a cost-effective alternative to semiconductor or photo-based counterparts. The potential for monitoring ion implantation effects on the material properties of the deposited films are also discussed.

### **State Space Feature Extraction Applied to Diffuse Ultrasonic Signals Using Simulated Chaotic Excitations**

---Diffuse ultrasonic waves for structural health monitoring offer the advantages of simplicity of signal generation and reception, sensitivity to damage, and large area coverage. However, one of the difficulties associated with these complex signals is extraction of robust features that can be related to progression of damage. This paper investigates feature extraction techniques in reconstructed state space, an approach that has been proposed for vibration-based structural health monitoring applications. In this state space approach, a continuous chaotic signal is typically used to excite the specimen to get a steady state response. However, diffuse waves are naturally transient and are usually formed using an impulsive or burst excitation. In this paper, a computer-generated continuous chaotic signal is convolved with the measured transient diffuse signal to simulate the chaotic excitation, which enables state space reconstruction from the transient diffuse signal. Then, various features are extracted from the reconstructed state. This convolution method is applied to data from two experiments on aluminum plates in which artificial flaws are introduced and incrementally enlarged. Selected state space features show ability to track increasing flaw growth with performance comparable to results reported in the vibration-based literature.

**Development Of LiNbO3 Transducer for Nonlinear Ultrasonic Measurement and Phased Array in the MHz Range**

---Recently, measurement and analysis of strong nonlinear effects are regarded as a promising tool in ultrasonic nondestructive evaluation. However, piezoelectric transducers such as by PZT are not stable at large amplitude operation, and it is the limitation in stability, repeatability and reliability of strong nonlinearity measurement. In this situation, we propose a LiNbO3 (LN) single crystal transducer with an appropriate buffer/wedge made of engineering plastics (e.g. polyimide) driven by a short tone burst amplified by a gated amplifier. Since no matching circuit is needed due to the high electromechanical coupling of LN, relatively broad bandwidth is achieved. Displacement amplitudes above 30 nm is feasible in the frequency range of 1 to 8 MHz, which has been stable over more than 50 hours of operation. When necessary, stacked or tapered crystal is employed. It realized the reliable nonlinear measurement in highly attenuating materials for the first time. In the study of imaging, nonlinear measurement system with a phased array for reception and the LN transducer for generation was newly constructed. This system is able to produce an image of closed cracks by taking only the linear or nonlinear components by digital signal processing of the output wave.

**Quantitative Evaluation of Closed Cracks in Stainless Steel by Using Time-Domain Analysis of Subharmonics and Tail Effect**

---Recently, stress corrosion cracks were detected in stainless steel of atomic power plants. Their ultrasonic testing sometimes suffers a huge error (~800%) probably because they are closed. In order to solve this problem, we proposed time domain analysis of subharmonics of frequency/2, /3, where  $f$  is the frequency of the input wave, because they are generated only at closed cracks with a higher S/N ratio than superharmonics. We subsequently reported that the tail of the waveform has a peculiar shape, and that it is a free oscillation of crack planes after stopping the large amplitude input wave. In this study, we applied this method to a partially closed crack in a stainless steel (SUS316L) specimen and observed subharmonics and tail effect. Then, from a time-frequency analysis based on the wavelet, we obtained the angular frequency and spectral width of the tail effect, from which MHz range resonance frequency and damping of crack planes were obtained. Next, we calculated a forced oscillation waveform, assuming an appropriate interaction-force function between crack planes. Finally, we tried to clarify the mechanism of the observed phenomena by comparing the calculated and observed waveforms, and obtained a remarkably good agreement considering the complexity of waveforms.

**Ultrasonic Evaluation of Concrete Using Nonlinear Methods**

---Nonlinear Ultrasonic techniques can be used effectively to detect damage in concrete members in the infrastructure. The primary advantage of non-linear testing is the ability to detect distributed damage at early stages in members. Nonlinearity in concrete results in the generation of harmonics when an ultrasonic wave encounters damage in the concrete. These harmonics produce relative amplitudes that can be compared to the fundamental in ratios of  $A_n/A_1n$  where n is the order of the harmonic (i.e. 2nd and 3rd). As damage increases the ratio will increase giving an indication of the extent of damage in the member. This relation has a viable potential of serving as a means of structural integrity monitoring (i.e. bridge deck monitoring). Harmonic generation associated with distributed damage will also be compared to hysteric effects related to frequency shifts. The objective is to determine which method is most sensitive for detecting distributed damage in its early stages and which is most practical for field applications.

**A Convolution-Based Approach for the Direct Comparison of Eddy-Current Data with Surface Topography**

---Ongoing research is aimed at characterizing the effects of noise sources such as surface roughness and material grain on eddy-current measurement data. Some procedure by which different contributing factors can be identified and separated is being sought. A convolution-based approach has been developed whereby the noise distribution due to surface roughness alone is computed and compared with actual measurements. Variations in the signal distributions for the computed and measured eddy-current response signals are attributed to other factors including the presence of flaws or signal variations caused by microstructural conditions.---This material is based on work supported by NASA under award NAG-1-029-98.

**Application of Air-Coupled Sensors to Surface Wave Detection in Civil Engineering**

---There are two major types of interface waves propagating along fluid/solid interfaces. Their existence and behavior depend on relative properties of the fluid and the solid. Leaky Rayleigh waves exist only at fluid/hard solid interfaces, while Scholte waves exist at interfaces for any fluid/solid combination. By measuring leaky Rayleigh waves or Scholte waves in the fluid using air-coupled sensors or geophones, properties of the solid can be revealed. In this study, air-coupled sensors are used to detect leaky Rayleigh waves at air-concrete surfaces, and dispersion curves are obtained by using SASW(spectral analysis of surface waves) and MASW(multichannel analysis of surface waves) methods. Test results show that air coupled sensors can be successfully applied to SASW and MASW tests to characterize concrete slabs, and that it shows promise for further developing non-contact NDT techniques for pavement evaluation.

Tuesday, August 2, 2005

**SESSION 11 – POSTERS**  
**SENSORS AND TECHNIQUES, IMAGE AND SIGNAL PROCESSING, CIVIL MATERIALS AND**  
**STRUCTURES, AND ULTRASONICS**  
Morrell Gymnasium

1:30 PM

Sensors and Techniques

**Detecting In-Plane AE/Transient Displacement Sources with Out-of-Plane Sensors**

---C. Merrey and **J. C. Duke, Jr.**, Virginia Tech, Engineering Science and Mechanics, MC 0219, Blacksburg, VA 24061

**Long-Term Durability Assessment of Optical Fiber Sensors**

---**D. Harold** and **J. C. Duke, Jr.**, Virginia Tech, Engineering Science and Mechanics, MC 0219, Blacksburg, VA 24061; S. Allison, NASA Langley Research Center, Nondestructive Evaluation Sciences Branch, Hampton, VA 23681

**Novel Methods for Crack Detection in Green and Sintered Parts**

---**Y. Zhu**, E. T. Hauck, and J. L. Rose, Department of Engineering Science and Mechanics, The Pennsylvania State University, University Park, PA 16802

**Length Inspection of a Rod Embedded in Rock Using Ultrasonic Guided Waves**

---**C. He** and Y. Song, College of Mechanical Engineering & Applied Electrics Technology, Beijing University of Technology, Beijing, PR China; J. Van Velsor and J. L. Rose, Department of Engineering Science & Mechanics, The Pennsylvania State University, University Park, PA 16802

**Ultrasonic Coupling for High Temperature Health Monitoring**

---**J. R. Sebastian** and M. T. Frede, University of Dayton Research Institute, Dayton, OH 45469

**Nondestructive Evaluation of Submicron Delamination at Polymer/Metal Interface in Flex Circuits**

---V. Nalladegga and **S. Sathish**, University of Dayton, Center for Materials Diagnostics, 300 College Park, Dayton, OH 45469-0120; A. S. Brar, Seagate Technology, 7801 Computer Avenue South, Bloomington, MN 55435-5489

Image and Signal Processing

**Optimized Image Processing for Eddy Current Thermography**

---G. Zenzinger, W. Satzger, and **J. Bamberg**, MTU Aero Engines, NDT – Technology, TEF, Dachauer Strasse 665, 80995 Munich, Germany

**Image Enhancement and Analysis of Ply Lift Dynamics**

---**E. R. Doering**, Rose-Hulman Institute of Technology, CM 108, 5500 Wabash Avenue, Terre Haute, IN 47803-3999; R. D. Beshears and S. A. Howse, NASA Marshall Space Flight Center, Engineering Directorate, Huntsville, AL 35805-6244

**A Bivariate Regression Model for Assessment of Multizone Ultrasonic POD**

---Y. Wang and **W. Q. Meeker**, Iowa State University, Dept. of Statistics, 304C Snedecor Hall, Ames, IA 50011

Tuesday, August 2, 2005

### Civil Materials and Structures

#### **Ultrasonic Study on Load-Induced Hysteresis in Modulus of Elasticity in Norway Spruce as a Function of Year Ring**

---**E. Haeggström**, T. Koponen, T. Karppinen, and R. Serimaa, Department of Physical Sciences, University of Helsinki, Helsinki, Finland; P. Saranpää, Finnish Forest Research Institute, Vantaa Research Centre, Finland

#### **Measurement of P-Wave Velocity Through Concrete Using Air-Coupled Transducers**

---**J. S. Popovics** and G. Cetrangolo, University of Illinois at Champaign-Urbana, Department of Civil & Environmental Engineering, 205 N. Mathews Avenue, MC 250, Urbana, IL 61801

#### **Detection of Air and Water-Filled Subsurface Defects in FRP Bridge Decks Using Infrared Thermography**

---U. B. Halabe, M. Roy, and H. V. S. GangaRao, West Virginia University, Department of Civil and Environmental Engineering, Constructed Facilities Center, Room 645, Engineering Sciences Building, 395 Evansdale Drive, Morgantown, WV 26506-6103; **P. Klinkhachorn**, West Virginia University, Lane Department of Computer Science and Electrical Engineering, Morgantown, WV 26506-6109

#### **Real Time Detection of Defects in FRP Bridge Decks Using Infrared Thermography**

---**P. Klinkhachorn** and G. M. Lonkar, West Virginia University, Lane Department of Computer Science and Electrical Engineering, Morgantown, WV 26506-6109; U. B. Halabe and H. V. S. GangaRao, West Virginia University, Department of Civil and Environmental Engineering, Constructed Facilities Center, Morgantown, WV 26505

#### **Shear Horizontal Wave Propagation Speed in Mylar Sheets and Coated Paper as a Function of Temperature**

---M. Leppänen, T. Karppinen, and **E. Haeggström**, Department of Physical Sciences, University of Helsinki, Finland; J. Stor-Pellinen, Vaisala Oyj, PB 26, Vantaa, Finland

### Ultrasonics

#### **Modeling of Ultrasonic Wave Propagation in Anisotropic and Layered Media by a Modular Gaussian Beam**

---**H. Jeong**, Wonkwang University, Division of Mechanical and Automobile Engineering, 344-2 Sinyong-Dong, Iksan, Jeonbuk 570-749, Korea; L. W. Schmerr, Jr., Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011

#### **Application of Ultrasonic Guided Waves on Fluid-Filled Pipe Nondestructive Inspection**

---**L. Yibo**, J. Shijiu, and S. Liying, Tianjin University, Precise Instrument and Opto-Electronics Engineering College, Precise Instrument Postbox 4, 92 Weijin Road, Nankai District, Tianjin City, 300072, China

#### **Development of Calculation Software for Guided Wave Propagation in a Pipe**

---**T. Hayashi** and M. Murase, Nagoya Institute of Technology, Nagoya, Japan; W.-J. Song, Research Institute of Industrial Science and Technology; I.-K. Park, Seoul National University of Technology

#### **Simulation of Ultrasonic Inspection with Phased Array Techniques**

---**L. Le Ber**, S. Chaffai-Gargouri, and S. Chatillon, CEA/LIST, CEA Saclay, 91191 Gif-sur-Yvette, Cedex, France

Tuesday, August 2, 2005

**The Kirchhoff and Born Approximations for Scattering in Both Isotropic and Anisotropic Elastic Solids**

---**R. Huang** and L. W. Schmerr, Jr., Iowa State University, Center for NDE, Department of Aerospace Engineering, Ames, IA 50011; A. Sedov, Department of Mechanical Engineering, Lakehead University, Thunder Bay, Ontario, Canada

**Study of Impact Excited Elastic Waves in Concrete by Scanning Laser Vibrometry**

---**B. Koehler** and F. Schubert, IZfP/FhG, Krueger strasse 22, Dresden, 01326, Germany

**Guided Waves in Fluid Loaded Transversely Isotropic Plate**

---**F. Y. Chohan** and S. Murashima, Department of Information & Computer Sciences, Graduate School of Science & Engineering, Kagoshima University, Kagoshima, Japan

**3:10 PM**

***Coffee Break***

**Detecting In-Plane AE/Transient Displacement Sources with Out-of-plane Sensors**

---Caroline Merrey and **J. C. Duke, Jr.**, Virginia Tech, Engineering Science and Mechanics, MC-0219, Blacksburg, VA 24061

---In that acoustic emission (AE) is a transient phenomenon it is often difficult to study systematically. Depending on the structure various modes of propagation are involved in transferring the transient stress waves, including dilatational and distortional bulk modes, extensional (symmetric) and flexural (antisymmetric) plate modes, as well as a Rayleigh surface wave mode. However, despite the nature of the wave mode it is manifest at the sensor location as some combination of in-plane and out-of-plane displacements. Often there is both an in-plane and out-of-plane component of displacement present at the sensor location. Unfortunately this might cause confusion as to whether a source excites in-plane or out-of-plane displacements if the basis is a detected signal. Using a combination of experimental measurements and guidance from a dynamic finite element model developed by Gary, O'Gallagher, and Hamstad the performance of conventional commercial and novel research sensors are compared. The implications for monitoring various forms of deterioration are discussed including reinforcing fiber breaks and adhesively bonded components.

**Long-Term Durability Assessment of Optical Fiber Sensors**

---**Douglas Harold** and J. C. Duke, Jr., Virginia Tech, Engineering Science and Mechanics, Blacksburg, Virginia 24061; Sidney Allison, NASA Langley Research Center, Nondestructive Evaluation Sciences Branch, Hampton, VA

---Optical fiber has been the subject of thorough study for several decades. Consequently, many of the factors that cause untimely failure of the fiber are well understood. For example, the ultimate mechanical strength of many types of optical fiber, as well as the temperature range to which it may be exposed, has long since been determined. Moreover, the effect of environmental concerns such as humidity and chemical intrusion on the optical properties and mechanical strength of the fiber is known. Even the effect that ionizing radiation has on optical fiber performance has been studied. Clearly it is important to determine such ultimate limitations of optical fiber and fiber optic sensor systems; however, it is equally important to characterize the durability of the system when exposed to repeated stresses of lesser magnitude. This presentation describes a study to characterize the durability of an optical fiber sensor system when deployed in a typical aerospace application where repeated cyclic mechanical loading is a factor.

**Novel Methods for Crack Detection in Green and Sintered Parts**

---**Yun Zhu**, Eric T. Hauck, and Joseph L. Rose, Department of Engineering Science and Mechanics, The Pennsylvania State University, University Park, PA 16802

---Crack detection in unsintered or green powder metal parts has been of interest for decades with no commercial solution available.

Traditional ultrasonic techniques using liquid couplant cannot be used with green parts since residue left behind from the couplant will degrade the final quality of the sintered part. In this paper, two couplant free techniques are presented for the inspection of green and sintered parts. The surface wave mediator technique uses point contact with a part to induce and receive Rayleigh surface waves which are sensitive to surface breaking cracks and density variations. The mediator tip can be shaped to effectively inspect both flat and curved geometries, such as boreholes.

Feasibility studies performed using ultrasonic Electromagnetic Acoustic Transducers (EMATs) on both green and sintered parts have been successful in impinging ultrasonic energy into the parts for defect detection. Due to the low aspect ratio of many powder metal parts, ultrasonic guided waves are can provide full part characterization. Shear horizontal waves were used to inspect the flange of a transmission parts and torsional waves have been used to inspect the welded region of sintered porous filters.

**Length Inspection of a Rod Embedded in Rock using Ultrasonic Guided Waves**

---**Cunfu He** and Yaxin Song, College of Mechanical Engineering & Applied Electrics Technology, Beijing University of Technology, Beijing, PR China; Jason Van Velsor and Joseph. L. Rose, Department of Engineering Science & Mechanics, The Pennsylvania State University, University Park, PA 16802

---Approximately 200,000 high-strength rock bolts were used in the construction of the five-step ship lock that allows ships to circumnavigate Three Gorges Dam in the Hubei Province of China. There is an imperative need for the length determination of these embedded rock bolts, both for determining the quality of construction and for health monitoring of the structure in service. Deviations from the pre-embedded length indicate a fractured bolt. In this study, the propagation of ultrasonic guided waves in a three-layered structure, composed of a solid rod, a thin layer of concrete and a semi-infinite rock, is investigated theoretically and experimentally. The longitudinal mode dispersion equation is analyzed with assumptions of continuous stress and displacement along the rod-concrete and concrete-rock interfaces. Numerical simulations of the longitudinal mode dispersion curves and particle displacement distributions are generated. Utilizing these theoretical and numerical simulations, a series of experiments involving longitudinal mode propagation in a rock bolt was completed. A 2 m. long, 22 mm. diameter, threaded steel rod was inspected in air and in a virtual embedded state by burying a rod in soil. Previous efforts have simulated the rod-concrete interaction by freezing water in a steel tube, with an inner diameter similar to that of a rock bolt. Finally, ultrasonic guided waves are used to inspect a rod embedded in veritable concrete. It is demonstrated that with the optimum mode, frequency and transducer, it is possible to perform a bolt length measurement using ultrasonic guided waves. In addition, it is shown that experimental results are in good agreement with theoretical analysis.

**Ultrasonic Coupling for High Temperature Health Monitoring**

---**James R. Sebastian** and Michael T. Frede, University of Dayton Research Institute, Dayton, OH 45469-0120

---Coupling between an ultrasonic transducer and test object is commonly achieved by immersion or with a thin layer of liquid, generally water. Commercial couplants are available for use at elevated temperatures, but are limited by maximum temperature or time at temperature. High temperature coupling methods were investigated to support the development of a very high temperature (>700C) ultrasonic transducer intended for permanent installation as a health-monitoring sensor for equipment operating at high temperature. Various metal foils were investigated experimentally, along with several molten glasses. Gold leaf (very thin foil) combined with moderate pressure was found to be the most promising choice for long-term ultrasonic coupling at high temperature.

**Nondestructive Evaluation of Submicron delamination at polymer/metal interface in Flex Circuits**

---Vijayaraghava Nalladegga and **Shamachary Sathish**, Center for Materials Diagnostics, University of Dayton, 300 College Park, Dayton, OH-45469-0120; Amarjit S. Brar, Seagate Technology, 7801 Computer Avenue South, Bloomington, MN 55435-5489

---The dimension of the defects in micro-electronic components has reached the resolution limit of many traditional quality control instruments. As the sizes of the components are reaching a few hundred microns, the life of the components will be limited by defects of submicron dimensions. In this regard there is a need for development of new NDE techniques to detect submicron defects. In this paper we examine the use of combined atomic force microscopy and acoustic assisted atomic force microscopy (AAAFM) to evaluate submicron and nanometer size delaminations at the polymer-metal interface. Surface topography images obtained using atomic force microscopy is compared with acoustic assisted atomic force microscopy images obtained on the same region of the flex circuits. The contrast in the acoustic assisted atomic force microscope shows detailed features of delamination present at the polymer/metal interface. It also reveals the microstructure of copper sandwiched between two polymer layers. Experiments were performed to image the growth and evolution of delaminations while a constant current is passed through the copper conductor. Results of microstructure of copper through a polymer layer and growth of delamination are presented. The role of the two microscopes as a quality control tool in micro-electronics and computer industries is discussed.

**Optimized Image Processing for Eddy Current Thermography**

---Guenter Zenzinger, Wilhelm Satzger, and **Joachim Bamberg**, MTU Aero Engines, NDT – Technology, TEF, Dachauer Strasse 665, 80995 Munich, Germany

---The eddy current thermography is a well known NDT-technique for the detection of open and hidden cracks in metallic parts. Cracks disturb the induced eddy currents and generate therefore characteristic temperature profiles. These temperature profiles are visualized by a thermographic camera. But, there is a problem arising from the fact that the heat produced by the eddy current coil itself is very inhomogeneous. This inhomogeneous heat transfer masks the temperature profile of the crack especially when inspecting complex shaped parts. It is shown that the masking can be removed effectively by using a Fourier transform algorithm focussed on a specific region in the temperature - time behavior of the heated surface. The processed final images are of binary form and easy to evaluate automatically. This image processing is presented for some aero engine parts inspected by eddy current thermography.

**Image Enhancement and Analysis of Ply Lift Dynamics**

---**Edward R. Doering**, Rose-Hulman Institute of Technology, CM 108, 5500 Wabash Avenue, Terre Haute, IN 47803-3999; Ronald D. Beshears and Sarah A. Howse, NASA Marshall Space Flight Center, Engineering Directorate, Huntsville, AL 35805-6244

---The Shuttle Reusable Solid Rocket Motor (RSRM) nozzle composed of a carbon phenolic composite occasionally exhibits separation and lifting, or ply lift, when subjected to high-temperature exhaust during static tests. In order to quantify ply lift dynamics, a convergent cone of carbon phenolic composite attached to the output of the Solid Fuel Torch (SFT) subscale rocket motor is imaged by a real-time radiography (RTR) system. Ply lift indications are noticeable in the original image sequence, but photon counting noise and low contrast obscure the indications for the casual observer. Moreover, a quantitative measurement of the ply lift height as a function of time is required. Image enhancement routines were developed to improve the interpretation of the RTR video sequence, and image analysis routines were developed to track the height of the plies as a function of time. Enhancement was accomplished by interframe averaging, darkfield subtraction, intraframe mean value subtraction to correct X-ray source variations, and initial frame subtraction to reveal ply lift changes. Analysis was performed by developing edge tracking algorithms customized to the ply lift features. The enhancement techniques rendered the ply lift indications easily visible, and the analysis techniques were shown to correlate well with independent measurements of pressure and temperature within the convergent cone.

**A Bivariate Regression Model for Assessment of Multizone Ultrasonic POD**

---Yurong Wang and **William Q. Meeker**, Iowa State University, Department of Statistics, 304C Snedecor Hall, Ames, IA 50011

---Standard assessment methods, known as  $a_{hat}$  vs  $a$ , use a linear regression model relating NDE signal response to flaw or defect size. The Multizone ultrasonic testing method, however, has a bivariate detection criterion, using both signal amplitude and a signal-to-noise ratio. This paper extends the standard  $a_{hat}$  versus  $a$  method to a bivariate response model that also allows for truncation and censoring that arise in actual field inspections. We illustrate the new model by estimating POD for hard alpha inclusions, using data from the Contaminated Billet Study.

**Ultrasonic Study on Load-Induced Hysteresis in Modulus of Elasticity in Norway Spruce as a Function of Year Ring**

---**Edward Hæggström**, Tiina Koponen, Timo Karppinen, and Ritva Serimaa, Department of Physical Sciences, University of Helsinki, Helsinki, Finland; Pekka Saranpää, Finnish Forest Research Institute, Vantaa Research Centre, Finland

---We present a preliminary study on nonlinear measures (hysteresis, acoustoelasticity) to determine the effect of wood growth rate on its properties as a construction material. We also search for a new non-destructive way to characterize wood and to investigate the relationship between wood structure and its mechanical properties. We studied acoustoelastic properties of Norway spruce in a constant environment ( $20 \pm 2.5\%RH$ ,  $22 \pm 0.5^\circ C$ ). The load-induced hysteresis in the stiffness modulus was determined in radial direction as a function of annual ring from the pith using thin ( $5 \times 5 \times 1 mm^3$ ) flawless dry-coupled longitudinal-tangential plane (LT) samples. The samples were subject to static external compressive loads ( $0.4-35 MPa$ ) coaxial with the wave propagation by means of custom-built 3MHz transducers featuring a load bearing brass delay-line. The stiffness modulus was calculated from broadband, pitch-catch time-of-flight, contact measurements using longitudinal and shear waves (polarized along grain and across grain). Sample density and thickness were calculated from separate measurements of inter-transducer distance and sample mass. LT-samples allow examination in a single growth ring (early wood zone). Hence it is possible to relate wood properties to growth conditions during a specific year. This could provide feedback for forest management, i.e. fertilization or thinning to optimize stiffness profiles or wood-production.

**Measurement of P-Wave Velocity Through Concrete Using Air-Coupled Transducers**

---**John S. Popovics** and Gonzalo Cetrangolo, University of Illinois at Champaign-Urbana, Department of Civil & Environmental Engineering, 205 N. Mathews Avenue, MC-250, Urbana, IL 61801

---Ultrasonic P-wave velocity (UPV) measurement has been applied with success to locate defects and characterize concrete structures. However, UPV requires good contact between the transducers and the concrete surface to obtain reliable data. Such contact measurements, which occasionally require concrete surface preparation, are time and labor intensive and may cause additional and undesirable variation in the data. In this paper the viability of completely contact-less UPV measurements using air-coupled transducers is investigated. For this task, modified transducers and testing configuration were utilized; these are described. The transducers make use of quarter wavelength matching layers made of polymeric materials. The testing configuration utilizes the natural resonance of the air-gap between transducer and concrete to enhance the inherent very low signal levels. Through thickness air-coupled UPV results obtained from concrete specimens are presented. The contact-less UPV results are compared to standard contact UPV measurements, and the utility of the approach is illustrated.

**Detection of Air and Water-filled Subsurface Defects in FRP Bridge Decks Using Infrared Thermography**

---Udaya B. Halabe, Merujyoti Roy, Hota V. S. GangaRao, West Virginia University, Department of Civil and Environmental Engineering, Constructed Facilities Center, Room 645 Engineering Sciences Building, 395 Evansdale Drive, Morgantown, WV 26506-6103; **Powsiri Klinkhachorn**, West Virginia University, Lane Department of Computer Science and Electrical Engineering, Morgantown, WV 26506-6109

---Any discontinuity within a structural component influences the transmission of thermal energy through its thickness, which leads to differences in surface temperatures just above the defective and defect-free areas. The variation in the surface temperatures are recorded using a digital infrared camera and the thermal images (thermograms) are analyzed to locate the presence of subsurface defects such as debonds and delaminations within the structure. While past studies focused on detection of air-filled subsurface defects (debonds and delaminations) in fiber reinforced polymer (FRP) bridge decks using infrared thermography, this paper includes the detection of fully and partially water-filled defects as well. Simulated water-filled defects were embedded within the flange-to-flange junction of adjacent FRP bridge deck modules to create delaminations. The deck specimens were then tested before and after the application of a 3/8" (9.5 mm) thick polymer concrete wearing surface. It was found that water-filled delaminations as small as 2" x 2" x 1/16" (51 mm x 51 mm x 1.6 mm) could be detected in case of specimens without wearing surface, but this was not possible after application of the wearing surface. The heating source considered included heater and solar radiation. Use of cooling sources such as cold water and liquid carbon dioxide were also explored. These results helped establish the limits of detection for fully and partially water-filled delaminations using Infrared Thermography. Additional studies included the detection of debond between 2" (51mm) thick asphalt overlay and the underlying composite deck and it was found that air-filled debonds as small as 4" x 4" x 1/16" (102 mm x 102 mm x 1.6 mm) could be detected using heater as well as solar radiation as heat sources.

**Real Time Detection of Defects in FRP Bridge Decks Using Infrared Thermography**

---**Powsiri Klinkhachorn** and Gajanan M. Lonkar, Lane Department of Computer Science and Electrical Engineering, West Virginia University, Morgantown, WV 26505; Udaya B. Halabe and Hota GangaRao, Department of Civil and Environmental Engineering, Constructed Facilities Center, WV

---This work is aimed at building a real time system to detect subsurface defects in FRP bridge decks using infrared thermography. The issues addressed are a) development of a real time defect detection system b) Image mosaicking to build a composite image map. In the tests conducted, a system was built in Matlab environment using the FLIR Software Development Kit to acquire image from the ThermoCAM S60 infrared camera. The images were then analyzed by defect detection algorithms. Efforts were made to minimize the time to detect defects in a captured image. In the second phase, image mosaicking was used to build a "composite image" that combines all the infrared images to form a single image. The images were combined to cover the entire area of the bridge deck. The location of defects in the "composite image" leads to a system that will be able to point out defects in the bridge as a whole. Both manual and automatic techniques for defect detection were investigated. The study creates a base that can be used for real time defect detection in FRP bridge decks. Image mosaicking demonstrated the advantage of having a "composite image" representation of the infrared image sequence and the associated defects.

**Shear Horizontal Wave Propagation Speed in Mylar Sheets and Coated Paper as a Function of Temperature**

---Mikko Leppänen, Timo Karppinen, and **Edward Hæggröm**, Department of Physical Sciences, University of Helsinki, Helsinki, Finland; Jyrki Stor-Pellinen, Vaisala Oyj, PB 26, Vantaa, Finland

---Soft membranes find application e.g. as pill or paper coatings, bio-filter membranes, and gas seals in food products. For these applications both the integrity and the mechanical properties of the membrane are important. We propose a rapid nondestructive acoustic method to estimate mechanical film characteristics with shear horizontal waves. A 23 kHz, 1-cycle square 20 Vpp signal was excited into a thin foil with a piezoceramic pickup (Ronette/ST105/Tonar) and received with an inductive pickup (Shure/M92E). The SNR was 20dB in 1-50 kHz bandwidth after 500x averaging. This actuation-detection scheme can be used to excite in-plane longitudinal, shear and even elliptic waves in a transparency. The method was validated by measuring shear wave time-of-flight at different actuator-receiver separations with part of the propagation path kept at an elevated temperature (22-150°C). The shear wave velocity in a 150±5 µm DuPont Mylar® polyester film (75x75 cm) was determined to be 1244±3 m/s at 22±0.5°C. This corresponds to a shear modulus of 2.54±0.09 GPa. The maximum shear modulus anisotropy and the shear modulus dependence on temperature were determined for mylar sheets and coated paper. Laser doppler vibrometry showed that the excited waves were confined in-plane.

**Modeling of Ultrasonic Wave Propagation in Anisotropic and Layered Media by a Modular Gaussian Beam**

---**Hyunjo Jeong**, Wonkwang University, Division of Mechanical and Automobile Engineering, 344-2 Sinyong-Dong, Iksan, Jeonbuk 570-749, Korea; Lester W. Schmerr, Jr., Iowa State University, Center for NDE and Department of Aerospace Engineering, Applied Science Complex II, 1915 Scholl Road, Ames, IA 50011

---This work describes a Gaussian beam model for calculating ultrasonic wave fields in anisotropic and layered media. The model is based on a modular form of a multi-Gaussian beam model developed recently for anisotropic media with multiple interfaces. This model is algebraically simple and able to handle both arbitrarily curved interfaces and a general anisotropic solid. The effect of material anisotropy and interface curvature on beam propagation is first addressed for semi-infinite anisotropic materials. The model is then extended to ultrasonic beam propagation in layered anisotropic media. Two types of structures are considered: Laminated composites and bimetallic weld structure. Both immersion and contact angle beam testing situations are simulated and results are presented.

**Application of Ultrasonic Guided Waves on Fluid-Filled Pipe Non-Destructive Inspection**

---**Li Yibo**, Jin Shijiu, and Sun Liying, Tianjin University, Precise Instrument and Opto-Electronics Engineering College, Precise Instrument Postbox 4, 92 Weijin Road, Nankai District, Tianjin City, China, 300072, China (PRC)

---Corrosion in pipework is a significant problem in the oil industry and there is also much interest in reducing leakage due to corrosion in water pipes. However, some underwater or half-underwater pipes of the offshore platform, especially those vertical pipes suffering from storm, tide, ice or other sea floaters, are difficult to be examined by conventional inspection method, such as radiography, penetration and ultrasonic. Guided ultrasonic waves can propagate along the pipe wall for over 100m long without distinguishable attenuation when the pipe was in ideal condition. Thus it enjoys promisingly broad application in pipe NDT. However, since vertical pipes of the offshore platform are usually fluid-filled and underwater, leakage of energy into the fluid by radiation is possible. In this paper, pipeline inspections were conducted using cylindrical guided waves. Experiment was set up to examine guided ultrasonic waves propagating in fluid-filled pipes when 4/5 of the pipe is immersed in water. In order to improve the evaluation of signal results, wavelet transform were applied. Results showed that it can enhance the analysis of the results. In the end, test was carried out on the vertical pipe of Bohai Oil offshore platform, and the results demonstrated its usefulness.

**Development of Calculation Software for Guided Wave Propagation in a Pipe**

---**Takahiro Hayashi** and Morimasa Murase, Nagoya Institute of Technology, Nagoya, Japan; Won-Joon Song, Research Institute of Industrial Science and Technology; Ik-Keun Park Seoul National University of Technology

---Guided wave has a great potential to rapid long range inspection for a pipe, but is not easy to analyze and understand its wave mechanics even for researchers as well as inspectors, due to multi-mode generation and strong dispersion. For helping our understanding such complex guided wave propagation, guided wave calculation software is developed in this study. Since a semi-analytical finite element technique is used for guided wave calculation, a region is not necessary to divide elements in the longitudinal direction, which enables us to calculate such a large calculation as guided wave propagation in a large pipe. Preprocessor for parameter input is developed with Visual C++ and post processor for visualizing guided wave propagation and obtaining waveforms at a selected point is developed with a free visualization software OPEN DX.

**Simulation of Ultrasonic Inspection With Phased Array Techniques**

---**L. Le Ber**, S.Chaffai -Gargouri, S.Chatillon, <sup>1</sup>CEA/LIST, CEA Saclay,91191 Gif sur Yvette Cedex, France

---Advanced techniques in Non Destructive Testing consider the ultrasonic inspection of components using phased array techniques. Use of simulation is essential to develop new methods. Within the CIVA software, are included a set of tools which allow to define adapted transducers and methods to specific configurations. Delay laws can be computed in complex structures (complex geometry, non homogeneous and/or anisotropic materials...), taking into account phase aberrations due to geometrical or material properties variations. Simulation tools allow prediction of the transmitted beam and echoes arising from flaws. Probe positioning and imperfect matching on irregular geometry are taken into account. This allows us to define optimized parameters according to the required performances. Complex configurations such as welds structure and/or irregular profiles induce beam variations according to the probe position. The prediction of defect responses in such cases involves a beam computation at each position of the transducer in order to take into account beam variations along the probe scanning. This paper presents some applications showing the ability of simulation tools to predict the actual performances of ultrasonic inspection methods on complex structures. It shows that simulation can provide help in evaluating the beam propagation and defect responses in complex configurations.

**The Kirchhoff and Born Approximations for Scattering in Both Isotropic and Anisotropic Elastic Solids**

---**Ruiju Huang** and Lester W. Schmerr Jr., Center for NDE, Department of Aerospace Engineering, Iowa State University, Ames, IA, 50011; Alexander Sedov, Dept. of Mechanical Eng., Lakehead University, Thunder Bay, Ontario, Canada

---It is shown that in the Kirchhoff approximation the pulse echo response of an arbitrary traction free scatterer in an isotropic elastic solid is identical to the same approximate response for a scalar (fluid) scattering model. This leads to simple analytical expressions for the pulse echo far field scattering amplitude of some canonical geometries (cracks and spherical voids). It is also shown that an explicit analytical expression for the early time (leading edge) pulse echo response for volumetric scatterers in general anisotropic elastic solids can be obtained by a high frequency asymptotic evaluation of the Kirchhoff approximation. For both isotropic and anisotropic elastic solids, the recently developed "doubly distorted" Born approximation is modified with simple amplitude and phase corrections. It is demonstrated that these modifications give improved Born scattering results for both weak and strong scattering inclusions.--- This work was partially supported by the National Science Foundation Industry/University Cooperative Research Center program at Iowa State University and partially supported by NASA. A. Sedov was supported by the Natural Sciences and Engineering Research Council of Canada.

**Study of Impact Excited Elastic Waves in Concrete by Scanning Laser Vibrometry**

---**Bernd Koehler** and Frank Schubert, IZfP/FhG, Krueger strasse 22, Dresden, 01326, Germany

---The propagation of elastic waves in solids and their interaction with in-homogeneities like flaws can be studied by numerical modelling. For that, precise material parameters (elastic constants, density), parameters of the component geometry and of the flaw geometry are necessary. There are a lot of situations where these parameters are not known and cannot be gained easily. Especially challenging is the situation when interfaces are not known precisely concerning to their elastic behaviour. Usually, interfaces play a significant role with respect to wave propagation, especially imperfect ones. That is the case for concrete with its numerous interfaces between cement matrix and gravel. Here, detailed experimental study of the wave propagation can be very helpful to clarify the influence of the interfaces to wave propagation. That's why a technique to visualise the propagation of elastic waves was applied to concrete in a previous paper. But several questions remained open. In the present paper improved experimental results could be obtained. So it was possible to clarify the nature of elastic waves generated by an impact near the corner of a concrete block. As in previous work, the interpretation of the experimental results is based also on supplementary modelling. Conclusions are drawn and possible future work is indicated.

**Guided Waves in Fluid Loaded Transversely Isotropic Plate**

---**Farkhanda Yousaf Chohan** and Sadayuki Murashima, Dept of Information & Computer Sciences, Graduate School of Science & Engineering, Kagoshima University, Kagoshima, Japan

---Propagation of antisymmetric guided waves in a fluid loaded transversely isotropic plate of infinite length is studied. Numerical results are presented for highly dense transversely isotropic material Cobalt, when immersed in water. The phase velocities are not significantly affected except for several modes in which energy leakage occurs into water over certain frequency ranges. Attenuation spectra for both the symmetric and antisymmetric cases are also plotted whose comparison shows that the attenuations in case of symmetric modes is larger as compared to the antisymmetric modes.

## *Session 12*

Tuesday, August 2, 2005

**SESSION 12**  
**IMPROVED AND NEW TECHNIQUES**  
**L. Brasche, Chairperson**  
**Druckenmiller Hall 016**

- 3:30 PM**      **Engineering Studies of Fluorescent Penetrant Inspection**  
---L. Brasche, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011
- 4:10 PM**      **All-Optical Elastic Characterization of Silicon Wafers and Cantilever Beams by Vibration Modes**  
---D. R. Franca\* and A. Blouin, Industrial Materials Institute, National Research Council of Canada, 75 de Mortagne Boulevard, Boucherville, Quebec J4B 6Y4, Canada; \*Current Address: Universidade de Brasilia, Faculdade de Tecnologia, Departamento de Engenharia Electrica, 70.919-970, Brazil
- 4:30 PM**      **All-Optical Mechanical Characterization of Silicon Wafers and Cantilever Beams Built on MEMS by Means of Vibration Modes**  
---A. Blouin, Industrial Materials Institute, National Research Council of Canada, Boucherville, Quebec, Canada; D. R. Franca, University of Brasilia, Department of Electrical and Computer Engineering, Brasilia, DF, Brazil
- 4:50 PM**      **Magnetic Particle Inspection Improvements for Aerospace Applications**  
---S. J. Lee, Y. Melikhov, D. C. Jiles, L. J. H. Brasche, and R. Lopez, Iowa State University, Center for NDE, Ames, IA 50011

### **Engineering Studies of Fluorescent Penetrant Inspection**

---**Lisa Brasche**, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011

---Fluorescent penetrant inspection (FPI) is a widely used inspection technique for surface crack detection in both aircraft and engine components during production qualification and inservice assessment. In a recent survey of airworthiness directives from 1995 - 1999, FPI was the third most frequent inspection called out behind visual and eddy current inspection methods. Although patented in 1941, significant changes have occurred in the chemicals/chemistry associated with the process, in many cases as a result of environmental considerations. In September 2001 a program was initiated to determine the most relevant FPI inspection factors for which existing data is insufficient, assess the parameter ranges that provide acceptable performance for typical aircraft and engine components, and document the results of these studies. Program plans and results are coordinated with industry partners to ensure they are applicable to aerospace practices and relevant specification modifications will be supported through participation in standards committees, such as SAE Committee K. In addition to engineering studies, other needs identified through industry input are also addressed. These include self-assessment tools that can be used by the airlines and OEMs to determine effectivity of internal processes and documentation of results which can be used by the industry in effectively instructing personnel in proper processing. The presentation will highlight the factors of most importance as prioritized by the industry partners and present results to date. A series of detailed technical papers are also being presented.---This material is based upon work supported by the Federal Aviation Administration under Contract #DTFA03-98-D-00008, Delivery Order #0016 and performed at Iowa State University's Center for NDE as part of the Center for Aviation Systems Reliability program in cooperation with partners at Boeing Commercial, Boeing Phantom Works, Delta Airlines, United Airlines, Rolls Royce, General Electric, Pratt & Whitney, Honeywell, D&W Enterprises, and Sherwin.

### **All-Optical Elastic Characterization of Silicon Wafers and Cantilever Beams by Vibration Modes**

---**D. R. Franca\*** and A. Blouin, Industrial Materials Institute, National Research Council of Canada, 75 de Mortagne Blvd., Boucherville, Québec J4B 6Y4, Canada. \*Current Address: Universidade de Brasília, Faculdade de Tecnologia, Departamento de Engenharia Elétrica, CEP: 70.919-970, caiza postal: 4.386, Brasília (DF), Brazil

---An all-optical technique is developed to determine mechanical parameters of both semiconductor wafers and cantilever beams through optical excitation and detection of vibration modes. The technique is remote, non-destructive and works on-line, making it an attractive inspection tool for use in semiconductor foundries and MEMS industries. Vibration modes are generated by a pulse from a frequency-doubled Q-switched Nd:YAG laser and detected by a Michelson interferometer. Two types of Silicon (Si) wafers are investigated, namely the anisotropic <100> and the isotropic <111> wafers. In both cases, it is observed that the resonance frequencies of certain selected modes correlate well with the in-plane and out-of-plane Young's Modulus ( $E$ ) and Poisson's Ratio ( $\sigma$ ). A novel inverse method is then derived to extract the in-plane and out-of-plane  $E$  and  $\sigma$  from the resonance frequency measurements, leading to a complete point-to-point mapping of the wafer's elastic parameters. For the cantilever beams, a new and simple generation method to excite vibration modes is proposed. The generation laser pulse is directed to the opposite face of the Si substrate of the MEMS board. Acoustic excitation of the whole Si board then forces the cantilevers to vibrate in an effective way, as a variety of resonance modes are simultaneously excited. Resonance frequency measurements of these modes are used to determine the Young's Modulus of the cantilever beams. Experimental results are compared with the values calculated by the theory of elasticity.

**All-Optical Mechanical Characterization of Silicon Wafers and Cantilever Beams Built on MEMS by Means of Vibration Modes**

---Alain Blouin, Industrial Materials Institute, National Research Council of Canada, Boucherville, Québec, Canada; **D. R. França**, Department of Electrical and Computer Engineering, University of Brasília, Brasília, DF, Brazil

---An all-optical technique is developed to determine mechanical parameters of both semiconductor wafers and cantilever beams through optical excitation and detection of vibration modes. The technique is remote, non-destructive and works on-line, making it an attractive inspection tool for use in semiconductor foundries and MEMS industries. Vibration modes are generated by a pulse from a frequency-doubled Q-switched Nd:YAG laser and detected by a Michelson interferometer. Two types of Silicon (Si) wafers are investigated, namely the anisotropic <100> and the isotropic <111> wafers. In both cases, it is observed that the resonance frequencies of certain selected modes correlate well with the in-plane and out-of-plane Young's Modulus (E) and Poisson's Ratio ( $\nu$ ). A novel inverse method is then derived to extract the in-plane and out-of-plane E and  $\nu$  from the resonance frequency measurements, leading to a complete point-to-point mapping of the wafer's elastic parameters. For the cantilever beams, a new and simple generation method to excite vibration modes is proposed. The generation laser pulse is directed to the opposite face of the Si substrate of the MEMS board. Acoustic excitation of the whole Si board then forces the cantilevers to vibrate in an effective way, as a variety of resonance modes are simultaneously excited. Resonance frequency measurements of these modes are used to determine the Young's Modulus of the cantilever beams. Experimental results are compared with the values calculated by the theory of elasticity.

**Magnetic Particle Inspection Improvements for Aerospace Applications**

---**S. J. Lee**, Y. Melikhov, D. C. Jiles, L. J. H. Brasche, and R. Lopez, Iowa State University, Center for Nondestructive Evaluation, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011

---Magnetic particle inspection (MPI) is a widely used nondestructive inspection method for aerospace applications, which until now has been limited to experiment-based approaches. No serious theoretical or modeling investigations have been attempted before. Yet reliable theory and modeling of magnetic particle inspection will allow identification of factors that affect MPI characteristics and should have the potential for reductions in inspection design time and cost and additionally will lead to improvement of analysis of experimental data. In this research a finite element method (FEM) has been employed for numerical simulation of magnetic particle inspection and magnetic flux leakage. The FEM method is known to be suitable for complicated geometries such as those around defects in samples. We will describe the research that was carried out, which aimed at providing a quantitative scientific basis for magnetic particle inspection. A new FEM solver for MPI simulation has been developed in this research which includes not only nonlinear reversible permeability materials but also irreversible hysteresis materials that are described by the Jiles-Atherton model. For this work, the material was assumed to have isotropic ferromagnetic properties (i.e., the magnetic properties of the material were assumed to be identical in all directions). Using direct current field modes, MPI situations have been simulated to calculate the volume of magnetic particles accumulated around defect sites before and after removing an applied magnetic field.---This work was supported by the Federal Aviation Administration under Contract #DTFA03-98-D-00008, Delivery Order #IA051 and performed at Iowa State University's Center for NDE as part of the Center for Aviation Systems Reliability program.

## *Session 13*

Tuesday, August 2, 2005

**SESSION 13**  
**INFRASTRUCTURE NDE**  
**Moulton Union Lower Level**

- 3:30 PM**      **Evaluation of Multilayered Pavement Structures from Measurements of Surface Waves**  
---**N. Ryden**, M. J. S. Lowe, and P. Cawley, Department of Mechanical Engineering, Imperial College, London SW7 2AZ, United Kingdom; C. B. Park, Kansas Geological Survey, Kansas University
- 3:50 PM**      **Step Frequency Ground Penetrating Radar Applications to Highway Infrastructure Measurement and System Integration Feasibility with Complementary Sensors**  
---**M. L. Scott** and N. Gagarin, Starodub, Inc., 3504 Littledale Road, Kensington, MD 20895; M. Oskard and P. Mills, Turner Fairbank Highway Research Center, Federal Highway Administration, McLean, VA 22101
- 4:10 PM**      **Sludge and Blockage Characterization Inside Pipes Using Guided Ultrasonic Waves**  
---**J. Ma**, F. Simonetti, and M. J. S. Lowe, Department of Mechanical Engineering, Imperial College, London, United Kingdom
- 4:30 PM**      **Excitation of Surface Wave Modes in Rails and their Application for Defect Detection**  
---**D. Hesse** and P. Cawley, Department of Mechanical Engineering, Imperial College, London, United Kingdom
- 4:50 PM**      **Miniature Submersible Surface Changing Robot for Inspection of Ship Hulls, Bridges, and Storage Tanks**  
---**B. Bridge**, T. P. Sattar, and Z. Zhao, London South Bank University, Faculty of Engineering, Research Centre for Automated and Robotic Nondestructive Testing, 103 Borough Road, London, SE1 0AA, United Kingdom

**Evaluation of Multilayered Pavement Structures From Measurements of Surface Waves**

---**Nils Ryden**, Michael J. S. Lowe, and Peter Cawley, Department of Mechanical Engineering, Imperial College, London SW7 2AZ, United Kingdom; Choon B. Park, Kansas Geological Survey, Kansas University

---Pavements are typically constructed using several layers of materials, and their durability depends on the quality of all of these strata. It is therefore very valuable to be able to determine the properties of the layers non-intrusively. A method is presented for evaluating the thickness and stiffness of multilayered pavement structures from guided waves measured at the surface. In this type of layered structure the interaction of leaky Lamb waves in the embedded layers generates surface waves corresponding only to certain portions of the dispersion curves, branches, measurable at the pavement surface. To resolve the different mode branches we measure the wavefield at the surface by using a light hammer as the source and an accelerometer as receiver, generating a synthetic receiver array. The recorded data is transformed to a phase velocity spectrum, which is then inverted to give the layer properties using the Fast Simulated Annealing (FSA) algorithm. So far the method has been applied to the testing of pavements, but it may also be applicable in other fields such as ultrasonic testing of coated materials. The paper will present the theoretical background to the method and experimental results of its application to pavement inspection.

**Step Frequency Ground Penetrating Radar Applications to Highway Infrastructure Measurement and System Integration Feasibility with Complementary Sensors**

---**Michael L. Scott** and Nicolas Gagarin, Starodub, Inc., 3504 Littledale Road, Kensington, MD 20895; Morton Oskard and Pete Mills, Turner Fairbank Highway Research Center, Federal Highway Administration, McLean, VA

---Step frequency ground penetrating radar (GPR) was used in this study to test novel subsurface highway infrastructure evaluation methods. Recent developments in step frequency GPR technology made these methods possible for the first time. Test hardware included an antenna array that incorporated thirty-one transmitter and receiver antenna pairs. The same antenna array was used to collect full depth three dimensional pavement data at highway speeds and detailed tomographic imaging data from concrete bridge decks and other facilities at slower speeds. Step frequency GPR results were compared with standard impulse GPR results over an eleven mile road section. Results from high speed and high resolution surveys showed that step frequency GPR hardware offered unique advantages relative to standard impulse GPR. Size, weight and customizability of step frequency GPR technology for system integration on a multi sensor vehicle platform were also studied for feasibility. The model platform for the multi sensor feasibility study was the Digital Highway Measurement (DHM) vehicle, under development by the Federal Highway Administration. Future implementation of step frequency GPR with DHM vehicle sensors is anticipated to provide comprehensive highway evaluation capabilities.

**Sludge and Blockage Characterization Inside Pipes Using Guided Ultrasonic Waves**

---**Jian Ma**, Francesco Simonetti, and Michael J. S. Lowe, Department of Mechanical Engineering, Imperial College, London, United Kingdom

---The accumulation of sludge and blockages in pipes is a problem which affects many industries. The possibility of using ultrasonic guided waves for detecting and perhaps characterizing, the sludge or blockage inside pipes is investigated. In a prescribed frequency range, the number of guided wave modes which can propagate in an empty pipe is increased by the presence of the blockage which generates new cut-off frequencies that depend on the blockage thickness and acoustic properties. This can be exploited in two ways using either local or remote measurements. If access to the pipe is possible, where the blockage is located, then local guided wave measurements can be made, and the extent of the blockage could be estimated by measuring the frequencies where these new cut-offs occur. On the other hand, if the blocked region is not accessible, remote measurement of the reflection from the place where blockage starts can be employed. Such measurements show that the reflection coefficient spectrum exhibits periodic maxima whose frequency spacing depends on the thickness and material properties of the blockage. The idea is investigated through theoretical analysis, finite element modeling and validated by experimental measurements. The potential of using this method in practice is also evaluated.

**Excitation of Surface Wave Modes in Rails and Their Application for Defect Detection**

---**Daniel Hesse** and Peter Cawley, Department of Mechanical Engineering, Imperial College, London, United Kingdom

---Surface cracks in rails induced by rolling contact fatigue are a common problem in modern railways and cannot always reliably be detected by conventional ultrasonic wheel probes. Shallow damage (e.g. spalling or multiple small cracks) often prevent sufficient penetration of bulk waves into the material and lead to 'shadow zones' in which rail integrity cannot be assessed. Short range guided waves confined to the surface have the potential to overcome these problems and could be applied as a complementary inspection method. In this work, suitable surface wave modes have been efficiently excited using a phased array probe. The signal-to-noise-ratio has been further enhanced by combining results from adjacent probe positions along the rail. A study of the scattering behavior from different defect geometries has shown that deep defects can be seen even with multiple smaller ones in front. The proposed method is therefore potentially a valuable addition to current inspection train technology.

**Miniature Submersible Surface Changing Robot for Inspection of Ship Hulls, Bridges and Storage Tanks**

---**B. Bridge**, T. P. Sattar, and Z. Zhao, London South Bank University, Faculty of Engineering, Research Centre for Automated and Robotic Nondestructive Testing, 103 Borough Road, London SE1 0AA, United Kingdom

---Field trials are described of a novel miniature mobile inspection robot which can move over floors, changes surfaces, climb walls or swim to allowing both total inspection coverage of large submerged structures or rapid access to targeted inspection areas. It is small enough to fit through a 450mm access hole to permit total inspection of most petrochemical and other industrial storage tanks, including those on ships and other offshore floating installations, without having to empty them. The small size of this mobile inspection instrument allows circular tank walls with a diameter as small as 3 metres to be climbed. Results are described of inspections carried out on test tanks in an oil refinery with the robot working payload consisting of an array of 10 ultrasonic probes including two panoramic long range ultrasonic sensors. The robot can deploy any kind of NDT sensor up to a payload limit of 10kg. The results show promise of an exceptionally versatile NDT robot which in principle can climb submerged walls of any material construction and inspect bridges, dams ship hulls and offshore structures below the water line in addition to broad family of storage tanks.

# *Session 14*

Tuesday, August 2, 2005

**SESSION 14**  
**SIGNAL ANALYSIS TECHNIQUES**  
**Moulton Union Main Lounge**

- 3:30 PM**      **Modal Decomposition of Double-Mode Lamb Waves**  
---**K. Luangvilai** and L. J. Jacobs, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA 30332; L. J. Jacobs and J. Qu, Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332
- 3:50 PM**      **Precise Depth Measurement of Surface-Breaking Tight Cracks by Laser-Induced Surface Acoustic Wave**  
---**T. Miura**, M. Ochiai, H. Kuroda, and T. Onodera, Power and Industrial Systems Research and Development Center, Toshiba Corporation, Yokohama, Kanagawa, Japan; F. Osakata, Information & Control Systems Division, Toshiba Plant Systems & Services Corporation, Kawasaki, Kanagawa, Japan; K. Tsuchihashi, Isogo Engineering Center, Toshiba Corporation, Yokohama, Kanagawa, Japan
- 4:10 PM**      **Characterization of Welding Defects by Fractal Analysis of Ultrasonic Signals**  
---**W. M. Ferreira**, E. P. de Moura, and A. P. Vieira, Centro de Tecnologia, Universidade Federal do Ceara, Fortaleza, Ceara, Brazil; **L. L. Goncalves**, Departamento de Fisica, Universidade Federal do Ceara, Fortaleza, Ceara, Brazil; J. M. A. Rebello, Departamento de Engenharia Metalurgica de Materials, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil
- 4:30 PM**      **Flaw Identification Using Eddy Current Differential Transducer and Artificial Neural Networks**  
---**T. Chady** and P. Lopato, Department of Electrical Engineering, Technical University of Szczecin, Szczecin, Poland
- 4:50 PM**      **A Simplified Ultrasonic Time-Delay Spectrometry (TDS) System Employing Digital Processing to Minimize Hardware Requirements**  
---**P. M. Gammell**, Gammell Applied Technologies, LLC, 6139 Pleasant Cove Drive, Exmore, VA 23350; S. Maruvada and G. R. Harris, Food and Drug Administration, Center for Devices and Radiological Health, Rockville, MD 20850
- 5:10 PM**      **Modal Analysis of Acoustic Leak Signal in Pipeline with Methods of Time-Frequency Analysis**  
---**J. Jiao**, **C. He**, B. Wu, X. Wang, and G. Song, College of Mechanical Engineering and Applied Electronic Technology, Beijing University of Technology, Beijing, China

**Modal Decomposition of Double-Mode Lamb Waves**

---**Kritsakorn Luangvilai** and Laurence J. Jacobs, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA 30332; Laurence J. Jacobs and Jianmin Qu, Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332

---This research proposes a technique to decompose a transient, multi-mode, Lamb wave, time-domain signal into its individual Lamb wave modes. The technique is derived for a plane-strain Lamb wave signal consisting of two Lamb wave modes (double-mode Lamb wave signal), and these Lamb wave modes may experience material attenuation. The proposed technique assumes knowledge of the propagation dispersion characteristics of Lamb waves, i.e. relationships between frequency and the real part of wavenumber of existing modes. These dispersion relationships can be obtained by other signal processing techniques such as the two-dimensional Fourier transform or the short-time Fourier transform. To demonstrate its accuracy, the proposed technique is verified on numerically simulated signals. The numerical simulation uses an eigen-expansion method that sums up the individual responses of all existing Lamb modes, and a prescribed material attenuation is added to each individual Lamb mode. The comparison between the decomposed and simulated signals demonstrates the validity of the proposed technique.

**Precise Depth Measurement of Surface-Breaking Tight Cracks by Laser-Induced Surface Acoustic Wave**

---**Takahiro Miura**, Makoto Ochiai, Hidehiko Kuroda, and Toru Onodera, Power and Industrial Systems Research and Development Center, Toshiba Corporation, Yokohama, Kanagawa, Japan; Fukashi Osakata, Information & Control Systems Division, Toshiba Plant Systems & Services Corporation, Kawasaki, Kanagawa, Japan; Kentaro Tsuchihashi, Isogo Engineering Center, Toshiba Corporation, Yokohama, Kanagawa, Japan

---A new method for depth measurement of shallow crack is proposed. This method is based on frequency analysis of surface acoustic wave (SAW) generated and detected by lasers. It is well-known that the energy of SAW is distributed within its one wavelength from the surface; the lower frequency components reach deeper portion of the media while the higher frequency components are localized within the thin surface layer. When the SAW transmits through a crack, its frequency and overall amplitude are therefore modified depending on the crack depth. In this paper, we report that experimental results for the depth measurement based on this principle. The SAW is generated by Q-switched Nd:YAG laser and is detected by long pulse Nd:YAG laser coupled with confocal Fabry-Perot interferometer. This laser-ultrasonic technique is a suitable tool for this measurement, since its features a wide detection bandwidth, which is necessary for the signals processing. A product function of the power spectrum of the transmitting SAW and a proper weighting function is used for the signal processing to obtain the absolute crack depth. It is also important to normalize the transmitting SAW using the other ultrasonic signals to eliminate noise factors, such as differences of surface condition, for the measurement. Sizing capability of this method is demonstrated by using an artificial surface-breaking slits and actual stress corrosion cracks (SCCs) having depth of 0-2mm in a stainless steel plate. In particular, depth profile of SCC is evaluated every 0.1mm over the crack aperture length. The evaluated depths are compared with the depths measured by the destructive testing. Finally, an application of this technique for nuclear reactor internal component is presented.

**Characterization of Welding Defects by Fractal Analysis of Ultrasonic Signals**

---Waydson M. Ferreira, Elineudo P. de Moura and Andre P. Vieira, Centro de Tecnologia, Universidade Federal do Ceara, Fortaleza, Ceara, Brazil; **Lindberg L. Goncalves**, Departamento de Fisica, Universidade Federal do Ceara, Fortaleza, Ceara, Brazil; João M. A. Rebello, Departamento de Engenharia Metalúrgica e de Materiais, Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ, Brazil

---In this paper it is presented a fractal analysis of ultrasonic signals obtained, by using the TOFD technique, in specimens with the following inserted welding defects: lack of fusion, incomplete penetration and porosity. The fractal characterization of the signals, which satisfy non-stationary distributions, has been determined by means of Hurst's analysis, detrended fluctuation analysis, minimal cover analysis and boxcounting dimension analysis, in a similar procedure recently introduced for the study of acoustic emission signals obtained in samples of composites. In order to eliminate the noise, the signals have been filtered by two different methods, namely, band pass and Savitzky-Golay, and it is shown the characteristic fractal parameters determined for these signals can discriminate all defects. It is also shown that the best discrimination is obtained from the signals filtered by using the Savitzky-Golay method.---Work partially financed by the Brazilian agencies CNPq, Finep (CT-Petro) and Capes.

**Flaws Identification Using Eddy Current Differential Transducer and Artificial Neural Networks**

---**Tomasz Chady** and Przemyslaw Lopato, Department of Electrical Engineering, Technical University of Szczecin, Szczecin, Poland

---In this paper we present a multi-frequency excitation eddy current differential transducer and neural models which were used to identify flaws in thin conducting plates. The transducer consists of a cylindrical ferrite core with five symmetrically placed columns. Central column include pickup coil. Four excitation coils are placed on remaining columns in pairs on two perpendicular axes. Each pair produce in pickup coil opposite (to another pair) directed magnetic flux, which is close to zero in equilibrium state. Samples are made of Inconel600. EDM notches have relative depth from 10% to 80% and length from 2 mm to 7 mm. The profiles of flaws are rectangular and more complex. Signals from measurements taken for rectangular profiles were used as training data for neural nets. A special approximation functions were proposed and utilized in order to remove noise influences and improve identification reliability. The neural networks with moving window were used. Wide range of feedforward and recurrent structures was examined. In this paper observed trends are presented and the optimal structure will be proposed.

**A Simplified Ultrasonic Time-Delay Spectrometry (TDS) System Employing Digital Processing to Minimize Hardware Requirements**

---**Paul M. Gammell**, Gammell Applied Technologies, LLC, 6139 Pleasant Cove Drive, Exmore, VA 23350; Subha Maruvada and Gerald R. Harris, Food and Drug Administration, Center for Devices and Radiological Health, Rockville, MD 20850

---Time Delay Spectrometry (TDS) is a broadband measurement method that produces spectral information directly and has an improvement in signal-to-noise ratio of several thousand over pulse techniques. It uses a swept frequency and employs a tracking filter to select signals with the desired transit time following the transmitted signal. Commercial TDS systems are available only in the audio frequency range. Several ultrasonic TDS systems have been constructed and used effectively for substitution calibration of hydrophones and for measurement of attenuation in materials. Unfortunately these systems depend on features of commercial equipment no longer manufactured. The system described here is easy to replicate, requiring only a frequency source with a reasonably linear frequency sweep, audio frequency filters, a double balanced mixer, a power splitter, and a digitizer and computer capable of handling audio frequency signals. The processing steps are performed with a simple m-file in MATLAB® (The Mathworks, Natick, MA). Substitution calibration measurements of hydrophones were obtained by this system and by a custom TDS system previously described by the authors. The data from these two TDS systems agree to within  $\pm 0.5$  dB over the 0.1-1.7 MHz frequency range used. Higher frequency source transducers could be used to extend this range.

**Modal Analysis of Acoustic Leak Signal in Pipeline with Methods of Time-Frequency Analysis**

---Jingpin Jiao, **Cunfu He**, Bin Wu, Xiuyan Wang, and Guorong Song, College of Mechanical Engineering and Applied Electronic Technology, Beijing University of Technology, Beijing, China

---Pipeline is one of the most convenient means of conveyance for transportation of petroleum, water and chemical materials. After long-term usage, there often exist leakages in the pipeline. It is necessary to monitor on the operation condition of pipeline. As a dynamic non-destructive testing technique, acoustic emission has been researched on the leak detection in pipeline. But the traditional cross-correlation leak location technique cannot perform well. Based on the theory of modal acoustic emission, the acoustic leak signal consists of multi-mode and has the characteristics of dispersion. Therefore a good leak location should consider the characteristics of multi-mode and dispersion. It is necessary to select the appropriate mode in acoustic leak location to obtain the good results. Considering the non-stationary stochastic of acoustic leak signal, time-frequency analyses were used to the analysis of acoustic leak signal. Based on the relation of time-frequency distribution of acoustic leak signal and the dispersion curves of guided waves, the mode components of acoustic leak signal were obtain, and the main modes in acoustic leak signals were determined. The research can provide guideline for the mode selection in pipeline leak location, and be help to improve the accuracy of leak location.

# *Session 15*

Tuesday, August 2, 2005

**SESSION 15**  
**RESIDUAL STRESS I**  
**P. Panetta, Chairperson**  
**Cleveland Hall 151**

- 3:30 PM**      **The Role of Cold Work in Eddy Current Residual Stress Measurements in Shot-Peened Nickel-Base Superalloys**  
---F. Yu and P. B. Nagy, Department of Aerospace Engineering and Engineering Mechanics, University of Cincinnati, Cincinnati, OH 45221-0070
- 3:50 PM**      **A High-Frequency Eddy Current Inspection System and its Application to the Residual Stress Characterization**  
---C. Lee, Y. Shen, and N. Nakagawa, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011
- 4:10 PM**      **Near-Surface Residual Stress Assessment in Inhomogeneous Nickel-Base Superalloys**  
---F. Yu and P. B. Nagy, Department of Aerospace Engineering and Engineering Mechanics, University of Cincinnati, Cincinnati, OH 45221-0070
- 4:30 PM**      **A New Multi-Gaussian Auto-Correlation Function for the Modeling of Realistic Rough Surfaces to Assess the Effect of Surface Roughness on Residual Stress Measurements Using Eddy Current**  
---W. T. Hassan, Honeywell ES&S, Phoenix, AZ 85034; M. Blodgett, AFRL/MLLP, NDE Branch, Wright Patterson AFB, OH 45433
- 4:50 PM**      **Stress Determination in Dented Pipelines Utilizing EMAT Velocity Measurements**  
---P. D. Panetta, M. Morra, S. R. Gossellin, K. I. Johnson, Pacific Northwest National Laboratory, 902 Battelle Boulevard, Richland, WA 99352; G. A. Alers, EMAT Consulting, 1328 Tanglewood Drive, San Luis Obispo, CA 93401
- 5:10 PM**      **Improvement of Magnetomechanical Properties of Cobalt Ferrite for Stress Sensor Applications**  
---C. C. H. Lo<sup>1</sup>, J. E. Snyder<sup>2,3</sup>, A. P. Ring<sup>1</sup>, Y. Melikhov<sup>1</sup>, P. Matlage<sup>1</sup> and D. C. Jiles<sup>1,2,3</sup>, <sup>1</sup>Center for Nondestructive Evaluation, <sup>2</sup>Materials and Engineering Physics Program, Ames Laboratory, Department of Materials Science and Engineering, Iowa State University, Ames, IA 50011

**The Role of Cold Work in Eddy Current Residual Stress Measurements in Shot-Peened Nickel-Base Superalloys**

---**Feng Yu** and Peter B. Nagy, Department of Aerospace Engineering and Engineering Mechanics, University of Cincinnati, Cincinnati, OH 45221-0070

---Recently, it was shown that eddy current methods can be adapted to residual stress measurement in shot-peened nickel-base superalloys. However, experimental evidence indicates that the piezoresistivity effect is simply not high enough to account for the observed apparent eddy current conductivity (AECC) increase. At the same time, X-ray diffraction data indicates that "cold work" lingers even when the residual stress is fully relaxed and the excess AECC is completely gone. It is impossible to account for both observations with a single coherent explanation unless we assume that instead of a single "cold work" effect there are two varieties of cold work; type-A and type-B. Type-A cold work (e.g., changes in the microscopic homogeneity of the material) is not detected by X-ray diffraction as it does not significantly affect the beam width, but causes substantial conductivity change and exhibits strong thermal relaxation. Type-B cold work (e.g., dislocations) is detected by X-ray, but causes little or no conductivity change and exhibits weak thermal relaxation. Based on the assumption of two separate cold-work variables and that X-ray diffraction results indicate the presence of type-B, but not type-A, all observed phenomena can be explained. If this working hypothesis is proven right, the separation of residual stress and type-A cold work is less critical because they both relax much earlier and much faster than type-B cold work.---This work was performed at the Center for NDE at Iowa State University with funding from the Air Force Research Laboratory on contract FA 8650-04-C-5228.

**A High-Frequency Eddy Current Inspection System and Its Application to the Residual Stress Characterization**

---**Changqing Lee**, Yuping Shen, and Norio Nakagawa, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Room 215B, Ames, IA 50011

---This paper reports on an eddy current task that is a part of the on-going project toward developing electromagnetic residual-stress characterization method. Recent publications show that the eddy current technique is a good candidate for such measurements for nickel-based alloys. In our approach, we treat residual stress measurements essentially as a "layer-substrate" problem (a shot-peened layer on an alloy substrate), which can be solved by the swept-frequency technique. Toward applying the swept-frequency technique for the residual stress measurement, a high-sensitivity eddy current system with operating frequency up to 50MHz has been recently developed and tested in our lab. Our instrumentation includes proprietary probes that are designed and fabricated by the PCB technology, and driven by laboratory-grade instruments under software control. The system performance has been studied. Indeed, we have collected preliminary data that distinguish clearly between surfaces before and after shot-peening for nickel-based alloys. The paper will describe experimental procedure and data themselves, as well as the calibration measurements. One of the goals of the aforesaid project is model-based stress profile inversion. We approach the inversion based on a residual stress and cold work profile model, and have developed a detailed plan to validate the forward and inverse models against measurements using mockup specimens. The steps and status of this model validation process will be presented here as well.---This work was performed at the Center for NDE at Iowa State University with funding from the Air Force Research Laboratory on contract #FA8650-04-C-5228.

**Near-Surface Residual Stress Assessment in Inhomogeneous Nickel-base Superalloys**

---Feng Yu and **Peter B. Nagy**, University of Cincinnati, Department of Aerospace Engineering and Engineering Mechanics, ML0070, Cincinnati, OH 45221-0070

---Recently, it has been shown that shot-peened nickel-base superalloys exhibit an approximately 1% increase in apparent eddy current conductivity at high inspection frequencies, which can be exploited for nondestructive subsurface residual stress assessment. Unfortunately, microstructural inhomogeneity in certain as-forged and precipitation hardened nickel-base superalloys, like Waspaloy, can lead to significantly larger electrical conductivity variations of as much as 4-6%. This intrinsic conductivity variation adversely affects the accuracy of residual stress evaluation in shot-peened and subsequently thermal-relaxed specimens, but does not completely prevent it. Experimental results are presented to demonstrate that the conductivity variation resulting from volumetric inhomogeneities in as-forged engine alloys do not display significant frequency dependence. This characteristic independence of frequency can be exploited to distinguish these inhomogeneities from near-surface residual stress and cold work effects caused by surface treatment, which, in contrast, are strongly frequency-dependent.---This work was performed at the Center for NDE at Iowa State University with funding from the Air Force Research Laboratory on contract FA 8650-04-C-5228.

**A New Multi-Gaussian Auto-Correlation Function for the Modeling of Realistic Rough Surfaces to Assess the Effect of Surface Roughness on Residual Stress Measurements Using Eddy Current**

---**Waled T. Hassan**, Honeywell ES & S, Phoenix, AZ 85034; Mark Blodgett, AFRL/MLLP, NDE Branch, WPAFB, Dayton, OH 45433

---Near surface residual stresses directly influence the fatigue life of critical engine rotating components. Under the US Air Force research initiative known as Engine Rotor Life Extension, the Air Force Research Laboratory (AFRL) has been sponsoring research to develop capabilities to, among other things, nondestructively measure subsurface residual stresses in surface-treated titanium and nickel based alloys. Shot peening is the main surface treatment of interest. A by-product of the shot peening process is random surface roughness that can affect the measurements of the resulting residual stresses and therefore impede their NDE assessment. High frequency eddy current conductivity measurements have the potential to assess these residual stresses in Ni based super alloys. However, the effect of random surface roughness is expected to become significant in the desired measurement frequency range of 10 to 100 MHz. Therefore, effective tools are needed to model the effect of randomly rough surfaces resulting from shot peening. In this paper, a new Multi-Gaussian (MG) auto-correlation function is proposed for modeling the resulting pseudo-random rough profiles. Its use in the calculation of the Apparent Eddy Current Conductivity (AECC) loss due to surface roughness is also demonstrated. The AECC loss is calculated in copper and in Ni based super alloys. The results show that the AECC loss in realistic profiles resulting from shot peening is higher than was expected before using profiles exhibiting Lorentzian auto-correlation function. The numerical results presented need to be validated with experimental measurements on randomly rough surface profiles from actual shot peened specimens.

**Stress Determination in Dented Pipelines Utilizing EMAT Velocity Measurements**

---**Paul D. Panetta**, Marino Morra, Steve R. Gossellin, Ken I. Johnson, Pacific Northwest National Laboratory, 902 Battelle Boulevard, Richland, WA 99352; George A. Alers, EMAT Consulting, 1328 Tanglewood Drive, San Luis Obispo, CA 93401

---Maintaining the integrity of the nation's aging infrastructure is of primary importance. Specifically, there is a desire to characterize plastically deformed regions in structures to monitor their integrity. Of particular importance is the accurate prediction of the lifetime of natural gas pipelines damaged by impact. In order to characterize the degree of plastic deformation, it is essential to accurately determine the stress and strain in the damaged region. Currently, determination of the stress and strain in damaged regions utilizing ultrasonic velocity measurements is complicated by the inherent texture variations in the alloys and the difficulty in separating these effects from the stress and strain contributions. We will report results of ultrasonic velocity measurements on plastically deformed steel specimens that elucidate the severity of damage. Recent measurements on dented pipelines will be related to results from standard tensile test to classify the severity of damage by determining the residual stress and strain levels around the dents. Ultrasonic results will be compared with finite element predictions of stresses and strains.---This work was supported by the Department of Energy, National Energy Technology Laboratory. Pacific Northwest National Laboratory is operated for the U.S. Department of Energy by Battelle under Contract DE-AC06-76RLO18310.

**Improvement of Magnetomechanical Properties of Cobalt Ferrite for Stress Sensor Applications**

---**C. C. H. Lo**<sup>1</sup>, J. E. Snyder<sup>2,3</sup>, A. P. Ring<sup>1</sup>, Y. Melikhov<sup>1</sup>, P. Matlage<sup>1</sup>, and D. C. Jiles<sup>1,2,3</sup>, Iowa State University, Ames, IA 50011; <sup>1</sup>Center for Nondestructive Evaluation; <sup>2</sup>Materials and Engineering Physics Program, Ames Laboratory; <sup>3</sup>Department of Materials Science and Engineering

---We have developed and implemented magnetic stress sensor materials based on cobalt ferrite in laboratory scale demonstrations which have shown their utility for stress detection. Magnetostrictive cobalt ferrite composites represent a class of smart materials that hold promise for use in advanced non-contact magnetomechanical stress and torque sensors because of their high sensitivity of magnetization to applied stress and high levels of magnetostriction. Their magnetization changes in response to applied stresses and such changes can be detected remotely by measuring the magnetic field at the materials surface. We report dramatic improvements in both magnetostriction level and strain derivative of polycrystalline cobalt ferrite as a result of magnetic annealing. The maximum magnetostriction at room temperature increased in magnitude from  $-200 \times 10^{-6}$  to  $-252 \times 10^{-6}$  (an increase of 26%) after annealing. The rate of change of magnetostrictive strain with applied field, which is related to stress sensitivity, increased from  $1.5 \times 10^{-9} \text{ A}^{-1} \text{ m}$  to  $3.9 \times 10^{-9} \text{ A}^{-1} \text{ m}$  (an increase of 163%). The improvements in magnetomechanical properties can be interpreted in the context of the uniaxial magnetic anisotropy induced by magnetic annealing. The present results demonstrate an alternative approach besides chemical substitution for enhancing the performance of nondestructive magnetic stress sensors through control of magnetomechanical properties.---This research was supported by the National Aeronautical and Space Administration (NASA) under award No NAG-1-02098.

# ***WEDNESDAY***

Session 16 – UT Phased Arrays .....	91
Session 17 – Eddy Currents .....	97
Session 18 – Residual Stress II .....	103
Session 19 – Sensors and Systems for Structural Health Monitoring .....	109
Session 20 – Image and Signal Analysis .....	115
Session 21 – Laser UT and Applications .....	121
Session 22 – Terahertz Imaging .....	127
Session 23 – NDE for Materials Characterization .....	132
Special Evening Session .....	138

# *Session 16*

Wednesday, August 3, 2005

**SESSION 16**  
**UT PHASED ARRAYS**  
**R. C. Addison, Jr., Chairperson**  
**Druckenmiller Hall 016**

- 8:30 AM**      **Enhanced Differential Methods for Guided Wave Phased Array Imaging Using Spatially Distributed Piezoelectric Transducers**  
---**J. E. Michaels** and T. E. Michaels, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0250
- 8:50 AM**      **Efficient Design of Ultrasonic Phased Array Transducer Surface Geometry**  
---**R. A. Roberts**, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011
- 9:10 AM**      **Phased-Array Focusing with Longitudinal Guided Waves in a Viscoelastic Coated Hollow Cylinder**  
---**W. Luo** and J. L. Rose, Pennsylvania State University, Department of Engineering Science and Mechanics, 212 Earth and Engineering Science Building, University Park, PA 16802
- 9:30 AM**      **Three-Dimensional Steering and Focusing Using an Ultrasonic 2D Array – Simulation and Experiment**  
---C. Didion, W. Gebhardt, R. Licht, H. Rieder, and **M. Spies**, University of Saarland, Physical Basics Department, Fraunhofer Institute for Nondestructive Testing, IZFP, Building 37, 66123 Saarbruecken, Germany
- 9:50 AM**      **Exploiting the Full Data Set from Ultrasonic Arrays by Post-Processing**  
---**P. D. Wilcox**, C. Holmes, and B. W. Drinkwater, University of Bristol, Department of Mechanical Engineering, Queen's Building, University Walk, Bristol, BS8 1TR, United Kingdom
- 10:10 AM**      **Coffee Break**
- 10:30 AM**      **Ultrasonic Guided Waves Focused Beyond a Weld in a Pipe**  
---**L. Zhang**, W. Luo, and J. L. Rose, Department of Science and Mechanics, Pennsylvania State University, University Park, PA 16802
- 10:50 AM**      **Improved Titanium Billet Inspection Sensitivity Through Optimized Phased Array Design, Part I: Design Technique, Modeling and Simulation**  
---**V. Lupien**, Acoustic Ideas, 27 Eaton Street, Wakefield, MA 01880; W. Hassan, Honeywell ES&S, 111 S. 34<sup>th</sup> Street, Phoenix, AZ 85034; P. Dumas, Imasonic SA, Besancon, France
- 11:10 AM**      **Improved Titanium Billet Inspection Sensitivity Through Optimized Phased Array Design, Part II: Experimental Validation and Comparative Study with Multizone**  
---**W. Hassan** and F. Vensel, Honeywell ES&S, 111 S. 34<sup>th</sup> Street, Phoenix, AZ 85034; V. Lupien, Acoustic Ideas, 27 Eaton Street, Wakefield, MA 01880
- 11:30 AM**      **Leak Detection in Spacecraft Using a 64-Element Multiplexed Passive Array to Monitor Structure-Borne Noise**  
---**S. D. Holland**<sup>1</sup>, J. Song<sup>1,2</sup>, D. E. Chimenti<sup>1,2</sup>, and R. Roberts<sup>1,2</sup>, Iowa State University, <sup>1</sup>Center for NDE, 1915 Scholl Road, Ames, IA 50011; <sup>2</sup>Department of Aerospace Engineering
- 11:50 AM**      **Control of Complex Components with Smart Flexible Phased Arrays**  
---O. Casula and **P. Benoist**, SYSSC CEA-SACLAY Gif-sur-Yvette, France; G. Cattiaux, IRSN, Fontenay-aux-Roses, France
- 12:10 PM**      **Lunch**

**Enhanced Differential Methods for Guided Wave Phased Array Imaging Using Spatially Distributed Piezoelectric Transducers**

---**Jennifer E. Michaels** and Thomas E. Michaels, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0250

---A number of tomographic and phased-array methods have been proposed for generating two dimensional images of plate-like structures using sparse arrays of spatially distributed ultrasonic transducers. The phased array differential approach is considered here whereby pulse echo and through transmission signals are recorded before and after localized damage is introduced, and differenced signals are combined using a focusing rule to produce an image of the plate. The application is structural health monitoring where the transducers are permanently bonded to the plate. The quality of the image is affected by many factors such as the number and location of the transducers, the characteristics of the damage, the signal-to-noise ratio, presence of edge reflections, and anything unrelated to damage that may perturb the ultrasonic signals such as temperature changes and transducer bonding variations. Furthermore, accurate knowledge of the wave velocity and transducer locations is necessary for successful imaging. Two methods for enhancing image quality are implemented and then evaluated as to their effectiveness under realistic measurement conditions. In the first method, each received signal is automatically scaled, shifted and stretched to best match the corresponding baseline signal in order to compensate for instrumentation drift and temperature changes. The second method utilizes multiple excitations at different frequencies to produce multiple images, and these images are then combined to obtain more robust detection and localization of damage. Results are reported for artificial defects introduced in aluminum plates.

**Efficient Design of Ultrasonic Phased Array Transducer Surface Geometry**

---**R. A. Roberts**, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011

---Maximizing the range of applicability of phased array instrumentation requires making the most efficient use of the available delay channels for beam formation. This requires the design of array transducers which will perform specified beam formation using as few elements as possible. The number of elements required in an array transducer to cover a range of focus is in large part determined by the geometry of the active surface into which the array elements are fabricated. A simple principle and consequent algorithm are presented in this talk which determines an efficient, and possibly optimum, active surface geometry onto which array elements can be prescribed. The underlying concepts will be described, followed by the presentation of various array transducer designs.

**Phased-Array Focusing with Longitudinal Guided Waves in a Viscoelastic Coated Hollow Cylinder**

---**Wei Luo** and Joseph L. Rose, Pennsylvania State University, Department of Engineering Science and Mechanics, 212 Earth and Engineering Science Building, University Park, PA 16802

---Guided wave phased-array focusing techniques have been studied and applied in the long-range guided wave inspection of industry pipelines with the advantages of longer inspection distance, greater wave penetration power and higher detection resolution. To preserve the integrity and safety of the pipelines, a large percentage of them are coated and/or encased and buried underground. A phased-array focusing study for guided waves is now considered on pipelines with viscoelastic coatings. In this paper, longitudinal guided wave focusing as well as axisymmetric wave propagation is studied in a bare pipe and a pipe with a viscoelastic coating from theoretical and experimental point of view. Dispersion curves are generated and a finite element model is studied. First of all, an investigation on whether the coating or soil has an affect on the axisymmetric guided wave propagation is reported. A study on the coating effects of partial loading is also considered added on each element of the phased array. Based on the result of a single element, phased array focusing with 4-element and 8-element segments are studied. This study provides a very useful tool and guidance for the analysis and examination of guided wave focusing in a real field pipeline under various coating and environmental conditions.

**Three-Dimensional Steering and Focusing Using an Ultrasonic 2D-Array – Simulation and Experiment**

---Christoph Didion, Wolfgang Gebhardt, Rudolf Licht, Hans Rieder, and **Martin Spies**, University of Saarland, Physical Basics Department, Fraunhofer Institute for Nondestructive Testing IZFP, Bldg. 37, 66123 Saarbruecken, Germany

---Single- or dual-element angle beam transducers exhibit operating characteristics suitable for a large range of practical NDE applications. These capabilities can be improved by operating such transducers as phased arrays, where each of the array elements can be pulsed with appropriate time delays, thus controlling the shape and the sound beam direction on a large scale. However, some applications suffer from the fact that the area of interest can not be properly scanned due to restricted access. In such cases the use of two-dimensional arrays allowing for a three-dimensional steering of the ultrasound beam can be beneficial. In this contribution we report on results obtained using a 16-by-16 (256) element array, operating at a center frequency of 2.25 MHz. A 256-channel electrical transmitter system has accordingly been developed to demonstrate the three-dimensional steering capabilities. This phased-array transmitter system has first been combined with a standard ultrasonic device: while steering the beam field in three dimensions, reception is performed with either a single element of the array or with a separate single element probe. The beam fields generated in water have been simulated using a point source superposition technique for various steering and focusing situations, where the proper time delays have been obtained using Fermat's principle. These results have been verified by experiments in a water tank showing excellent agreement. Having obtained these results, the 256-channel transmitter system has been coupled with a standard 16-channel phased-array receiver system. With this combined system the 3D imaging of defects inside components has been addressed only by electrical steering and focusing. The performance of this system will be demonstrated by respective experimental results.

### **Exploiting the Full Data Set from Ultrasonic Arrays by Post-Processing**

---**Paul D. Wilcox**, Caroline Holmes, and Bruce W. Drinkwater, University of Bristol, Department of Mechanical Engineering, Queen's Building, University Walk, Bristol, BS8 1TR, United Kingdom

---The full data set from an ultrasonic array can be obtained by firing each element individually while receiving on all elements. Hence the time-domain signal from every transmit-receive element pair is obtained and the desired beam-forming is performed in post processing. This technique enables a multitude of processing methodologies to be explored including many that could not be feasibly achieved using the traditional parallel firing technique for array control. Previously the authors have demonstrated that optimum imaging performance can be obtained from an array by applying the Total Focusing Method (TFM) to the full data set. Physically, the TFM represents the complete array being focused in transmission and reception at every point in an image. In this paper, a technique for obtaining the angular reflectivity characteristics of any point in a sample is presented. Conceptually this is achieved by implementing the TFM algorithm as a vector rather than a scalar addition. The results enable, for example, the orientation of small reflectors to be determined and hence for more accurate defect characterization to be performed. Simulated data is used to illustrate the concept and experimental results are presented from a number of samples containing artificial and genuine defects.

### **Ultrasonic Guided Waves Focused Beyond a Weld in a Pipe**

---**Li Zhang**, Wei Luo, and Joseph L. Rose, Department of Engineering Science and Mechanics, Pennsylvania State University, University Park, PA 16802

---The phased array focusing technique is being developed with an intent to inspect hundreds of feet of pipeline from a single array position. The single array position is beneficial if access to a pipe is limited, e.g. steam pipes onboard U.S. Naval ships or underground gas lines. Focusing the ultrasonic energy at a predetermined location along the length of the pipe enhances the ability to detect defects that current state of the art axisymmetric inspection systems cannot. False alarms are reduced and circumferential location of a defect can be determined by moving the focal spot around the circumference. Focusing is achieved by applying excitation time delays to a multi-channel signal generation system. The excitation sources are equally spaced about the circumference of the pipe. Time delays are calculated using theoretically generated angular displacement profiles in a hollow cylinder. These theoretical displacement profiles are dependent upon excitation source influences. In this paper, the excitation source influence for focusing potential was studied. A challenge of this technique is to focus beyond welds, defects, or other obstructions. This problem is discussed along with an experimental example.

**Improved Titanium Billet Inspection Sensitivity Through Optimized Phased Array Design, Part I: Design Technique, Modeling And Simulation**

---**Vincent Lupien**, Acoustic Ideas, 27 Eaton Street, Wakefield, MA 01880; **Waled Hassan**, Honeywell ES&S, 111 S. 34th Street, Phoenix, AZ 85034; **Philippe Dumas**, Imasonic SA, Besançon, France

---As part of an effort to increase the safety and longevity of the commercial and military aircraft fleet, the Federal Aviation Administration (FAA) and major aircraft engine manufacturers have identified the need to reduce the size of the smallest detectable embedded defects in engine grade titanium. FAA funded research in the ultrasonic properties of titanium (Iowa State University) has revealed that reductions in the beam diameter and pulse duration of focused ultrasound causes an increase in the signal to noise ratio of defects whose sizes lie at or near current detection limits. In practice, reductions in beamwidth require increases in aperture, which are not easy to achieve due to manufacturing difficulties in ensuring sub-wavelength shape tolerances. Phased arrays have the unique advantage of providing shape error compensation through corrective delays applied to each element. The main challenge in realizing a large aperture phased array transducer for billet inspection is ensuring that the number of elements remains practical, i.e. within the budget allotted to the driving electronics. Honeywell Engines, Systems and Services sought to resolve such challenges through research and development, in the hopes of improving titanium billet inspection sensitivity. Acoustic Ideas designed the transducer using its patent pending Continuum Optimized Transducer Design Techniques, realizing an array for full coverage inspection of 8 inch titanium billets that has twice the aperture (half the beamwidth - 1 mm) but the same number of elements as existing phased arrays for 8 inch titanium billet inspection. The transducer was successfully manufactured to design specifications by Imasonic SA. Part I of this two-part series presents the design, simulation and modeling steps, while Part II presents the experimental validation and comparative study to multizone.

**Improved Titanium Billet Inspection Sensitivity Through Optimized Phased Array Design, Part II: Experimental Validation and Comparative Study With Multizone**

---**Waled Hassan** and **Fred Vensel**, Honeywell ES & S, 111 S. 34th Street, Phoenix, AZ 85034; **Vincent Lupien**, Acoustic Ideas Inc., 27 Eaton Street, Wakefield, MA 01880

---The inspection of critical rotating components of aircraft engines has made important advances over the last decade. Improvements in transducers and inspection schemes have made it possible to find smaller defects under well-controlled conditions. The development of Phased Array (PA) inspection capability for billet and forging materials used in the manufacturing of critical engine rotating components has been a priority for Honeywell Engines, Systems, and Services (ES & S). The demonstration of improved inspection system sensitivity over what is currently used at the inspection houses is a critical step in the development of this technology and its introduction into the supply base as a production inspection. This effort summarizes the up-to-date development efforts at Honeywell towards achieving this goal. As described in Part I, a new phased array transducer was designed and manufactured for optimal inspection of eight inch diameter Ti-6Al-4V billets (the largest size billet Honeywell ES & S uses). The design of the transducer included innovative ideas that allowed for improved performance with out the need for a very large number of elements on the surface of the transducer. The transducer can be driven by 128 pulser/receiver system with 32 delay generators. After confirming that the transducer was manufactured in accordance with the design specifications a study was conducted to assess the sensitivity improvement of the inspection over the current capability of Multi-zone (MZ) inspection (a production inspection procedure that is considered to be the most sensitive). The results from this study will be presented and discussed. A four dB average improvement of the PA inspection sensitivity over that of MZ will be demonstrated.

**Leak Detection in Spacecraft Using a 64-Element Multiplexed Passive Array to Monitor Structure-Borne Noise**

---**Stephen D. Holland**<sup>1</sup>, Junho Song<sup>1,2</sup>, D. E. Chimenti<sup>1,2</sup>, and Ron Roberts<sup>1,2</sup>, Iowa State University, <sup>1</sup>Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011; <sup>2</sup>Department of Aerospace Engineering

---We demonstrate an array sensor method intended to locate leaks in manned spacecraft using leak-generated, structure-borne ultrasonic noise. We have developed and tested a method for sensing and processing leak noise to reveal the leak location involving the use of a 64-element phased-array. Cross-correlations of ultrasonic noise waveforms from a leak into vacuum have been used with a phased-array analysis to find the direction from the sensor to the leak. This method measures the propagation of guided ultrasonic Lamb waves passing under the PZT array sensor in the spacecraft skin structure. This paper will describe the custom-designed array with integrated electronics, as well as the performance of the array in prototype applications. We show that this method can be used to successfully locate leaks to within a few millimeters on a 0.6-m square aluminum plate.

**Control of Complex Components with Smart Flexible Phased Arrays**

---Olivier Casula and **Philippe Benoist**, SYSSC CEA-SACLAY Gif-Sur-Yvette France ; Gérard Cattiaux, IRSN, Fontenay-Aux-Roses France

---The inspections of components on nuclear equipments are mainly performed in contact with ultrasonic wedge transducers. The realistic surfaces and the complex geometries of components (butt weld, nozzle, elbow) create an irregular coupling layer between the fixed shape of the wedge and the local surface. During the scanning, this mismatch leads to beam distortions and losses of sensitivity. Previous studies have shown that these two phenomena lead to shadow area, split beam, ... and contribute to reduce the inspection performances. To improve such controls, the concept of contact "smart flexible phased array transducer" has been developed. These linear or matrix phased arrays are flexible to fit the 2D or 3D complex surfaces and to minimize the thickness of the coupling layers. The independent piezoelectric elements composing the radiating surface are mechanically assembled (2D) or molded in a soft resin (3D) in order to build a flexible structure. The instrumentation, embedded in the probe, measures the local surface distortion allowing to compute, in real-time, the optimized delay laws according to the 2D or 3D distortions. Those delay laws are transferred to the real-time UT acquisition system, which applies them to the piezoelectric elements. This self-adaptive process preserves, during the scanning, the features of the focused beam (orientation and focal depth) in the specimen. The concept of Smart Flexible Phased Arrays has been validated on 2D and 3D geometries. Prototypes have been designed and integrated to detect flaws machined in mock-ups with realistic irregular 2D and 3D shapes. The first prototypes of this kind of probes are presented and their performances are illustrated.

# *Session 17*

Wednesday, August 3, 2005

**SESSION 17**  
**EDDY CURRENTS**  
**Moulton Union Lower Level**

- 8:30 AM**      **The Effect of Opening on Eddy Current Probe Response for an Idealized Through Crack**  
---J. R. Bowler, **F. Fu**, and T. Theodoulidis, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011
- 8:50 AM**      **Efficient Solution of Electromagnetic Scattering Problems Using Spatial Decomposition Algorithms**  
---**J. S. Knopp**<sup>1</sup>, H. A. Sabbagh<sup>2</sup>, J. C. Aldrin<sup>3</sup>, R. K. Murphy<sup>2</sup>, E. H. Sabbagh<sup>2</sup>, and J. Hoffman<sup>4</sup>,  
<sup>1</sup>Materials and Manufacturing Directorate, Air Force Research Laboratory, 2230 Tenth Street, Suite 1, Wright-Patterson AFB, OH 45433; <sup>2</sup>Victor Technologies, LLC, Bloomington, IN; <sup>3</sup>Computational Tools, Gurnee, IL; <sup>4</sup>S&K Technologies, Dayton, OH 45440
- 9:10 AM**      **An Experimental and Theoretical Study of Eddy Current End Effects in Finite Rods**  
---S. K. Burke, DSTO, 506 Lorimer Street, Fishermans Bend VIC, 3207, Australia; J. R. Bowler, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011; **T. P. Theodoulidis**, University of West Macedonia, Energy Department, Kozani, Greece
- 9:30 AM**      **Transient Eddy Current Response Due to an Open Crack in a Conductive Plate**  
---**F. Fu** and J. R. Bowler, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011
- 9:50 AM**      **Method for Crack Characterization with Noise Invariance for Eddy Current Inspection of Fastener Sites**  
---**J. C. Aldrin**<sup>1</sup> and J. S. Knopp<sup>2</sup>, <sup>1</sup>Computational Tools, Gurnee, IL; <sup>2</sup>NDE Branch, Materials and Manufacturing Directorate, U.S. Air Force Research Laboratory, Wright-Patterson AFB, OH 45433
- 10:10 AM**      **Coffee Break**
- 10:30 AM**      **Experimental Confirmation of 3D Numerical Simulations of Remote Field Signal from Defects in Magnetic Steam Generator Tubes**  
---**O. Mihalache**, T. Yamaguchi, M. Ueda, and T. Yamashita, Japan Nuclear Cycle Development Institute, International Cooperation & Technology Development Center, 1 Shiraki, Tsuruga-shi, Fukui-ken, 919-1279, Japan
- 10:50 AM**      **A Novel Multi-Frequency Eddy Current Measurement Technique for Materials Characterization**  
---**R. T. Ko**, S. Sathish, and T. R. Boehnlein, Structural Integrity Division, University of Dayton Research Institute, 300 College Park, Dayton, OH 45469-0120; M. P. Blodgett, Metals, Ceramics, and NDE Division, Air Force Research Laboratory, Wright-Patterson AFB, OH 45433
- 11:10 AM**      **Potential Drop Spectroscopy for Characterization of Complex Defects**  
---**G. Sposito**, F. Simonetti, P. Cawley, and P. B. Nagy, Imperial College, Department of Mechanical Engineering, Room 564, Exhibition Road, London, SW7 2AZ, United Kingdom
- 11:30 AM**      **Development of the Nondestructive Evaluation System Using the Eddy Current Probe for Detection of Fatigue Damage of a Stainless Steel**  
---**M. Oka**, Department of Computer and Control Engineering, Oita National College of Technology, Oita, Japan; T. Yakushiji, Department of Mechanical Engineering, Oita National College of Technology, Oita, Japan; Y. Tsuchida and M. Enokizono, Department of Electrical & Electronic Engineering, Oita University, Oita, Japan
- 11:50 AM**      **A Study on the Influence of Sodium Deposits on Remote Field Eddy Current Testing of Ferromagnetic Steam Generator Tubes**  
---S. Thiruvanukkarasu, B. P. C. Rao, S. Vaidyanathan, **T. Jayakumar**, P. Kalyanasundaram, and B. Raj, Indira Gandhi Centre for Atomic Research, Nondestructive Evaluation Division, Kalpakkam, Tamil Nadu 603102, India
- 12:10 PM**      **Lunch**

**The Effect of Opening on Eddy Current Probe Response for an Idealized Through Crack**

---J. R. Bowler, **Fangwei Fu**, and T. Theodoulidis, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011

---A structure representing an idealized crack was formed by placing two coplanar aluminum rectangular plates next to one another with their edges separated by a small distance. The eddy current coil response variation with position was measured as a coil was moved over the adjacent plate edges. An analytical theory is used to evaluate the coil impedance change due to the gap between the plates. This theory is based on the truncated region eigenvalue expansion method. The difference between the eddy current probe signal due to a notch compared with that of a crack can be accounted for by the difference in the opening. We have investigated the effect of varying the opening using the idealized crack. We show theoretically and experimentally how the effect of changing the opening of an idealized crack varies with frequency.---This work was supported by NASA, grant number NAG-1-01040.

**Efficient Solution of Electromagnetic Scattering Problems Using Spatial Decomposition Algorithms**

---**Jeremy S. Knopp**<sup>1</sup>, Harold A. Sabbagh<sup>2</sup>, John C. Aldrin<sup>3</sup>, Ronald K. Murphy<sup>2</sup>, Elias H. Sabbagh<sup>2</sup>, Jochen Hoffman<sup>4</sup>, <sup>1</sup>Materials and Manufacturing Directorate, Air Force Research Laboratory, 2230 Tenth Street, STE 1, WPAFB, OH 45433; <sup>2</sup>Victor Technologies, LLC, Bloomington, IN; <sup>3</sup>Computational Tools, Gurnee, IL; <sup>4</sup>S&K Technologies, Dayton, OH

---In the past few decades, numerical simulations of eddy current inspections have been developed based on integral equation formulations where a flaw is represented by current sources that are due to departures in permeability or conductivity of the material. Previous modeling work has been quite successful when flaws are in an infinite half-space or a single layer of a multi-layered material; however, if a flaw extends across several layers of a multi-layered material, such as cracks or corrosion around fasteners in multiple layers of an aging aircraft structure, one must turn to other numerical formulations. This work introduces spatial decomposition algorithms which will enable the integral equation formulation to efficiently solve problems where the flaws extend across several layers or when multiple flaws in multiple layers are present. Numerical solutions for problems with two flaw regions were calculated using both full discretization and the spatial decomposition methods and evaluated in terms of model accuracy, memory requirements and solution time. Studies also demonstrate the practical benefit of the spatial decomposition approach for modeling complex aging aircraft inspections.

**An Experimental and Theoretical Study of Eddy-Current End Effects in Finite Rods**

---S. K. Burke, DSTO, 506 Lorimer St., Fishermans Bend VIC, 3207, Australia; J. R. Bowler, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011; and **T. P. Theodoulidis**, University of West Macedonia, Energy Department, Kozani, Greece

---The problem of electromagnetic induction in a rod of finite length coaxial with an encircling coil has recently been examined using the truncated region eigenfunction expansion (TREE) method. The TREE method, which is semi-analytical, provides a useful complement to the finite element method for this axisymmetric geometry and also provides some advantages in computational speed. In this paper, the predictions of the TREE method are compared with experimental results in which the coil impedance is measured when a series of finite length Al-alloy and Nickel-Aluminium-Bronze (NAB) rods are passed through an encircling coil. The nature of the end effects for the nonmagnetic (Al-alloy) and magnetic case (NAB) are examined in detail as well as the effect of the rod length. One of the crucial steps in applying the TREE method is to solve an eigenvalue equation with complex eigenvalues. Various strategies for determining the eigenvalues for the problem are also described.

**Transient Eddy Current Response Due to an Open Crack in a Conductive Plate**

---**Fangwei Fu** and J. R. Bowler, Iowa State University, Center for NDE, Ames, IA 50011

---Calculations have been carried out to evaluate pulsed eddy current interactions with a planar subsurface crack in a conductive plate. We consider a probe in which flaws are detected by measuring the changes in the magnetic field that occur when an induced current is perturbed. In previous work, the evolution of magnetic field change due to an open crack in a conductor was evaluated with the assumption that the conductor can be treated as a half space. The response is obtained by solving an electrical field integral equation with a half space Green's function kernel. Recently, a time domain dyadic Green's function for a plate was developed in a series form, which allows us to extend the analysis to more general cases. The effect of plate thickness together with crack opening have been investigated.---This work was supported by NASA, grant number NAG-1-01040.

**Method for Crack Characterization with Noise Invariance for Eddy Current Inspection of Fastener Sites**

---**John C. Aldrin**<sup>(1)</sup>, Jeremy Knopp<sup>(2)</sup>, <sup>(1)</sup> Computational Tools, Gurnee, IL, <sup>(2)</sup> NDE Branch, Materials and Manufacturing Directorate, U.S. Air Force Research Laboratory, Wright-Patterson AFB, OH

---There is a need for research in eddy current (EC) nondestructive evaluation (NDE) to improve the reliability to detect, locate and size cracks around fastener sites in multi-layer structures. The objective of this work is to develop feature extraction and classification algorithms for crack characterization with invariance to noise features for eddy current inspection of fastener sites. Model-based parametric studies are first performed to explore potential features sensitive to radial fatigue cracks and insensitive to variation in gaps between fastener and hole, probe liftoff variation, probe tilt and fastener material. Through these studies, a particularly promising feature with noise invariance was found through analysis of changes in the eddy current response along a circumferential direction in a region away from the hole center. An interpolation-based approach was developed to evaluate the feature using 2D raster scan data. In addition, experimental studies are discussed that further explore the reliability of this feature in the presence of experimental noise and adjacent holes in close proximity. Through the development of an automated algorithm to quantify this feature, results for the experimental study demonstrate the ability to improve the capability to detect small cracks around fasteners while maintaining a low false call rate.

**Experimental Confirmation of 3D Numerical Simulations of Remote Field Signal from Defects in Magnetic Steam Generator Tubes**

---**Ovidiu Mihalache**, Toshihiko Yamaguchi, Masashi Ueda, and Takuya Yamashita, Japan Nuclear Cycle Development Institute, International Cooperation & Technology Development Center, 1 Shiraki, Tsuruga-shi, Fukui-ken, 919-1279, Japan

---One of the methods used to detect defects in magnetic steam generator (SG) tubes of nuclear power plants is the remote field eddy current technique (RFEC). The main advantage of RFEC technique is that it can detect with equal sensitivity both inner and outer defects. Until now, three-dimensional (3D) simulation of interaction of RFEC effect with defects was completely successful only in case of non-magnetic SG tubes. Several attempts to simulate the 3D RFEC effect in magnetic tubes were partially successful with relatively large discrepancy between simulation and experimental measurements, especially for partial small defects and at higher excitation frequencies. In this paper, the authors report a very accurate experimental confirmation of the 3D numerical simulation of RFEC effect in magnetic SG tubes for all kinds of defects (full circumferential and partial). The numerical simulations were performed using a 3D parallel finite element code (FEM), developed in-house, based on the reduced magnetic vector potential and using both linear and non-linear finite elements.

**A Novel Multi-Frequency Eddy Current Measurement Technique for Materials Characterization**

---**Ray T. Ko**, Shamachary Sathish, and Thomas R. Boehnlein, Structural Integrity Division, University of Dayton Research Institute, 300 College Park, Dayton, OH 45469-0120; Mark P. Blodgett, Metals, Ceramics, and NDE Division, Air Force Research Laboratory, Wright-Patterson Air Force Base, Dayton, OH

---In an effort to meet the needs for high frequency eddy current measurement and be able to distinguish small conductivity variations in different materials, a new eddy current module capable of measuring magnitude, phase, and frequency shift was developed and integrated into a general-purpose scanning system. A series of measurements has been carried out on specimens of different conductivity and liftoff while testing the performance of this eddy current module. Data of magnitude, phase, and frequency shift in the eddy current signals were collected and analyzed. Comparisons of three different parameter images are presented. The basis for the contrast for each image is discussed. The potential application of the multi-frequency, multi-parameter eddy current measurement technique for materials characterization to discriminate small conductivity changes due to defect, stress etc. will be presented.---This work was performed on-site in the Nondestructive Evaluation Branch of the Air Force Research Laboratory (AFRL/MLLP) at WPAFB, Ohio under Air Force contract # F33615-03-C-5219.

**Potential Drop Spectroscopy for Characterization of Complex Defects**

---**Giuseppe Sposito**, Francesco Simonetti, Peter Cawley, and Peter B. Nagy, Imperial College, Department of Mechanical Engineering, Room 564, Exhibition Road, London, SW7 2AZ, United Kingdom

---Surface-breaking defects of complex geometries, such as stress corrosion cracks (SCC), are commonly encountered in many industrial applications. Electromagnetic methods like conventional eddy current techniques can be used for the detection of such defects, but sizing is difficult because of their complex geometry. It would be very valuable to be able to define the envelope of the defect as this would allow the maximum depth to be determined, which is usually the critical factor in stress calculations. A very low frequency (quasi dc) current will follow a similar path whether a defect of a given maximum depth is a simple crack or has multiple branches; in contrast, as the frequency is increased the skin depth is reduced, and the current will tend to follow the individual branches of a complex defect. Potential Drop (PD) Spectroscopy combines quasi-dc measurements with measurements of frequency dependence, and therefore seems to be a promising solution for sizing both single and multiple defects. PD Spectroscopy also exploits spatial diversity, as currents can be injected and voltage drops measured from different positions around a defect; the possibility of using the large amount of information collected to develop inversion algorithms and find the defect envelope is being investigated. The predictions of simple two-dimensional finite-element models have been confirmed by the results of fully three-dimensional experimental measurements on specimens with simple and complex defects.

**Development of the Non-Destructive Evaluation System Using the Eddy Current Probe for Detection of Fatigue Damage of a Stainless Steel**

---**Mohachiro Oka**, Department of Computer and Control Engineering, Oita National College of Technology, Oita, Japan; Terutoshi Yakushiji, Department of Mechanical Engineering, Oita National College of Technology, Oita, Japan; Yuji Tsuchida and Masato Enokizono, Dept. of Electrical & Electronic Engineering, Oita University, Oita, Japan

---A stainless steel is widely being used in structural components of industries such as a power plant, a chemical factory, etc. In order to prevent accidents, it is very important to detect fatigue damage of a stainless steel. Up to now, in the laboratory, the remanent magnetization method was effective to evaluate the amount of fatigue damage in austenitic stainless steels (SUS304). However, this method was hard to use on the site. Then, we developed the eddy current probe to detect the amount of fatigue damage in stainless steels. This eddy current probe consists of a ferrite core, an excitation coil and two pick-up coils. Two pick-up coils are located in the terminal part of the leg of the ferrite core. Now, we are investigating the relationship between plane bending fatigue damage and an output voltage of the eddy current probe. This probe can detect the change in electromagnetic properties such as permeability and conductivity in a specimen. In this paper, we will show the non-destructive evaluation system comprising this eddy current probe. And, we will discuss detected results of fatigue damage in a stainless steel.

**A Study on the Influence of Sodium Deposits on Remote Field Eddy Current Testing of Ferromagnetic Steam Generator Tubes**

---Sannasi Thiruvanukkarasu, Bhagi P. C. Rao, S. Vaidyanathan, **Tammana Jayakumar**, Perumal Kalyanasundaram, and Baldev Raj, Indira Gandhi Centre for Atomic Research, Non Destructive Evaluation Division, Kalpakkam, Tamil Nadu, 603102, India

---Periodic non-destructive inspection of steam generator (SG) tubes of prototype fast breeder reactor assumes great importance, in view of undesirable sodium-water reaction at leak regions in SG tubes. As the tubes are made of modified 9Cr-1Mo ferromagnetic steel, conventional eddy current testing is difficult and hence, remote field eddy current (RFEC) method is proposed for in-service inspection. A systematic developmental work has been undertaken to evolve a comprehensive NDE technology encompassing instrumentation, sensor and robotic device to meet the stringent inspection requirements. It is anticipated that presence of sodium deposits on outer surface of the tube as well as within defect regions, if any, may influence RFEC testing, essentially because sodium is electrically conductive. In this direction, systematic mock-up studies and finite element model simulations have been carried out. SG tubes with uniform wall thinning grooves of varying wall loss have been exposed to sodium (500° C) in a test vessel and RFEC signals have been acquired before and after sodium exposure. Detailed analysis of the signals has been performed to examine the influence of sodium on detection and sizing of defects in SG tubes. Details of experimental studies and numerical model simulations are presented in this paper and results of the studies are discussed.

# *Session 18*

Wednesday, August 3, 2005

## **SESSION 18**

### **RESIDUAL STRESS II**

**P. Nagy, Chairperson**

**Cleveland Hall 151**

- 8:30 AM**      **Incorporating Residual Stresses in Life Management of Turbine Engine Components**  
---R. John and M. J. Shepard, AFRL, Wright-Patterson AFB, Dayton, OH 45433
- 8:50 AM**      **Next Generation Neutron Facilities for Non-Destructive Evaluation of Residual Stress Throughout Components**  
---C. R. Hubbard, Oak Ridge National Laboratory, Metals and Ceramics Division, MS 6064, Bldg. 4515, Oak Ridge, TN 37830-6064
- 9:10 AM**      **Residual Stress Measurements to Assess Performance of Engineering Components Using X-Ray Diffraction Method**  
---B. Raj and T. Jayakumar, Indira Gandhi Centre for Atomic Research, Nondestructive Evaluation Division, Tamil Nadu, 603102, India
- 9:30 AM**      **NDE Research Problems for the Implementation of Measurement Tools for Residual Stress Profiling in USAF Turbine Engine Components**  
---M. P. Blodgett, AFRL/MLLP, 2230 Tenth Street, Suite 1, Wright-Patterson AFB, OH 45433
- 9:50 AM**      **A Study of the Relation Between Surface Residual Stress and Conductivity Profiles**  
---N. Nakagawa, C. Lee, and Y. Shen, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011; A. M. Frishman, Iowa State University, Department of Physics, Ames, IA 50011
- 10:10 AM**      **Coffee Break**
- 10:30 AM**      **Exploiting the Versatility of EMATs for Stress Measurement**  
---G. A. Alers, EMAT Consulting, 1328 Tanglewood Drive, San Luis Obispo, CA 93401; R. B. Alers, Sonic Sensors of EMAT Ultrasonics, Inc., San Luis Obispo, CA 93401; P. D. Panetta, Pacific Northwest National Laboratory, Richland, WA 99352
- 10:50 AM**      **Local Bulk and Surface Wave Velocities and X-Ray Diffraction Stress Measurements in Shrink Fit Specimens**  
---R. W. Martin and S. Sathish, University of Dayton Research Institute, Structural Integrity Division, Dayton, OH 45469-0120; M. P. Blodgett, Metals, Ceramics, and NDE Division, Air Force Research Laboratory, Wright-Patterson Air Force Base, Dayton, OH 45433-7817; M. Namkung and E. I. Madaras, NASA Langley Research Center, Nondestructive Evaluation Science Branch, Hampton, VA 23681-0001
- 11:10 AM**      **Laser-Generated Surface Skimming Longitudinal Wave Measurement of Residual Stress in Shot Peened Samples**  
---C. Bescond, D. Lévesque, M. Lord, and J.-P. Monchalain, Industrial Materials Institute, National Research Council of Canada, 75 de Mortagne Blvd., Boucherville, Québec, J4B 6Y4, Canada; S. Forgues, L-3 Communications MAS Canada, 10 000, Helen-Bristol Street, Montreal International Airport – Mirabel, Mirabel, Québec, J7N 1H3, Canada
- 11:30 AM**      **Performance Comparison of Two LCR Probes Using a Reference Frame**  
---D. E. Bray, D. E., Bray, Inc. P. O. Box 10315, College Station, TX 77842-0315
- 11:50 AM**      **Laser-Ultrasonic Measurements of Residual Stresses in a 7075-T651 Aluminum Sample Surface-Treated with Low Plasticity Burnishing**  
---A. Moreau, Industrial Materials Institute, National Research Council of Canada, 75 boul. De Mortagne, Boucherville, Québec, J4B 6Y4, Canada; C.-S. Man, University of Kentucky, Department of Mathematics, 715 Patterson Office Tower, Lexington, KY 40506-0027
- 12:10 PM**      **Lunch**

**Incorporating Residual Stresses in Life Management of Turbine Engine Components**

---**Reji John** and Michael J. Shepard, Air Force Research Laboratory, Wright-Patterson AFB, Dayton, OH 45433

---Current damage-tolerance based life management practices do not explicitly account for the beneficial effects of compressive residual stresses induced by shot peening and other processes. This role of residual stresses in improved life prediction methodologies will be discussed in terms of the requirements for enhanced NDE capabilities for the nondestructive determination of in-depth residual stresses. As an example, recent progress under the Air Force Engine Rotor Life Extension (ERLE) program in the area of service-induced redistribution of shot peening stresses will be discussed. Recent studies have shown that shot peening induced residual stresses in engine components redistribute during service. Typically, this relaxation effect occurs across the entire residual stress profile. Hence, reliable NDE techniques are required to measure the residual stress profile during inspections. The role of more advanced surface treatment techniques will also be briefly discussed. These processes offer the potential for even higher performance damage tolerant designs since they are capable of inducing compressive residual stresses to depths over 1mm. The impact of these stress states on damage tolerant designs and the associated NDE requirements will be briefly reviewed.

**Next Generation Neutron Facilities for Non-Destructive Evaluation of Residual Stress Throughout Components**

---**Camden R. Hubbard**, Oak Ridge National Laboratory, Metals and Ceramics Division, MS 6064, Bldg. 4515, Oak Ridge, TN 37830-6064

---The use of neutron diffraction to measure residual stresses within the volume of a sample or component grew substantially throughout the 1990's. At the beginning of the decade there were a couple laboratories characterizing residual stresses using the neutron diffraction method. During the decade several sources of aberration on the measured d-spacings were identified, and methods to minimize their impact were developed. An international group under the auspices of VAMAS set out to develop a standard for use of the method. Round robins were conducted, and their recommendations are the basis for current efforts to establish international standards for use of the method. By the end of the decade the number of neutron centers making residual stress measurements increased nearly 10 fold. More importantly, second generation facilities were proposed and funded. Second generation facilities typically involve extended detector arrays, use of state-of-the-art neutron optics, and instrumentation designed specifically for stress mapping. At ORNL we have just completed the building and commissioning of a new, 2<sup>nd</sup> generation instrument at the High Flux Isotope Reactor (HFIR) and are in the midst of build a 3<sup>rd</sup> generation instrument for use at the Spallation Neutron Source in a couple years. Details of the design, performance, types of projects, and how industrial and academic engineers and scientists can gain access to the new instrument at HFIR will be presented.---Research sponsored by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of FreedomCAR and Vehicle Technologies, as part of the High Temperature Materials Laboratory User Program, Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract number DE-AC05-00OR22725.

**Residual Stress Measurements to Assess Performance of Engineering Components Using X-Ray Diffraction Method**

---Baldev Raj and **Tammana Jayakumar**, Nondestructive Evaluation Division, Indira Gandhi Centre for Atomic Research, Kalpakkam, Tamil Nadu, 603102, India

---Residual stresses introduced during fabrication, heat treatment and in service influence the performance of engineering components. Generation and / or redistribution of residual stresses during fabrication and heat treatment may affect the dimensional stability and in service performance. In general, tensile residual stresses together with applied tensile stresses cause premature failure by overload, fatigue and stress corrosion cracking. The resistance of components to fatigue and stress corrosion cracking is enhanced by introducing compressive residual stresses in the surface regions by processes such as shot peening. X-ray diffraction (XRD) technique is widely used for measurement of surface residual stresses. In this paper, we discuss the application of XRD technique based residual stress measurements for assessment of (1) fatigue damage in fir-tree root regions of steam turbine blades and undercarriages of aircrafts, (2) influence of deep cryogenic treatment on improvement in fatigue crack initiation in AISI type 304 stainless steel and (3) performance of hardfaced (with Ni-base Co-free Colmonoy-5) AISI type 316LN austenitic stainless steel sleeves subjected to thermal cycling, before and after stress relieving treatment.

**NDE Research Problems for the Implementation of Measurement Tools for Residual Stress Profiling in USAF Turbine Engine Components**

---**Mark P. Blodgett**, AFRL/MLLP, 2230 Tenth Street, Suite 1, Wright-Patterson AFB, OH 45433

---Under the Air Force Research Laboratory initiative known as ERLE, Engine Rotor Life Extension, residual stress profiles resulting from surface processing (e.g., shot peening, laser peening, low plasticity burnishing) are being considered for incorporation into the life assessment of turbine engine components. Many fundamental, technical, and applied problems have been identified in relation to the development of nondestructive measurement tools to assess near-surface residual stress profiles in alloys of interest, which will require significant NDE research attention to achieve the USAF implementation goals. One of the main objectives of this initiative is to pursue the development of physics-based solutions to the measurement problem. Some preliminary successes have been achieved in demonstrating an eddy current based approach for nickel-base superalloy materials, but this approach will not likely work for the generally more noisy titanium alloys of interest. This presentation will discuss the risks, transition strategy, and underlying NDE research problems associated with developing the capability to measure residual stress profiles in titanium and nickel-base alloys used in USAF turbine engine components.

**A Study of the Relation Between Surface Residual Stress and Conductivity Profiles**

---**N. Nakagawa**, C. Lee, and Y. Shen, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011; A. M. Frishman, Iowa State University, Department of Physics, Ames, IA 50011

---This paper reports on a project toward developing electromagnetic residual-stress characterization method for shot-peened rotating engine components. The objective is to measure the surface residual stress profile electromagnetically. Last year we laid out the approach, namely from AC resistivity measurement data such as eddy current and injection-current measurements, we determine the stress profile by inversion. Since this particular inverse problem is ill-posed, we introduced a biased inversion procedure that starts with a hypothesized functional form of the conductivity profile, and determines the profile function parameters by model-based inversion. While this procedure almost guarantees convergence, we must ensure that the resulting profile function represents the reality, avoiding false convergence. Our strategy is to write down the resistivity profile function based on the knowledge of residual-stress and cold-work profiles, each of which is parameterized empirically from the known profile data. This paper draws on our preceding result, and expands our understanding of the origin of these profile shapes. Based on a first-principle model of shot-peening process, we will describe 1) how each individual shot particle induces surface strain in average based on contact mechanics, 2) how to relate the resulting strain distribution to dislocation density distributions, and then 3) how to calculate the profiles of our interest. We intend to use this model result to reduce the number of independent variables appearing in the hypothesized resistivity profile function. In addition, we will briefly summarize our eddy current measurements, as well as forward and inverse model validations, deferring the details elsewhere.

**Exploiting the Versatility of EMATs for Stress Measurement**

---**George A. Alers**, EMAT Consulting, 1328 Tanglewood Drive, San Luis Obispo, CA 93401; Ron B. Alers, Sonic Sensors of EMAT Ultrasonics, Inc., San Luis Obispo, CA 93401; Paul D. Panetta, Pacific Northwest National Laboratory, Richland, WA 99352

---EMATs are considered useful because they do not require a couplant fluid. Unfortunately, this belittles their many real values. They are easily scanned over large areas so they can display stress distributions. They can make high precision transit time measurements for detecting stress induced sound velocity shifts. They generate and detect shear waves with high efficiency - hence, birefringence measurements made easy. They can control specific guided wave modes in plates and pipes to aid in separating stress and texture effects. Shear Horizontal (SH) plate wave modes are readily available for stress measurements that are free of texture contributions. Properly designed longitudinal wave EMATs can exploit the high acousto-elastic coefficients characteristic of these waves. Surface wave EMATs operated at various frequencies can measure a stress gradient in the surface of metal parts. Electromagnetic Acoustic Resonance (EMAR) can be the foundation of a variety of stress monitoring devices.

**Local Bulk and Surface Wave Velocities and X-Ray Diffraction Stress Measurements in Shrink Fit Specimens**

---Richard W. Martin and **Shamachary Sathish**, Structural Integrity Division, University of Dayton Research Institute, Dayton, OH 45469-0120; Mark P. Blodgett, Metals, Ceramics, and NDE Division, Air Force Research Laboratory, Wright-Patterson Air Force Base, Dayton, OH 45433-7817; Min Namkung and Eric I. Madaras, Nondestructive Evaluation Science Branch, NASA Langley Research Center, Hampton, VA 23681-0001

---Local through the thickness longitudinal wave velocity and surface wave velocities were measured using focused acoustic beam in shrink fit samples of Ti-6Al-4V and nickel base super alloy. On the same samples x-ray diffraction technique was used to measure the surface residual stress in both radial and hoop directions. Measurements of acoustic wave velocities and residual stress measurements are compared. X-ray diffraction surface residual stress and focused acoustic beam surface wave velocity measurements do not show systematic changes expected across the diameter of the samples. The through thickness longitudinal wave velocity across the diameter of the sample shows distinct variations. Experimentally measured results are compared with analytical model. Implication of the results on the development of bulk and surface residual stress standard samples is discussed.

**Laser-Generated Surface Skimming Longitudinal Wave Measurement of Residual Stress in Shot Peened Samples**

---**C. Bescond**, D. Lévesque, M. Lord, and J.-P. Monchalain, Industrial Materials Institute, National Research Council of Canada, 75 de Mortagne Blvd., Boucherville, Québec, J4B 6Y4, Canada; S. Forgues, L-3 Communications MAS Canada, 10 000, Helen-Bristol Street, Montreal International Airport – Mirabel, Mirabel, Québec, J7N 1H3, Canada

---Shot peening is a surface enhancement technique that produces a compressive residual stress in a thin surface layer to extend the fatigue life and prevent stress corrosion cracking of structural components. There is an industrial need to measure non-destructively the residual stress state of parts. In this work, a laser-ultrasonic non-contact technique is used for determining residual stresses in metals produced by shot peening. The method is based on the acoustoelastic effect by monitoring the small ultrasonic velocity change of the laser-generated surface skimming longitudinal wave (LSSLW) propagating just below the surface. The surface skimming longitudinal wave is found to be more sensitive to residual stress and less affected with surface roughness than the Rayleigh surface acoustic wave. Measurements in a four-point bending experiment and in shot-peened samples are presented to point out the advantages of the LSSLW for residual stress measurements. Moreover, we will discuss on the potential of the laser-ultrasonic technique for measuring residual stress in shot peened samples using at the same time the LSSLW and Rayleigh wave velocity changes to circumvent other factors such as minute path length changes and cold working effects.

**Performance Comparison of Two LCR Probes Using a Reference Frame**

---**Don E. Bray**, Don E. Bray, Inc., P. O. Box 10315, College Station, TX 77842-0315

---Ultrasonic stress evaluation using the LCR technique has shown good results in both laboratory and field demonstrations.

Applications, however, have been limited to applied uniaxial stress fields where a known zero stress condition exists. This is due to the uniaxial nature of the LCR wave. An attempt was made to build static, residual stress calibration frame with known zero stress conditions as well as a predictable uniaxial stress field. The stress conditions were complex, and non-uniform stresses occurred in some of the members. Further, the stress field that resulted was not the same on each side, as had been anticipated. Instead, apparent buckling of the center member of the frame created a stress differential for the two sides. These unexpected stress conditions did yield an opportunity to evaluate the performance of two LCR probes under complex conditions. In the midsection of the frame, where uniaxial conditions are more dominant, the performance of the newer rotating wedge probe was shown to be statistically comparable to the earlier flexible strip probe. Comparison with strain gauge and finite element results and visual observations are used.

**Laser-Ultrasonic Measurements of Residual Stresses in a 7075-T651 Aluminum Sample Surface-Treated with Low Plasticity Burnishing**

---**André Moreau**, Industrial Materials Institute, National Research Council of Canada, 75 boul. De Mortagne, Boucherville, Québec, J4B 6Y4, Canada

---Low-plasticity burnishing (LPB) is an emerging processing technique used to introduce deep compressive surface residual stresses that improve the durability of parts. A non-destructive measurement of residual stresses, their anisotropy, and their distribution as a function of depth is being sought by various groups to verify process quality and residual stress retention over time. To this end, laser-ultrasonics is one of the more promising candidate technologies because it is non-contact, wideband, versatile, and highly precise. In our work, surface roughness difficulties were avoided because we utilized a LPB surface process which preserved the surface smoothness of our AA7075-T651 aluminum alloy sample. Simultaneous laser-ultrasonic velocity measurements of P waves and Rayleigh waves were made as a function of propagation angle with respect to the LPB process. This allowed to separate texture and residual stress effects and to provide what should be an intrinsically accurate measurement of residual stress anisotropy. Velocity measurements were also made as a function of frequency. The high frequency part of the spectrum (20–70 MHz) corresponded to the near acoustic field where diffraction effects are negligible and insured that the surface waves were localized sufficiently near the surface. As a result, the laser-ultrasonic measurements are in excellent agreement with x-ray measurements of surface residual stress made on the same sample. In addition, another highly significant finding was made: the laser-ultrasonic pulse generation mechanism and the phase spectrum of the generated ultrasound pulse were surface-process dependent. This finding has essential implications in the experimental procedure and data analysis.---  
The authors thank Michael J. Shepard of the U.S. Air Force Research Laboratory who graciously provided the sample.

# *Session 19*

Wednesday, August 3, 2005

## SESSION 19

### **SENSORS AND SYSTEMS FOR STRUCTURAL HEALTH MONITORING** **Moulton Union Main Lounge**

- 8:30 AM**      **Nondestructive Inspection Program in Support of Condition Based Maintenance**  
---**K. G. Lipetzky**, Welding, Processing and NDE Branch, Code 611; Naval Surface Warfare Center Carderock Division, West Bethesda, MD 20817; R. DeNale, Metals Division, Code 61, Naval Surface Warfare Center Carderock Division, West Bethesda, MD 20817
- 8:50 AM**      **Novel Wavelength Demodulation Scheme for Fiber Bragg Grating Sensors Based on Adaptive Two-Wave Mixing Interferometry**  
---**Y. Qiao**, Y. Zhou, and S. Krishnaswamy, Northwestern University, Mechanical Engineering, Evanston, IL 60208
- 9:10 AM**      **Evaluation of a Low-to-High Frequency Damage Index Using Laser Vibrometry**  
---V. K. Sharma, Millinennium Dynamics Corporation, Acworth, GA 30101; M. Ruzzene, S. Hanagud, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0250
- 9:30 AM**      **Unilateral Magnetic Resonance with Optimized Magnet Arrays – NDT of Aircraft Control Structures**  
---I. Mastikhin and **B. J. Balcom**, University of New Brunswick, UNB MRI Centre, Department of Physics, Bailey Drive, Fredericton, New Brunswick, E3B 5A3, Canada
- 9:50 AM**      **Hybrid Magnetoquasistatic/Electroquasistatic Methods for Coating Characterization**  
---I. Shay, D. Schlicker, A. Washabaugh, R. Lyons, and **N. Goldfine**, JENTEK Sensors, Inc., 110-1 Clematis Avenue, Waltham, MA 02453-7013
- 10:10 AM**      **Coffee Break**
- 10:30 AM**      **The Long-Term Stability of Guided Wave Structural Health Monitoring Systems**  
---G. Konstantinidis, **B. W. Drinkwater**, and P. D. Wilcox, University of Bristol, Department of Mechanical Engineering, Bristol, BS8 1TR, United Kingdom
- 10:50 AM**      **Characterization of Bonded Piezoelectric Sensor Performance and Durability in Simulated Aircraft Environments**  
---**J. L. Blackshire** and A. Cooney, Air Force Research Laboratory, Materials and Manufacturing Directorate, Nondestructive Evaluation Branch, WPAFB, OH 45433-7817
- 11:10 AM**      **Ultrasonic Sensor Placement Optimization in Structural Health Monitoring Using CMA Evolutionary Strategy**  
---**H. Gao** and J. L. Rose, The Pennsylvania State University, Department of Engineering Science and Mechanics, University Park, PA 16802
- 11:30 AM**      **Ultrasonic Guided Wave Annular Array Transducers for Structural Health Monitoring**  
---**H. Gao**, M. J. Guers, and J. L. Rose, The Pennsylvania State University, Department of Engineering Science and Mechanics, University Park, PA 16802; G. Zhao and C. Kwan, Intelligent Automation, Inc., Rockville, MD 20855
- 11:50 AM**      **Continuous Structural Monitoring of Oil Rig Sub-Sea Structures for Flood Member Detection Using Axisymmetric Guided Waves**  
---R. Mijarez and **P. Gaydecki**, The University of Manchester, School of Electrical and Electronic Engineering, P. O. Box 88, Manchester, M60 1QD, United Kingdom; F. M. Burdekin, The Fatigue Monitoring Bureau, Macclesfield, Sk10 5LX, United Kingdom
- 12:10 PM**      **Lunch**

**Nondestructive Inspection Program in Support of Condition Based Maintenance**

---**Kirsten G. Lipetzky**, Welding, Processing and NDE Branch, Code 611; Naval Surface Warfare Center Carderock Division; West Bethesda, MD 20817; Robert DeNale, Metals Division, Code 61; Naval Surface Warfare Center Carderock Division, West Bethesda, MD 20817

---Many of the maintenance tasks performed on US Navy ships correspond to depot availabilities or a time-based maintenance schedule. In-service nondestructive inspection, of various shipboard components is one example of such routine maintenance tasks. Due to changing world conditions and the ever-increasing need for the availability of our military assets, the Fleet has started to push for longer periods between routine depot maintenance schedules. While an increased periodicity between inspection would lead to reduced inspection costs and hence total ownership costs, these benefits must be weighed against the potential risks of component failure. Scientific based approaches to data acquisition, analysis, and direct inspection-to-inspection comparisons (i.e. trending) are necessary in order to support the desired increased inspection periodicities. This paper discusses recent efforts in trending of in-service data in support of condition based maintenance approaches to nondestructive inspection of shipboard heat exchanger tubing.

**Novel Wavelength Demodulation Scheme for Fiber Bragg Grating Sensors Based on Adaptive Two-Wave Mixing Interferometry**

---**Yi Qiao**, Yi Zhou, and Sridhar Krishnaswamy, Mechanical Engineering, Northwestern University, Evanston, IL 60208

---Structural health monitoring networks that are designed to monitor impact damage and acoustic emissions can provide a continuous assessment of the mechanical integrity of critical structures. These structural health-monitoring networks can be either embedded into the structure during fabrication, or retrofitted on critical areas of existing structures. For such networks to be viable for in service use, they must be low-cost and reliable. At Northwestern University, we are developing structural health monitoring networks using large arrays of fiber-optic sensors. These sensors are for detection of dynamic strains associated with ultrasound (induced or due to acoustic emissions). In this paper, we demonstrate a novel method to demodulate the wavelength shift caused by dynamic strains applied on fiber Bragg grating (FBG) sensors. This scheme is based on two-wave mixing (TWM) interferometry in a photorefractive InP: Fe crystal. The wavelength shift of the FBG sensor is first converted into phase shift which is then demodulated by the TWM interferometer. The unique feature of this scheme lies in the fact that it is adaptive to quasistatic strain or temperature drift, which enables this scheme to function without any feedback electronics that other demodulation schemes typically need. Another of its attractive properties is that the TWM interferometer can be easily multiplexed to demodulate large networks of FBG sensors in parallel. We will demonstrate that the TWM wavelength demodulator has a cut-off frequency of 100Hz and can adapt to temperature drifts up to 20C/s. As an example, we demonstrate parallel detection of impact-induced Lamb waves from multiple points in a thin plate.

**Evaluation of a Low-to-High Frequency Damage Index Using Laser Vibrometry**

---**V. K. Sharma**, Millinennium Dynamics Corporation, Acworth, GA 30101; M. Ruzzene, S. Hanagud, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0250

---We propose a SHM strategy based on the structural analysis over a wide frequency range, spanning from the lowest modes of the structure up to the low ultrasonic range, which allows coverage of various types of defects. The analysis is performed using a single actuator/sensor pair. Specifically, piezoceramic discs are employed as actuators, while a Scanning Laser Doppler Vibrometer (SLDV) is used as a sensing device. The piezoceramic discs are inexpensive and easy to operate, while the SLDV measures the velocity of the structure at points on a user-defined grid, thus providing an unprecedented amount of information. The objective is to obtain a comprehensive SHM methodology able to overcome drawbacks and exploit advantages of various techniques. In the low-to-medium frequency range, modal parameters are normally less sensitive to localized defects, but generally provide indications regarding global changes as a result of damage. Such changes localize defects and potentially estimate their severity. In parallel to modal monitoring, the SLDV is used as an ultrasonic sensor. The two techniques are applied sequentially: vibration-based monitoring first provides indication of potential areas of damage, on which the SLDV then focuses to perform ultrasonic testing and to obtain detailed damage information. The technique is demonstrated experimentally on plate-like structures, and on aircraft components affected by hairline cracks caused by operational loads.

**Unilateral Magnetic Resonance with Optimized Magnet Arrays – NDT of Aircraft Control Structures**

---Igor Mastikhin and **Bruce J. Balcom**, University of New Brunswick, UNB MRI Centre, Department of Physics, Bailey Drive, Fredericton, New Brunswick, E3B 5A3, Canada

---More than a decade ago German researchers introduced a revolutionary magnetic resonance device termed the NMR-MOUSE, the Mobile Universal Surface Explorer. This simple hand held device employs two bar magnets of opposite polarity, along with a surface coil RF probe between the two magnets to define a sensitive spot, removed from the magnet face. A variety of magnetic resonance measurements may be employed to interrogate the properties of the material in the sensitive spot. While a number of variations on this principle have appeared in the literature, the limiting feature of most designs is the small size of the sensitive spot, and the significantly inhomogeneous static magnetic field within the spot. We introduce a new systematic procedure for the design and fabrication of unilateral magnet arrays for single-sided magnetic resonance measurements. The new design strategy permits one to begin with the parameters of the sensitive spot - lateral size, depth, field homogeneity and magnetic resonance frequency, and then reduce this to a systematic design with distributed magnets and customized pole caps. The application of these new magnet arrays for several material science magnetic resonance measurements will be described. Our principal goal is a magnet array design which will permit non-destructive measurement of deleterious water content in honeycomb composite aircraft control structures.

**Hybrid Magnetoquasistatic  
Electroquasistatic Methods for Coating  
Characterization**

---Ian Shay, Darrell Schlicker, Andrew Washabaugh, Robert Lyons, and **Neil Goldfine**, JENTEK Sensors, Inc., 110-1 Clematis Avenue, Waltham, MA 02453-7013

---This paper describes a novel (patent pending) method for combining data from Magnetoquasistatic (MQS) and Electroquasistatic (EQS) sensors to characterize the properties of layered material constructs such as coatings on gas turbine blades. This same method can be used to combine data from other multiple sensor modalities, if an accurate model or other means are available for generating the precomputed databases of sensor responses. The method described here begins by defining the unknown parameters that require estimations/measurement. In the MQS regime, the possible unknowns will include the layer thicknesses, electrical conductivity, and magnetic permeability for each material layer. In the EQS regime, the unknowns may include layer thicknesses, electrical conductivity, and dielectric constant. EQS sensors work well for relatively insulating materials such as ceramic, glass, plastic, epoxies, adhesives, paint, and paper. MQS sensors work well for relatively conducting materials such as metal and graphite, and for magnetizable materials. This paper will describe specific demonstrations of capability using a combination of MQS (with MWM sensors) and EQS (using IDDED sensors) sensing modalities.

**The Long-Term Stability of Guided Wave  
Structural Health Monitoring Systems**

---George Konstantinidis, **Bruce W. Drinkwater**, and Paul D. Wilcox, Department of Mechanical Engineering, University of Bristol, Bristol, BS8 1TR, United Kingdom

---Guided waves offer an attractive means of performing structural health monitoring (SHM). It is desirable for such a system is to have maximum sensitivity with minimum sensor density. However, in all but the most simple structures the wave interactions become too complex for the time domain signals to interpreted directly. One approach to overcoming this complexity is to subtract a baseline reference signal from the measured system. This strategy enables changes in the system to be identified. Two key issues must be addressed to allow this paradigm to become a reality. Firstly, the system must be sufficiently sensitive to small reflections from defects such as cracking. Secondly, it must be able to distinguish between benign changes and those due to structural defects. In this paper this subtraction approach is used to detect defects in a simple rectangular plate. The system is shown to work well in the sort-term and good sensitivity to defects is demonstrated. The performance degrades over the long-term. The principal reason for this degradation is shown to be the temperature of the system. These effects are quantified and strategies for overcoming them are discussed.

**Characterization of Bonded Piezoelectric Sensor Performance and Durability in Simulated Aircraft Environments**

---**James L. Blackshire** and Adam Cooney, Air Force Research Laboratory, Materials and Manufacturing Directorate, Nondestructive Evaluation Branch, WPAFB, OH 45433-7817

---Significant progress has recently been reported in the area of integrated structural health monitoring, with many sensor systems being deployed in actual operational environments. For aerospace systems, there is currently a need for monitoring cracking, corrosion, and disbond events in difficult access, remote locations within the aircraft structure. A key question that needs to be addressed and answered with regard to successfully implementing structural health monitoring technologies in Air Force systems involves the long-term operability, durability, and survivability of integrated sensor systems and their associated hardware. In this activity, the performance characteristics of surface-bonded piezoelectric sensors have been studied under accelerated exposure conditions typically found in an operational aircraft environment. In particular, sensor performance was studied for freeze-thaw, moderate heat levels, humidity, electrochemical attack, substrate bend and tensile strains, and dynamic vibration conditions. The sensor performance was characterized using displacement-field imaging, pitch-catch signal transmission, and pulse-echo signal transmission. Evidence of general performance reduction, sensor cracking, and sensor disbonding were all observed. Future activities will focus on identifying critical durability and survivability issues through advanced sensor modeling and additional accelerated testing efforts, with the ultimate goal of improving the robustness of health monitoring systems through improved sensor system design and packaging.

**Ultrasonic Sensor Placement Optimization in Structural Health Monitoring Using CMA Evolutionary Strategy**

---**Huidong Gao** and Joseph L. Rose, Department of Engineering Science and Mechanics, The Pennsylvania State University, University Park, PA 16802

---Ultrasonic guided wave technology is one of the commonly used methods in monitoring the health conditions of aerospace, civil, and mechanical infrastructures. In structural health monitoring (SHM) research, sensor network scale and sensor distribution become very important decisions which greatly affects the sensor network performance as well as the system cost. Based on the current research works of individual sensor design, a quantitative sensor placement optimization method with covariance matrix adaptation evolutionary strategy (CMAES) is presented in this paper, which improves the state-of-the-art from commonly used empirical sensor distributions. In this paper, a damage detection probability model is developed for a passive ultrasonic guided wave sensor network. Sensor network configurations with minimum missed-detection probability are obtained from the results of evolutionary optimization. The tradeoff relationship between optimized sensor network performance and the number of sensors is obtained which provides a guideline for real world applications. Two sample problems, one for isotropic, and one for anisotropic structures are studied.

**Ultrasonic Guided Wave Annular Array Transducers for Structural Health Monitoring**

---**Huidong Gao**, Manton J. Guers, and Joseph L. Rose, Department of Engineering Science and Mechanics, The Pennsylvania State University, University Park, PA 16802; George Zhao and Chiman Kwan, Intelligent Automation Inc., Rockville, MD 20855

---The application demand of structural health monitoring has spread over the areas of aerospace, aircraft, fleet, civil, and mechanical infrastructure maintenance. Ultrasonic guided wave damage detection methods can be used in these areas alone or collaboratively with other health monitoring technologies. The work presented in this paper is a series study of annular array PVDF transducers, which explored the benefits of wave mode selection and mode control capability from the previously studied piezoelectric disc sensors for structural health monitoring. Finite element methods are used to assist the optimized transducer design. A scanning laser vibrometer system is used to experimentally validate the wave excitation characteristics of the annular array transducers. Finally, the arrayed transducers are used in a health monitoring problem of corrosion detection on a metallic plate structure.

**Continuous Structural Monitoring of Oil Rig Sub-Sea Structures for Flood Member Detection Using Axisymmetric Guided Waves**

---Rito Mijarez and **Patrick Gaydecki**, The University of Manchester, School of Electrical and Electronic Engineering, P. O. Box 88, Manchester, M60 1QD, United Kingdom; F. Michael Burdekin, The Fatigue Monitoring Bureau, Macclesfield, Sk10 5LX, United Kingdom

---The possibility of using axisymmetric guided wave sensors to detect the presence of seawater in hollow cross member beams of offshore steel oil rig platforms is explored in this work. Underwater NDT methods such as ultrasound have been conventionally used to test for the presence of seawater in these applications, often in conjunction with remote operating vehicles. In this work, a monolithic PZT guided wave transducer which can be permanently attached to a sub-sea installation and is powered by the action of the seawater is described. Upon activation, the transducer sends ultrasound-encoded signals to a receiver in the form of a real-time digital signal processing system at surface level for further processing. Experiments were performed using a jointed steel pipe structure, 10 m x e 0.5 m x 16 mm, completely immersed in seawater. Using the modelling package Disperse, an optimal frequency of 38 kHz was used and the results were contrasted with those previously obtained for 21 kHz. The results corroborate the attenuation values predicted by the theoretical model, by successfully identifying the received signals with a great improvement in the SNR.

## *Session 20*

Wednesday, August 3, 2005

**SESSION 20**  
**IMAGE AND SIGNAL ANALYSIS**  
**Moulton Union Main Lounge**

- 1:30 PM**      **Breaking the Resolution Limit: A New Perspective for Imaging in NDE**  
---**F. Simonetti**, Imperial College, Department of Mechanical Engineering, London, United Kingdom
- 1:50 PM**      **Guided Wave Imaging Based on Mode Extraction and Reconstruction of Guided Waves**  
---**T. Hayashi**, M. Nagao, and M. Murase, Nagoya Institute of Technology, Nagoya, Japan
- 2:10 PM**      **Detection of Several Cracks in Materials Using the Randomized Hough Transform on Ultrasonic Image**  
---**T. M. Meksen** and M. Boudraa, Universite des Sciences et Technologie H. Boumedienne, Faculté d'Informatique et d'Electronique, El Alia, BP 32, Algiers, Algeria; R. Draï, LTSI, Centre de Soudage et Controle, Cheraga, Aliers, Algeria
- 2:30 PM**      **The Application of Threshold and Region Growing Techniques in the Automatic Interpretation of Ultrasonic NDT Data**  
---**E. Asemota**, S. Gallagher, B. Lees, and S. Cochran, University of Paisley, School of Computing, Microscale Sensors Research Group, Paisley, PA1 2BE, United Kingdom
- 2:50 PM**      **MFL Signal Analysis Scheme for Classification and Characterization of Anomalies in Pipeline Wall**  
---**V. P. Lunin**, Moscow Power Engineering Institute (Technical University), Electrical Engineering & Introscopy Department, 14 Krasnokazarmennaja, 111250, Moscow, Russia
- 3:10 PM**      **Coffee Break**
- 3:30 PM**      **Ultrasonic Testing of Austenitic Welds: Modeling and Experimental Results**  
---**B. Koehler**, M. Spies, V. Schmitz, W. Müller, A. Zimmer, and K. J. Langenberg, IzfP/FhG, Krueger strasse 22, Dresden, 01326, Germany
- 3:50 PM**      **Prediction and Evaluation of Rotating Pancake Coil Probe Signals Simulated from Steam Generator Tubes**  
---**J. Y. Yoo**, C.-H. Kim, H. J. Jeong, S.-J. Song, Y. H. Choi, S. C. Kang, M. H. Song, and H.-K. Jung, Sungkyunkwan University, School of Mechanical Engineering, Suwon, Korea, Korea Institute of Nuclear Safety, Daejeon, Korea, Korea Atomic Energy Research Institute, Daejeon, Korea
- 4:10 PM**      **Natural Crack Sizing Based on Eddy Current Image and Electromagnetic Field Analyses**  
---**H. Endo**, T. Uchimoto, and T. Takagi, Tohoku University, Institute of Fluid Science, Sendai, Miyagi, Japan; A. Nishimizu, M. Koike, and T. Matsui, Hitachi Co. Ltd., Hitachi, Ibaraki, Japan
- 4:30 PM**      **An Approach for Image and Height Calibration for Borescope Based Optical Surface Characterization**  
---**F. Inanc**, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011
- 4:50 PM**      **Statistical Detection of Longitudinal and Circular Defects in Radiographic Images of Welds**  
---**D. Kazantsev**, G. Salov, and V. Pyatkin, Institute of Computational Mathematics and Mathematical Geophysics, Novosibirsk, 630090, Russia

**Breaking the Resolution Limit: A New Perspective for Imaging in NDE**

---**Francesco Simonetti**, Department of Mechanical Engineering, Imperial College, London, United Kingdom

---There is continuing interest in accurate sizing and imaging of flaws in NDE. This is a consequence of a general trend which aims to extend the useful life of structures and for which a precise estimate of the defect extent is needed. Although a number of advanced imaging techniques have been developed in parallel with the tremendous progress in array technology, the image resolution has been limited by the wavelength,  $\lambda$ , that can be propagated according to the "Diffraction Limit" (DL), which excludes the possibility of achieving subwavelength resolution. This implies that in order to enhance the resolution,  $\lambda$  has to be decreased. However, as  $\lambda$  decreases the wave experiences an increasing attenuation, which ultimately reduces the maximum imaging depth, this being the major limitation of current ultrasonic and microwave imaging systems. Recent progress in microscopy has shown that by exploiting the super-oscillatory properties of evanescent fields, resolution several orders of magnitude smaller than the wavelength can be achieved so leading to Near Field Scanning Optical Microscopy. Based on a similar argument, this paper investigates the possibility of obtaining super resolution in the far field (here far field refers to a distance greater than  $\lambda$ ), which would enable high resolution imaging at relatively large depth. The theoretical principles which result in the DL are reviewed and new strategies to overcome it are proposed. An advanced imaging algorithm for linear and two-dimensional array probing systems is presented and its capability of resolving targets as close as  $\lambda/3$  is demonstrated experimentally, the targets being at several wavelength distance from the array. The results show that the method is superior to conventional techniques such as Synthetic Aperture Focusing, Synthetic Phased Arrays and Time Reversal.

**Guided Wave Imaging Based on Mode Extraction and Reconstruction of Guided Waves**

---**Takahiro Hayashi**, Masahiro Nagao, and Morimasa Murase, Nagoya Institute of Technology, Nagoya, Japan

---Guided wave inspection is expected to become a powerful tool for rapid long-range NDE of pipes. Received signals of guided waves, however, are very difficult to analyze in practical application due to the complex characteristics such as dispersion and multi-modal nature. A defect imaging technique is developed in this study to overcome the complexities of guided wave analyses. Received signals that contain many modes with different velocities are firstly separated into a single mode of guided wave using an array sensor system, and then spatial waveforms on the pipe surface at an arbitrary time are reconstructed using theoretical dispersion curves. The predicted waveforms at the moment when incident wave arrives at the defect region can provide a defect image. The defect imaging technique is experimentally verified for 4inch aluminum pipes with artificial holes of 10 mm in diameter. For various types of defect, imaging patterns are confirmed with computer simulation of guided wave propagation.

**Detection of Several Cracks in Materials Using the Randomized Hough Transform on Ultrasonic Image**

---**Thouraya Merazi Meksen** and Malika Boudraa, Universite des Sciences et Technologie H. Boumedienne, Faculté d'Informatique et d'Electronique, El Alia, BP 32, Algiers, Algeria; Redouane Draï, LTSI, Centre de Soudage et Controle, Cheraga, Aliers, Algeria

---Time of Flight Diffraction (TOFD) is a non destructive testing (ndt) technique using the diffraction of ultrasonic waves by defects in the materials. In this technique, the data are displayed in the form of images on which processing algorithms can be applied allowing thus automatic detection and pattern recognition of defects. The work we present here is an image processing algorithm which permits to detect and locate several cracks presents in a structure by analyzing a TOFD image. This algorithm consists of two phases: In the first , a pre-processing reduce the image to a sparse matrix containing only significant pixels followed by a sharing in order to separate different populations of pixels. The second phase (the decision one) is an application of the Randomized Hough Transform on each group of pixels in order to detect and locate parabola characterizing each crack defect.

**The Application of Threshold and Region Growing Techniques in the Automatic Interpretation of Ultrasonic NDT Data**

---**Ekhurutomwen Asemota**, Steve Gallagher, Brian Lees, and Sandy Cochran, Microscale Sensors Research Group, School of Computing, University of Paisley, Paisley, PA1 2BE, United Kingdom

---To automatically interpret ultrasonic non-destructive testing (NDT) B-Scan images, regions of interest within the image must be identified and interpreted. Identifying these regions requires a combination of both image segmentation and region extraction processes. The segmentation process identifies constituent regions within the image whilst the region extraction process then extracts these regions. Further processing on the extracted region(s) is then possible. Image segmentation is achieved either by applying edge detection transforms (EDTs) or image thresholding (IT). Although EDTs can be applied without prior knowledge of the image, they are computationally expensive. By contrast, IT involves fewer computational processes but often requires some prior knowledge of the image and the availability of a suitable threshold. B-Scan images contain a background from which a threshold for segmentation can be generated. Application of a suitable region growing technique to the resultant data from this threshold process yields larger regions which can then be analyzed and interpreted as either defects or not. This paper outlines the development of a software system that utilizes IT and a region growing process to extract regions of interest within a B-Scan image. Once extracted, these can be used within an automatic interpretation system.

**MFL Signal Analysis Scheme for Classification and Characterization of Anomalies in Pipeline Wall**

---**Valery P. Lunin**, Electrical Engineering & Introscopy Department, Moscow Power Engineering Institute (Technical University), 14 Krasnokazarmennaja, 111250 Moscow, Russia

---Typically, diagnostic data in magnetic flux leakage (MFL) pipeline inspection is two-dimensional signal composed by one or two flux density components measured during testing operation. Required processing techniques must not only be capable to enhance the low signal-to-noise ratio and successfully extract defect information but should be computationally inexpensive and adaptive to automated analysis. This paper is oriented on effective techniques for advanced MFL signal analysis. Among techniques it is included: extraction of an anomaly influenced signal region (region of interest ROI); global classification of these regions; characterization of metal-loss defect class (crack, corrosion). Series of experiments was performed on specially fabricated test pipe having welding zones, structure elements and more than 50 metal-loss defects of different shapes and sizes. It was found to meet industry specifications for defect depth prediction with accuracy of 15% wall thickness.

**Ultrasonic Testing of Austenitic Welds: Modelling and Experimental Results**

---**B. Koehler**, M. Spies, V. Schmitz, W. Müller, A. Zimmer, and K. J. Langenberg, IzfP/FhG, Krueger strasse 22, Dresden, 01326, Germany

---Ultrasonic testing (UT) of austenitic welds is complicated by the elastic anisotropy of the grain crystallites. Thus, the usual rules for UT concerning the selection of wave modes, frequencies and incident angles cannot be applied in the same way as for isotropic materials. Various methods for modelling of the sound propagation in this situation have been developed. We apply these methods to a weld containing an inter-crystalline stress corrosion crack. Three simulation tools with different advantages and disadvantages are applied: Ray Tracing, Gaussian Beams and Elastodynamic Finite Integration Technique (EFIT). It is demonstrated that by applying these techniques an UT configuration can be found, which is optimal for detection of the crack through the weld.

**Prediction and Evaluation of Rotating Pancake Coil Probe Signals Simulated from Steam Generator Tubes**

---**Joo Young Yoo**, Chang-Hwan Kim, Hee Jun Jeong, Sung-Jin Song, Young Hwan Choi, Suk Chull Kang, Myung Ho Song, and Hyun-Kyu Jung, Sungkyunkwan University, School of Mechanical Engineering, Suwon, Korea, Korea Institute of Nuclear Safety, Daejeon, Korea, Korea Atomic Energy Research Institute, Daejeon, Korea

---The rotating pancake coil (RPC) probe is widely used for detection and evaluation of steam generator tubes in nuclear power plant. For characterization of flaws (flaw size and type) from RPC signals, amplitude and phase angle terms are used. However, it does not quite often perform well since amplitude and phase angle information are easily affected by various factors. To overcome this problem, the evaluation of RPC signals is usually performed after calibration and verification procedures using calibration (or reference) signals obtained from a calibration tube. But, the calibration signals can also be distorted by the various factors. Therefore, in this study, we generate the calibration signals using an electromagnetic numerical analysis technique that is suitable to model of RPC probes. Based on the numerical simulation technique, we also simulate the RPC signals for steam generator tubes. Using the simulated RPC signals, flaw evaluation results is performed and compared to the experiments.

**Natural Crack Sizing Based on Eddy Current Image and Electromagnetic Field Analyses**

---**Hisashi Endo**, Tetsuya Uchimoto, and Toshiyuki Takagi, Institute of Fluid Science, Tohoku University, Sendai, Miyagi, Japan; Akira Nishimizu, Masahiro Koike, and Tetsuya Matsui, Hitachi Co. Ltd., Hitachi, Ibaraki, Japan

---Combination of Eddy Current Testing (ECT) images and electromagnetic field calculation sizes up natural cracks such as Stress Corrosion Cracking (SCC) in this paper. Multi-coil ECT probes consisting of 48 channels with Transmit-Receive (TR) type sensors one-dimensionally scan on the target metal structures, giving the ECT image instantaneously. Since the TR type sensor is composed of a couple of exciting and pickup coils, then the output signal distribution represents the surface breaking. The multi-coil ECT probes works in two modes. One is T scan arranging the TR type sensors in the x-direction with high sensibility. The other is U scan for the y-direction with high spatial resolution. These two modes comprise the ECT image measuring length and width of surface breaking. The inversion base on finite elements for the eddy current field quantitatively evaluates the crack profiles. The ECT image measurement narrows the area to be evaluated. This paper applies to the austenitic stainless steel specimens with fatigue cracks (FC) and SCC. According to fracture test, the crack depths of these specimens were less than 5mm. The comparisons with the results of the fracture test support our approach.

**An Approach for Image and Height Calibration for Borescope Based Optical Surface Characterization**

---**Feyzi Inanc**, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011

---When the topology of a surface is determined through the reflection of a structured light beam, the image quality and calibration of the CCD pixel offset against a height variation assumes utmost importance. A typical optical inspection system used for evaluating a product or monitoring a process is adversely affected by the distortions introduced into the images by the components in the optical systems. In this specific case, the optical system employs a borescope and the distortions in such a system are visible even to a naked untrained eye. For the cases where the view angle of a borescope is adjustable, the image is subjected to a magnification variation along the borescope axis as well. When these two effects are combined, the resulting image is highly distorted. If the borescopes are to be used for quantitative characterization purposes as in surface characterization, distortions in the images need to be corrected. Relying on measuring the offset in the CCD chip for measuring surface height is a popular approach if it comes with a way of mapping the amount of offset into a specific amount of height variation. In this presentation, we will introduce an algorithm on how we remove the distortions from borescope images and how we perform a height calibration for determining the surface topology through a borescope based system.---This material is based on work supported by NASA under award NAG-1-029-98.

**Statistical Detection of Longitudinal and Circular Defects in Radiographic Images of Welds**

---**D. Kazantsev**, G. Salov, and V. Pyatkin, Institute of Computational Mathematics and Mathematical Geophysics, Novosibirsk, 630090, Russia

---In this paper we investigate applicability of statistical techniques for defect detection in radiographic images of welds. The objective of this work is as follows: (1) given a false alarm level, (2) detect blob-like defects (as cavities or voids) and longitudinal flaws (as cracks) in (3) austenitic welds in (4) realistic computer time. We try to investigate the possibilities of automatic image processing of weld defects with the help of statistical hypothesis testing using nonparametric statistical tests. We consider several tests which theoretically, for a given level of false alarm, provide us with a threshold resulting in a map of possible defects. Practical problems of traditional image enhancement and noise reduction are discussed as well as the task of automatic thresholding. Numerical experiments with real and test data within MATLAB's abilities are performed.

## *Session 21*

Wednesday, August 3, 2005

## SESSION 21

### **LASER UT AND APPLICATIONS**

**M. Dubois, Chairperson**

**Druckenmiller Hall 016**

- 1:30 PM**      **Keynote: Picosecond Ultrasonics and Non-Destructive Evaluation of Computer Chips**  
---**H. Maris**, Brown University, Department of Physics, Providence, RI 02912
- 2:10 PM**      **High Frequency Laser-Based Ultrasound**  
---**R. D. Huber** and D. J. Chinn, University of California, Lawrence Livermore National Laboratory, L-333, 7000 East Avenue, Livermore, CA 94550; T. W. Murray, Boston University, Department of Aerospace and Mechanical Engineering, Boston, MA 02215
- 2:30 PM**      **Effects of Broadband Laser Generated Ultrasound on Array Gain**  
---**A. Kita** and I. C. Ume, G. W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332
- 2:50 PM**      **Review of Progress of the LaserUT® Technology at Lockheed Martin Aeronautics Company**  
---**T. E. Drake**, M. Dubois, M. Osterkamp, K. Yawn, T. Do, D. Kaiser, J. Maestas, and M. Thomas, Lockheed Martin Aeronautics Company, Laser Ultrasonic Technology Center, P. O. Box 748, Fort Worth, TX 76101
- 3:10 PM**      **Coffee Break**
- 3:30 PM**      **Robust Laser-Ultrasonic Interferometer Based on Random Quadrature Demodulation**  
---**B. F. Pouet**, S. Breugnot, and P. Clemenceau, Bossa Nova Technologies, Venice, CA 90291
- 3:50 PM**      **Laser Ultrasonic Thickness Measurements of Very Thick Walls at High Temperatures**  
---S. E. Kruger, M. Lord, and **J.-P. Monchalín**, NRC-Industrial Materials Institute, 75, Boul. De Mortagne, Boucherville, Québec, J4B 6Y4, Canada
- 4:10 PM**      **Laser-Ultrasonic Measurement of the Thickness of Oil Spills from an Airplane**  
---C. Néron, C. Padioleau, and **J.-P. Monchalín**, Industrial Materials Institute, National Research Council of Canada, 75 De mortagne Blvd., Boucherville, Québec, J4B 6Y4, Canada; M. Choquet, Tecnar-Automation, St-Bruno, Québec, Canada; C. E. Brown and M. F. Fingas, Environment Canada, Ottawa, Ontario, Canada
- 4:30 PM**      **Laser Ultrasonic Measurement of Elastic Properties of Moving Paper: Mill Demonstration**  
---**P. L. Ridgway** and R. E. Russo, Lawrence Berkeley National Laboratory, Berkeley, CA 94720; E. F. Lafond, T. G. Jackson, G. A. Baum, and X. Zhang, Institute of Paper Science and Technology, Georgia Tech, Atlanta, GA 30332-0355
- 4:50 PM**      **Laser-Generated Ultrasonic Source for a Real-Time Dry-Contact Imaging System**  
---**G. Petculescu**, Y. Zhou, I Komsky, and S. Krishnaswamy, Northwestern University, Center for Quality Engineering and Failure Prevention, Evanston, IL 60208

**Keynote: Picosecond Ultrasonics and Non-Destructive Evaluation of Computer Chips**

---**Humphrey Maris**, Department of Physics, Brown University, Providence, RI 02912

---Picosecond ultrasonics has become a widely used metrology tool in the semiconductor device industry. It provides an accurate method for the measurement of the thickness of thin films, can determine the quality of the bonding between a film and a substrate, and gives information about mechanical properties. We will describe the development of this technology starting from work in the research laboratory and following through to the development of an automated instrument for use in computer chip fabrication.

**High Frequency Laser-Based Ultrasound**

---**Robert D. Huber** and Diane J. Chinn, University of California, Lawrence Livermore National Laboratory, L-333, 7000 East Avenue, Livermore, CA 94550; Todd W. Murray, Boston University, Department of Aerospace and Mechanical Engineering, Boston, MA 02215

---Characterization of materials and structures with micrometer resolution using ultrasound requires frequencies approaching 1 GHz. Generating and detecting ultrasound in this frequency regime presents challenges not faced using lower frequencies. Although piezoelectric transducers such as those in acoustic microscopes will generate ultrasound in excess of 1 GHz, these are typically only surface inspection instruments. By using pulsed lasers with sub nanosecond pulse widths, ultrasound with frequencies in excess of 100 MHz can be generated directly in the material. A non-contact laser-based ultrasound using such a pulsed laser coupled with a Michelson interferometer capable of detecting ultrasound up to 1 GHz is being evaluated for use in inspecting materials requiring resolution approaching 1 micrometer.

**Effects of Broadband Laser Generated Ultrasound on Array Gain**

---**Akio Kita** and I. Charles Ume, G. W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332

---An Array Gain is a common parameter used in laser phased array research. This paper will present a new parameter called the frequency modulation of laser phased array (FMLPA). The array gain model for laser phased arrays was derived using an assumption that ultrasound from each array member interferes with each other. This would be true if laser generated ultrasound is narrow band. However, laser generation of ultrasound is broad band. Broad band ultrasound signals have short duration in the time domain. If the time delay between generated wave fronts from each array member is longer than the duration of the broad band ultrasound signal from each array member, the ultrasound signals from each array member will not interfere with each other. The time delay between generated wave fronts from each array member is 0 sec at a laser phased array's beam steering angle and increases away from the beam steering angle. Therefore, ultrasound from each array member interferes at angles close to the beam steering angle. However, ultrasound from each array member may not interfere at angles away from the beam steering angle depending on the time delay between generated wave fronts and duration of the broad band ultrasound signal. A theoretical model of the FMLPA was developed and experimentally verified for use when ultrasound from each array member does not interfere with each other. It was experimentally verified that current array gain equations still apply when ultrasound from array members interfere with each other. The FMLPA can be applied in inspection systems where angle of ultrasound propagation from the ultrasound generation location can be used such as measuring weld penetration depth, crack location, and dimensions of objects.

**Review of Progress of the LaserUT® Technology at Lockheed Martin Aeronautics Company**

---**Thomas E. Drake**, Marc Dubois, Mark Osterkamp, Kenneth Yawn, Tho Do, David Kaiser, Jeff Maestas, and Mike Thomas, Lockheed Martin Aeronautics Company, Laser Ultrasonic Technology Center, P. O. Box 748, Fort Worth, TX 76101

---LaserUT® has been used for high-volume, affordable ultrasonic testing of complex composite materials for the manufacturing of advanced fighter aircraft since June, 2000. A second production LaserUT system was recently put on-line at the Lockheed Martin Aeronautics facility in Fort Worth, Texas. These two production systems, along with the original R&D facility, have evaluated over 10,000 parts and have provided important statistics regarding system reliability and operational cost. Of particular note has been the performance of the generation and detection lasers in an industrial environment. This paper will review the elements incorporated in the most recent LaserUT systems that provided significant performance improvement over the previous systems and will discuss the new approaches currently under study for additional reduction in operational costs and further improvements in system reliability and speed.

**Robust Laser-Ultrasonic Interferometer Based on Random Quadrature Demodulation**

---**Bruno F. Pouet**, Sebastien Breugnot, and Philippe Clemenceau, Bossa Nova Technologies, Venice, CA 90291

---In order to fully take advantage of possibilities offered by laser-ultrasonic inspection and to broaden their integration into industrial inspection systems, further improvements are still needed. A critical component of a laser-ultrasonic inspection system is the receiver. The high cost associated with currently available high-performance receivers is a major limitation. Last year we presented preliminary results on a new interferometer scheme specially adapted for industrial laser-ultrasonic system. This novel architecture combined a classical interferometric design (Michelson interferometer) with an innovative multi-speckle processing technique based on quadrature detection. This interferometer exhibited high sensitivity to ultrasound on rough surfaces without requiring accurate positioning, path stabilization, high power laser or special environmental protections. We present the recent advances toward the development of this robust and sensitive interferometer for industrial laser-ultrasonic system. The random distribution of coherent light scattered by a rough surface is generally seen as a limiting factor for classical interferometers. In our novel quadrature detection scheme, the random distribution of the coherent light is taken advantage for reducing the system complexity, cost and further improving the interferometer performances. Results demonstrating the system performance and this new principle of operation based on speckle statistic will be presented.

**Laser Ultrasonic Thickness Measurements of Very Thick Walls at High Temperatures**

---Silvio E. Kruger, Martin Lord, and **Jean-Pierre Monchalin**, NRC-Industrial Materials Institute, 75, Boul. De Mortagne, Boucherville, Quebec, J4B 6Y4, Canada

---Laser-ultrasonics presents many advantages compared to conventional ultrasonics, but is generally considered as less sensitive. As a consequence, laser-ultrasonics should not be adequate for ultrasonic measurements in coarse microstructure materials or measurements of large thicknesses. However, since the generated waves extend to very low frequencies, measurements in such conditions can be successfully performed if a photorefractive interferometer sensitive also to these low frequencies and properly balanced is used for detection. This is demonstrated by measurements of thicknesses up to 100 mm (4") for various steel grades and at temperatures up to 1250 °C that we report in this paper.

**Laser-Ultrasonic Measurement of the Thickness of Oil Spills from an Airplane**

---C. Néron, C. Padioleau, and **J.-P. Monchalín**, Industrial Materials Institute, National Research Council of Canada, 75 De mortagne Bvd., Boucherville, Québec, J4B 6Y4, Canada; M. Choquet, Tecnar-Automation, St-Bruno, Québec, Canada; C. E. Brown, M. F. Fingas, Environment Canada, Ottawa, Ontario, Canada

---Laser-ultrasonics is by now a recognized NDE technique with industrial use in aerospace (inspection of polymer-matrix composites) and steel industry (wall thickness and microstructure measurement of hot tubes). Its remote sensing feature allows however to consider its use in other fields and in particular for the measurement of the thickness of oil spills at sea. As in any other ultrasonic thickness measurement, the principle consists in measuring the reverberation time of generated longitudinal waves launched through the oil layer floating on top of water. Although many convincing results have been obtained previously in the laboratory or on the ground and had shown the feasibility of such an application, its demonstration from the air had encountered many difficulties. We are reporting finally here such a successful measurement taken from a low flying DC3 airplane (200 feet, 60 meters) on artificial spills made in wave-agitated tanks.

**Laser Ultrasonic Measurement of Elastic Properties of Moving Paper: Mill Demonstration**

---**Paul L. Ridgway** and Richard E. Russo, Lawrence Berkeley National Laboratory, Berkeley, CA 94720; Emmanuel F. Lafond, Theodore G. Jackson, Gary A. Baum, and Xinya Zhang, Institute of Paper Science and Technology, Georgia Tech, Atlanta, GA 30332-0355

---A prototype laser-based ultrasonic sensor for non-contact measurement of the elastic properties of paper was demonstrated on a paper manufacturing machine during commercial operation with paper moving at about 20 m/s. We believe this to be the highest sample speed reported to date for a commercial application of laser ultrasonics. Ultrasonic waves were generated in the paper with a pulsed Nd:YAG laser and detected with a Mach-Zehnder interferometer coupled with a scanning mirror/timing system to compensate for paper motion. Measurements of flexural rigidity (FR) and out-of-plane shear rigidity (SR) were determined by fitting of the frequency dependence of the phase velocity of  $A_0$  mode Lamb waves to a model equation. Variation in FR and SR across the width the paper sheet (cross-direction profiles), effects of changes in paper manufacturing process variables on measured FR and SR, comparisons with traditional mechanical stiffness tests and an estimate of the economic value of the sensor will be presented. Laboratory data indicate that this technology is directly transferable to measurements on sheet metals.

**Laser-Generated Ultrasonic Source for a Real-Time Dry-Contact Imaging System**

---**Gabriela Petculescu**, Yi Zhou, Igor Komsky, and Sridhar Krishnaswamy, Center for Quality Engineering and Failure Prevention, Northwestern University, Evanston, IL 60208

---Ultrasonic NDI methods have an impressive record of applications on metal and composite structures. However, two major weaknesses are encountered: the need for a wet couplant between the specimen and the transducer and the rather long inspection times necessitated by point-by-point scanning of large structures. To overcome these limitations, we are developing a real-time dry-contact imaging system. The system incorporates three technologies: laser generation of ultrasound, polymer dry couplant, and a commercially available real-time ultrasonic imaging system, namely the "Acousto-cam". In this paper we present results on the laser generation of ultrasound in a constrained dry-couplant layer, which constitutes the ultrasonic source of the Acousto-cam. For a specific laser source, the efficiency and frequency of ultrasonic generation from a constrained layer depend directly on the layer properties. An optimum condition for generation can be achieved by creating a composite layer of mixed materials, where some of the elements provide enhanced optical absorption while the others give a large thermal expansion. In addition, when the active materials involved are in powder form, their volume density in the matrix can be varied in order to change the optical penetration depth of the incident light and, consequently, the generated ultrasonic frequency. Another important aspect is the coupling of the ultrasound into the test sample. Choosing a soft polymer matrix for the composite layer allows us to use the layer itself as a dry couplant. We will present results on the efficiency of ultrasonic generation with the above mentioned method, using a 1064 nm Nd:YAG laser, when the properties of the constrained-layer components are varied. Work supported by the Office of Naval Research through contract no. N00014-040C-0192.

## *Session 22*

Wednesday, August 3, 2005

## **SESSION 22**

### **TERAHERTZ IMAGING**

**H. Ringermacher, Chairperson**  
**Moulton Union Lower Level**

- 1:30 PM Numerical Modeling of Terahertz Imaging Applications**  
---**V. R. Melapudi**, L. Udpa, and S. S. Udpa, Michigan State University, Department of Electrical and Computer Engineering, East Lansing, MI 48823; W. P. Winfree, NASA Langley Research Center, Nondestructive Evaluation Sciences and Branch, Hampton, VA 23681-0001
- 1:50 PM Modeling and Processing of Terahertz Imaging in Space Shuttle External Tank Foam Inspection**  
---**C.-P. Chiou**<sup>1</sup>, R. B. Thompson<sup>1</sup>, B. Winfree<sup>2</sup>, E. Madaras<sup>2</sup>, and J. Seebo<sup>3</sup>, <sup>1</sup>Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011; <sup>2</sup>NASA Langley Research Center, MS 231, Hampton, VA 23681-2199; <sup>3</sup>Lockheed Martin, Hampton, VA 23681
- 2:10 PM A Wavelet Based Signal Processing Technique for Image Enhancement in Terahertz Imaging Data**  
---**N. V. Nair**, V. R. Melapudi, S. Ramakrishnan, L. Udpa, S. S. Udpa, Michigan State University, Electrical and Computer Engineering, 2120 Engineering Building, East Lansing, MI 48823; W. P. Winfree, NASA Langley Research Center, NDE Branch, Hampton, VA 23681-2199
- 2:30 PM Quantum Cascade Terahertz Emitters for Subsurface Defect Detection**  
---**A. T. Cooney**<sup>1</sup>, A. M. Sarangan<sup>2</sup>, T. R. Nelson<sup>3</sup>, R. Alkuwari<sup>2</sup>, P. E. Powers<sup>2</sup>, and J. L. Blackshire<sup>1</sup>, <sup>1</sup>Air Force Research Lab (AFRL/MLLP), Wright-Patterson AFB, OH 45433; <sup>2</sup>University of Dayton (Electro-Optics Graduate Program), 300 College Park, Dayton, OH 45469; <sup>3</sup>Air Force Research Lab (AFRL/SNDD), Wright-Patterson AFB, OH 45433
- 3:10 PM Coffee Break**
- 3:30 PM High Speed Large Area Terahertz Non Destructive Evaluation**  
---**D. Zimdars**, G. Stuk, J. S. White, A. Chernovsky, and S. Williamson, Picometrix, Inc., 2925 Boardwalk Dr., Ann Arbor, MI 48104
- 3:50 PM Sensing and Imaging with Continuous-Wave Terahertz**  
---**A. Redo**, N. Karpowicz, X. Li, and X.-C. Zhang, Rensselaer Polytechnic Institute, 110 8<sup>th</sup> Street, Troy, NY 12180-3590
- 4:10 PM Pulsed Terahertz Frequency Electromagnetic Flaw Detection in Sprayed on Foam Insulation**  
---**W. P. Winfree** and E. I. Madaras, NASA Langley Research Center, Hampton, VA 23681; J. L. Walker and J. D. Richter, NASA Marshall Space Flight Center
- 4:30 PM Terahertz NDE for Under Paint Corrosion Detection and Evaluation**  
---**R. F. Anastasi**, NASA Langley Research Center, US Army Research Laboratory, Vehicle Technology Directorate, AMSRD-ARL-VT-SM, MS-231, B1230, R220, Hampton, VA 23681-2199; E. I. Madaras, NASA Langley Research Center, Nondestructive Evaluation Sciences Branch, Hampton, VA 23681-2199

**Numerical Modeling of Terahertz Imaging Applications**

---**V. R. Melapudi**, L. Udpa, and S. S. Udpa, Department of Electrical and Computer Engineering, Michigan State University, East Lansing, MI 48823; William P. Winfree, Nondestructive Evaluation Sciences Branch, NASA Langley Research Center, Hampton, VA 23681-0001

---Development of stable laser sources, in recent years, for generating electromagnetic waves in terahertz bandwidth has made terahertz imaging a practical tool in many applications. Terahertz imaging techniques have received considerable attention in diverse fields including medical, industrial and space applications. Modeling the scattering of such very short wavelengths by realistic objects using conventional numerical methods such as finite element analysis, method of moments (MoM) or hybrid techniques such as finite element-boundary integral (FEBI), etc. is impractical as the number of unknowns can rapidly grow to very large values. This paper conducts a systematic study of the error between a numerical model and ray-tracing model predictions in an effort to investigate the feasibility of using a ray-tracing model for terahertz applications.

**Modeling and Processing of Terahertz Imaging in Space Shuttle External Tank Foam Inspection**

---**Chien-Ping Chiou**<sup>1</sup>, R. Bruce Thompson<sup>1</sup>, Bill Winfree<sup>2</sup>, Eric Madaras<sup>2</sup>, and Jeff Seebo<sup>3</sup>, <sup>1</sup>Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011; <sup>2</sup>NASA Langley Research Center, MS 231, Hampton, VA 23681-2199; <sup>3</sup>Lockheed Martin, Hampton, VA 23681

---The urgent need for suitable methods to inspect the space shuttle external tank foam insulation has become the focus of current national interest. Recently, terahertz ray (T-ray) imaging emerged as one of the most promising techniques to meet the need. This technique, however, is still in its infancy, and requires much further refinement. This paper demonstrates the application of state-of-the-art computer processing and modeling technologies to assist in such refinement. The current practice of T-ray inspection and its limitations are first reviewed. Possible new strategies for data processing and the use of modeling are then proposed to improve on the flaw detection. Preliminary results will be presented, including a time-frequency analysis of T-ray signals and the comparison between model and experimental data from foam samples. The characterization of a recent upgraded system will also be provided.

**A Wavelet Based Signal Processing Technique for Image Enhancement in Terahertz Imaging Data**

---**Naveen V Nair**, Vikram R. Melapudi, Sridhar Ramakrishnan, Lalita Udpa, Satish S. Udpa, Michigan State University, Electrical and Computer Engineering, 2120 Engineering Building, East Lansing, MI 48823; William P. Winfree, NASA Langley Research Center, Nondestructive Evaluation Sciences Branch, Hampton, VA 23681-2199

---Terahertz imaging is a relatively new technique for sub-surface imaging using radiation in the spectral range between 0.1 to 10 THz. The technique has been used to image artificially induced inserts that simulate disbonds in metal-foam interfaces. These studies show that the technique has significant promise as a possible nondestructive evaluation technique for evaluating the bonding quality of foam. The data in these cases is obtained by scanning across a surface on top of the foam coated on metal structures and collecting the time signal in a window of interest at each point in the scan plane. Proper data processing and visualization techniques become critical in being able to detect the disbonds and delaminations. The problem becomes even more challenging due to the wide variety of artifacts and support structures that are present on the metal substrates. In this work we discuss a wavelet based signal enhancement algorithm that provides an effective scheme for visualizing the data and provides a very high contrast between disbonded areas and the normal substrate. The technique also shows promise as a first step towards automatic detection and classification of the disbonds. Preliminary results, obtained on data collected using simulated disbonds that demonstrate the usefulness of the algorithm will be presented.

**Quantum Cascade Terahertz Emitters for Subsurface Defect Detection**

---**Adam T. Cooney**<sup>1</sup>, Andrew M. Sarangan<sup>2</sup>, Thomas R. Nelson<sup>3</sup>, Rashid Alkuwari<sup>2</sup>, Peter E. Powers<sup>2</sup>, and James L. Blackshire<sup>1</sup>, <sup>1</sup>Air Force Research Lab (AFRL/MLLP), Wright-Patterson AFB, OH 45433; <sup>2</sup>University of Dayton (Electro-Optics Graduate Program), 300 College Park, Dayton, OH 45469; <sup>3</sup>Air Force Research Lab (AFL/SNDD), Wright-Patterson AFB, OH 45433

---The transmission and penetration capability of electromagnetic waves with terahertz frequencies promises nondestructive subsurface inspection capabilities using low energy, non-harmful radiation. The development of compact and portable terahertz frequency radiation sources and detectors is crucial to the practical implementation of future terahertz based nondestructive evaluation tools for aerospace, medical, security, and electronic industries. Recent progress in the bandstructure engineering of multi-quantum well heterostructures offers the potential to design miniature, efficient, high power, and direct terahertz emitters using standard semiconductor materials and fabrication techniques. Using a recently developed terahertz spectrometer, combined with near and mid-Infrared spectroscopy data, we report on the transmission characteristics of aerospace coatings over a broad spectrum from near-Infrared to terahertz frequencies. The design of quantum cascade emitters based on the obtained transmission data is presented.

**High Speed Large Area Terahertz Non Destructive Evaluation**

---**David Zimdars**, Greg Stuk, Jeffrey S. White, A. Chernovsky, and S. Williamson, Picometrix, Inc., 2925 Boardwalk Drive, Ann Arbor, MI 48104

---We report a large area time domain THz imager capable of imaging 1 square meter in less than 30 minutes at 100 to 600 pixels/sec. To date, this system scans the largest area at the highest speed of any THz imager. Stationary objects are imaged in transmission and/or reflection. A novel stationary object transmission imaging system will be demonstrated. Results from a high resolution reflection transceiver will be shown. The system employs a novel optical time delay scanner capable of recording a 320 picosecond waveform at 100 Hz. This represents up to 2 inches of reflection window. THz imaging has shown great promise in 2 and 3 dimensional non-contact inspection of non-conductive materials such as plastics, foam, composites, ceramics, paper, wood and glass. In addition to density and attenuation measurements, THz pulses can be analyzed spectroscopically to reveal chemical content. Applications include aerospace NDE (recently Space Shuttle external tank foam and TPS tiles). A linear array, under development, could image 0.3 square meter in <5 seconds for rapid NDE and homeland security applications.

**Sensing and Imaging with Continuous-Wave Terahertz**

---**Albert Redo**, Nicholas Karpowicz, Xia Li, and X.-C. Zhang, Rensselaer Polytechnic Institute, 110 8<sup>th</sup> Street, Troy, NY 12180-3590

---We present recent results of sensing and imaging with continuous wave (CW) terahertz (THz) systems. THz waves are generated by Gunn diodes and a terahertz gas laser. Detection is performed with a Schottky diode, a Goly cell and a pyroelectric detector. In order to focus and guide the THz beam, a spherical, Fresnel and hyperbolic polyethylene lenses are designed and fabricated. The combination of the Gunn diode and Schottky diode results in a compact and portable system, which is an idea system for the field inspection. Examples for non-destructive imaging inspection and industrial applications for quality control are presented.

**Pulsed Terahertz Frequency Electromagnetic Flaw Detection in Sprayed on Foam Insulation**

---**William P. Winfree** and Eric I. Madaras, NASA Langley Research Center, Hampton, VA 23681; James L. Walker and Joel D. Richter, NASA Marshall Space Flight Center

---The detection and repair of flaws such as voids and delaminations in the sprayed on foam insulation of the external tank reduces the probability of foam debris during shuttle ascent. The low density of sprayed on foam insulation along with its other physical properties makes detection of flaws difficult with conventional techniques. An emerging technology that has application for quantitative evaluation of flaws in the foam is pulsed electromagnetic waves at terahertz frequencies. The short wavelengths of these terahertz pulses make them ideal for imaging flaws in the foam. This paper examines the application of terahertz pulses for flaw detection in foam that is characteristic of the foam insulation of the external tank. Of particular interest is detection of small voids encapsulated in the foam or at the interface between the foam and a metal backing. By processing the time response to take advantage of the frequency response of the foam, the detectability of flaws is shown to significantly improve. The technique is demonstrated on both fabricated and natural flaws.

**Terahertz NDE for Under Paint Corrosion Detection and Evaluation**

---**Robert F. Anastasi**, NASA Langley Research Center, US Army Research Laboratory, Vehicle Technology Directorate, AMSRD-ARL-VT-SM, MS-231, B1230, R220, Hampton, VA 23681-2199; Eric I. Madaras, NASA Langley Research Center, Nondestructive Evaluation Sciences Branch, Hampton, VA 23681-2199

---Corrosion under paint is not visible until it has caused the paint to blister, crack, or chip. At this point damage to the metal substrate may be minimal, but if corrosion continues it can weaken the substrate and cause a structure to fail. Terahertz NDE is being examined as a method to inspect and evaluate corrosion under paint. In this application, paint is a dielectric layer that terahertz radiation penetrates and the metallic substrate reflects. Thus, properties of the paint, corrosion, and corrosion products affect the returned terahertz signal. A sample with an aluminum substrate was manufactured with corrosion defects and flat bottom holes and then primed and painted. The sample was inspected with a commercial terahertz NDE system that scanned the sample and generated a data set of time-domain signals. The signals were post processed to reveal thickness changes in the paint and scattering effects due to surface non-uniformity. The signals were then examined in the frequency domain for spectral variations that may indicate areas of oxidation.

## *Session 23*

Wednesday, August 3, 2005

**SESSION 23**  
**NDE FOR MATERIALS CHARACTERIZATION**  
**Cleveland Hall 151**

- 1:30 PM**      **Elastic Constant Mapping on Polycrystalline Copper by Resonant-Ultrasound Microscopy**  
---**H. Ogi**, T. Tada, J. Tian, H. Niho, and M. Hirao, Osaka University, Graduate School of Engineering Science, Toyonaka, Osaka 560-8531, Japan
- 1:50 PM**      **Elastic Constants Inversion from Ultrasonic Transmission Spectra Obtained Using a Wide Aperture PVDF Sensor**  
---P. P. Kumar, C. V. Krishnamurthy, and **K. Balasubramaniam**, Indian Institute of Technology Madras, Department of Mechanical Engineering, Chennai 600036, Tamil Nadu, India
- 2:10 PM**      **Anisotropic Elastic Constants of Cu Thin Films: RUS/Laser Method**  
---**N. Nakamura**, H. Nitta, H. Ogi, and M. Hirao, Osaka University, Graduate School of Engineering Science, Toyonaka, Osaka 560-8531, Japan
- 2:30 PM**      **HBAR Spectroscopy Used for Materials Characterization**  
---**M. Viens** and Z. Wang, Department of Mechanical Engineering, École de Technologie Supérieure, 1100, Notre-Dame Street West, Montreal, Québec, H3C 1K3, Canada
- 2:50 PM**      **Photoacoustic Evaluation of the Mechanical Properties of Aluminum/Silicon Nitride Thin Films**  
---**F. Zhang** and S. Krishnaswamy, Northwestern University, Center for Quality Engineering and Failure Prevention, 2137 Tech Drive, Room 327, Catalysis Building, Evanston, IL 60208; C. M. Lilley, University of Illinois at Chicago, Department of Mechanical Engineering, Chicago, IL 60607
- 3:10 PM**      **Coffee Break**
- 3:30 PM**      **Ultrasonic Band Gaps in Periodic Stack of Plates – Simulation and Experiments**  
---B. C. Ram, P. P. Kumar, **C. V. Krishnamurthy**, K. Balasubramaniam, Centre for Nondestructive Evaluation, Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036, India; M. S. Sivakumar, Department of Applied Mechanics, Indian Institute of Technology Madras, Chennai 600036, India
- 3:50 PM**      **The Use of a Normalized Derivative Approach for Ultrasonic Attenuation Coefficient Estimation**  
---**S. P. Neal** and R. Cepel, University of Missouri-Columbia, Mechanical and Aerospace Engineering, E2412 Lafferre Hall, Columbia, MO 65211
- 4:10 PM**      **Ultrasonic Prediction of Neutron Irradiated Fluence in a Nuclear Reactor Vessel Material**  
---**S. Lee**, K. Chang, B. Kim, and C. Yoo, Nuclear Materials Technology Development, Korea Atomic Energy Research Institute, Daejeon, Korea
- 4:30 PM**      **Frequency-Dependence of Relative Permeability in Steel**  
---**N. Bowler**, Iowa State University, Center for Nondestructive Evaluation, 279 ASCII, 1915 Scholl Road, Ames, IA 50011-3042
- 4:50 PM**      **Measurement of Local Strain Distribution of Austenitic Stainless Steels by Using Magnetic Sensors**  
---Y. Tsuchida and M. Enokizono, Oita University, 700 Dannoharu, Oita 870-1192, Japan; M. Oka and T. Yakushiji, Oita National College of Technology, 1666 Maki, Oita 870-0152, Japan

**Elastic Constant Mapping on Polycrystalline Copper by Resonant-Ultrasound Microscopy**

---**Hirotsugu Ogi**, Toyokazu Tada, Jiayong Tian, Hiroki Niho, and Masahiko Hirao, Graduate School of Engineering Science, Osaka University, Toyonaka, Osaka, 560-853, Japan

---Quantitative evaluation of local Young modulus was performed on a polycrystalline copper using resonant-ultrasound microscopy with an isolated langasite oscillator. The free-vibration resonant frequency of the oscillator changes when it contacts the specimen, depending on the stiffness of the specimen at the local contact area. Thus, the local stiffness of the specimen is obtained by measuring the resonant frequency accurately. Quantitative evaluation, however, requires only one-point contact with the specimen and isolation of the oscillator from any other acoustical contacts. We achieved this demand by supporting the oscillator at the nodal point on the side faces and by making the wireless electrode-less measurement of the resonant frequency using the solenoid coil surrounding the oscillator. The elastic constant is obtained for individual grains and compared with that calculated by the individual orientation measured by the electron-backscattering pattern measurement. The resonant-ultrasound microscopy gave the elastic constant which is in good agreement with that calculated for most grains. We found, however, poor agreement for some grains: The measured elastic constant was smaller. We attribute this to defects and twins in grains.

**Elastic Constants Inversion from Ultrasonic Transmission Spectra Obtained Using a Wide Aperture PVDF Sensor**

---P. Padma Kumar, C. V. Krishnamurthy, and **Krishnan Balasubramaniam**, Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036, Tamil Nadu, India

---Ultrasonic wave propagation provides a method for Nondestructive Characterization of the elastic constants of materials. Goniometry based ultrasonic measurements were conducted in through transmission mode for isotropic and anisotropic materials using a conventional ultrasonic immersion transducer as a transmitter and a large aperture sensor made from Polyvinylidene Fluoride (PVDF) as receiver. The experimental results using this probe configuration were found to give improved transmission spectra that provides improved corroboration with the theoretical predictions based on Plane Wave Stiffness-Matrix based transmission factor model. Inversion of the elastic constants of materials, from the measured ultrasonic transmission spectra, was evaluated using two methods: (a) Genetic Algorithm and (b) Targeted Reconstruction. The inversions were carried out on transmission spectra obtained from both isotropic (Aluminum) and anisotropic materials (fiber reinforced graphite epoxy). The effectiveness of the large aperture receiver is also demonstrated from the results from inversion of the measured transmission spectra.

**Anisotropic Elastic Constants of Cu Thin Films: RUS/Laser Method**

---**Nobutomo Nakamura**, Hiroki Nitta, Hirotsugu Ogi, and Masahiko Hirao, Graduate School of Engineering Science, Osaka University, Toyonaka, Osaka, 560-853, Japan

---Copper thin film shows good electrical conductivity and high tolerance to electromigration damaging. For these characteristics, copper is replacing aluminum in fabricating microelectronic circuits. Mechanical properties of copper thin films have received intensive studies for the practical uses. Measurement of the elastic constants can be a powerful approach to evaluate reliability of electric devices, because they change with texture, internal stress, and invisible small defects. In this study, we determined anisotropic elastic constants of copper thin films by the resonant-ultrasound spectroscopy/laser (RUS/laser) method, which we originally developed. It determines the elastic constants of thin films from many free-vibration resonance frequencies of the film/substrate layered specimen. Determined elastic constants showed transverse isotropy and copper thin films possessed five independent elastic constants. The in-plane elastic constant  $C_{11}$  was larger than the out-of-plane elastic constant  $C_{33}$ , and we found elastic anisotropy between the in-plane and out-of-plane directions.

**HBAR Spectroscopy Used for Materials Characterization**

---**Martin Viens** and Zuoqing Wang, Department of Mechanical Engineering, École de Technologie Supérieure, 1100, Notre-Dame Street West, Montreal, Quebec, H3C 1K3, Canada

--- Resonance spectra of a High-over-tone Bulk Acoustic Resonator (HBAR), consisting of a substrate plate and a piezoelectric transducer, can be used to characterize properties of substrate material. Parallel resonance frequency spectrum is the only measurement required for the determination of the density and the elastic constants of this material. Because resonant frequency could be measured with an accuracy of only few ppb, the accuracy of the method could be pretty high. When resonant modes of the HBAR are "well separated", the mechanical loss of the material can also be determined by the BVD-equivalent circuit model. In this paper, three major factors are analyzed and numerical simulations are performed to characterize the impact of these factors on the accuracy of the method. Results show that (1) The selection of the substrate plate thickness is based on a compromise that may have an effect on measurement accuracy; (2) The effects of the electrodes on the accuracy of the method can't be ignored in high frequency cases. An approximate model is thus derived to take this factor into account; (3) The attenuation in the piezoelectric material and the electrodes have negligible effect on density and elastic constant measurement but have significant effects on the mechanical loss measurement. Applications to the characterization of some industrial materials are discussed. Both high (metals, ceramics, polymers) and low mechanical loss materials (silicon wafer, YAG and sapphire crystals) are given as examples.

**Photoacoustic Evaluation of the Mechanical Properties of Aluminum/Silicon Nitride Thin Films**

---**Feifei Zhang** and Sridhar Krishnaswamy, Center for Quality Engineering and Failure Prevention, Northwestern University, 2137 Tech Drive, Room 327, Catalysis Building, Evanston, IL 60208; Carmen M. Lilley, Department of Mechanical Engineering, University of Illinois at Chicago, Chicago, IL 60607

---The development of devices made of micro- and nano-structured materials has resulted in the need for advanced measurement techniques to characterize their properties. The mechanical properties of thin films can be investigated using nano-indentation tests, or through Brillouin scattering, or electron and atomic force microscopy, and acoustic microscopy. All these techniques are either destructive or are not suited for in-situ testing. In contrast, photoacoustic techniques, which use pulsed laser irradiation to nondestructively induce very high frequency ultrasound in a test object via rapid thermal expansion, are noncontacting and nondestructive. In this paper, we compare two photoacoustic techniques to characterize the mechanical parameters of edge-supported aluminum/silicon nitride double-layer thin films. Such edge-supported thin film structures form an integral part of many MEMS devices such as mirror arrays and pressure sensors. The elastic properties and residual stresses in such films affect their performance. In a first set of experiments, the femtosecond transient pump-probe technique is used to investigate the Young's moduli of the aluminum and silicon nitride layers by launching bulk acoustic waves in the films. The measured transient thermoelastic signals are compared with simulated transient thermoelastic signals in multi-layer structures, and the material properties (elastic moduli) are determined iteratively. Independent pump-probe tests on silicon substrate-supported region and unsupported region are in good agreement. In a second set of experiments, dispersion curves of A0 mode of the Lamb waves that propagate along the unsupported region are measured using a broadband photoacoustic guided-wave method. The residual stresses and flexural rigidities for the same set of double-layer membranes are determined from these dispersion curves. Comparisons of the results measured by the two photoacoustic techniques are made and discussed.

**Ultrasonic Band Gaps in Periodic Stack of Plates - Simulation And Experiments**

---B. C. Ram, P. Padma Kumar, **C. V. Krishnamurthy**, Krishnan Balasubramaniam, Centre for Nondestructive Evaluation, Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036, India; M. S. Sivakumar, Department of Applied Mechanics, Indian Institute of Technology Madras, Chennai 600036, India

---Ultrasonic band gaps were simulated using various numerical techniques for 1-D periodic structures. The pulse propagation characteristics were simulated using Transient Finite element analysis. The frequency domain characteristics were simulated using forced periodic response analysis, Thompson Haskell transfer matrix and acoustic impedance based calculations. Dispersion curves were also obtained using eigen value lattice simulations. Simulation of the band gaps obtained using these numerical methods agreed well with each other. Experiments were carried out on layered material (Aluminum-Plexiglas) at ultrasonic frequencies. The measured band gaps matched with the simulation results. Numerical and experimental results are also presented for mirror symmetric periodic stacks.

**The Use of a Normalized Derivative Approach for Ultrasonic Attenuation Coefficient Estimation**

---**Steven P. Neal** and Raina Cepel, University of Missouri-Columbia, Mechanical and Aerospace Engineering, E2412 Lafferre Hall, Columbia, MO 65211

---The ultrasonic attenuation coefficient is an acoustic parameter routinely estimated in nondestructive evaluation (NDE) and biological tissue characterization. For single-scattering backscatter from depth-independent materials, attenuation causes a decay of the measured signals while beam field variations can cause an increase or decrease in measured signals with time or depth into the material. For materials showing depth dependence in attenuation and/or scattering, the situation is more complicated. Variations in scattering can cause an increase or decrease in measured signals with time or depth, and variations in attenuation will result in varying rates of decay of the measured signals. Attenuation coefficient estimation is typically achieved by finding the slope of a line on a semi-log plot of signal magnitude vs. propagation distance, at each frequency. The semi-log slope is the derivative of log of the magnitude, which is the normalized derivative or log derivative. Starting with linear-system models, we reformulate the attenuation coefficient estimation problem by taking normalized derivatives at the models stage. Depth independence and depth dependence in scattering and attenuation are considered. The experimental diffraction correction approach is also addressed in the context of normalized derivatives. This research was supported in part by the National Science Foundation.

**Ultrasonic Prediction of Neutron Irradiated Fluence in a Nuclear Reactor Vessel Material**

---**SamLai Lee**, KeeOk Chang, ByoungChul Kim, and ChoonSung Yoo, Nuclear Materials Technology Development, Korea Atomic Energy Research Institute, Daejeon, Korea

---The assurance of nuclear reactor pressure vessel integrity plays the most important role in achieving the safety and extending the life of nuclear power plants. While various material tests using surveillance specimen have been performed in order to evaluate the degree of degradation of reactor vessel, current method has not been considered to provide sufficient information. Thus, nondestructive evaluation method has been sought as an alternative way to overcome such difficulty. Ultrasonic testing, one of nondestructive evaluation methods was tried. Ultrasonic signals from Charpy impact test specimen have been analyzed. Base and weld metal specimen that were extracted from reactor vessel according to the schedule of the surveillance test required by the related regulations during plant routine overhaul have been used. Ultrasonic test parameters including attenuation were analyzed for different frequencies and were correlated with the quantity of material degradation such as neutron fluence. Test results showed that the ultrasonic parameters had close correlations with the amount of neutron irradiation for specimen and also certain possibility where an ultrasonic evaluation could be used to predict the fluence of the neutron irradiation in nuclear reactor vessel materials.

**Frequency-Dependence of Relative Permeability in Steel**

---**Nicola Bowler**, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Room 279, Ames, IA 50011-3042

---A study to characterize metal plates by means of a model-based, broadband, four-point potential drop measurement technique has shown that the relative permeability of carbon steel is a function of frequency. A clear relaxation in the relative permeability is observed at around 1 kHz, with the real part declining from a value of approximately 280 at low frequencies (1 to 10 Hz) to approximately 90 at 100 kHz. The most likely mechanism responsible for this effect is phase lag in the motion of magnetic domain walls, with respect to the applied alternating current injected into the plate. Here, the observed relaxation is characterized in terms of a parametric model. Factors which influence the frequency, amplitude and breadth of the relaxation, such as sample geometry, amplitude of the applied current and disorder (e.g. percent carbon content) in the steel, are discussed.

**Measurement of Local Strain Distribution of Austenitic Stainless Steels by Using Magnetic Sensors**

---**Yuji Tsuchida** and Masato Enokizono, Oita University, 700 Dannoharu, Oita 870-1192, Japan; Mohachiro Oka and Terutoshi Yakushiji, Oita National College of Technology, 1666 Maki, Oita 870-0152, Japan

---SUS 304 is widely used in many fields from household appliances to nuclear power stations all over the world. SUS 304 is classified as austenitic stainless steel and non-magnetic material. However, the plastic part of SUS 304 transforms into martensitic crystal structure from austenitic crystal structure by applying strain. We have made clear the relationship between the remanent magnetization and the strain by the tensile stress test for SUS 304. We try to measure remanent magnetization of stainless steel SUS 316 and 316L. SUS 316 and its low carbon grade SUS 316L are also classified into austenitic stainless steel, however, these stainless steels are very stable and corrosion resistant. Therefore, these are considered that they don't transform into martensitic crystal structure and never get magnetized under room temperature. We assumed that the remanent magnetization could not have been measured because the amounts are very small. Therefore, we tried to use a high sensitive thin-film flux-gate (TFG) magnetic sensor for SUS 316 and 316L after the tensile stress test. In the presentation, the results from SUS 304, 304L, 316 and 316L will be shown and the differences between SUS 304, 304L and SUS 316, 316L will be discussed.

Wednesday, August 3, 2005

**SPECIAL EVENING SESSION**  
**Moulton Union Main Lounge**

**8:00 PM**

**Technology to Enable the Vision for Space Exploration**

---**F. Peri** and W. K. Belvin, NASA Langley Research Center, Mail Stop 172, Hampton, VA 23681

---NASA's future missions will utilize various large space systems for cargo and crew transport in support of science and exploration. These long duration, human and robotic exploration missions entail the development of transfer vehicles, cryogenic fuel depots, power and infrastructure platforms, habitats (both in-space and surface), and many other systems yet to be defined. Advanced technology investments are being made in the following areas to support the Vision for Space Exploration (VSE):

- Advanced Materials and Structural Systems
- Computing, Communications and Information Systems
- Power, Propulsion and Chemical Systems
- Crew Mobility and Human Support Systems
- Launch Systems

One of the key technologies that will permit long duration exploration involves the concept of sustaining engineering. With sustaining engineering, field measurements of system performance and health are utilized to qualify and maintain the readiness of space systems and their components. This briefing will describe the types of exploration missions under study and critical technology needs for the VSE. The discussion emphasizes the role of in-situ, non-destructive sensing and evaluation to provide integrated vehicle health management (IVHM).

# ***THURSDAY***

Session 24 – Health Monitoring .....	139
Session 25 – Materials Microstructure and Damage Mechanisms.....	145
Session 26 – Eddy Current Probes and Applications .....	151
Session 27 – UT Transducers, Devices, and Fields.....	157
Session 28 – Posters: Nonlinear Techniques, UT Transducer and Arrays, Detection and Sizing, Material Properties, Coatings and Bonds, Viscous Materials, Electromagnetic and Thermal Methods, Degradation Mechanisms, New Techniques, and Fluorescent Penetrants.....	163
Session 29 – Benchmark Studies .....	191
Session 30 – New Sensors .....	194
Session 31 – New Techniques and Applications.....	198
Session 32 – X-Ray Techniques and Applications.....	201

# *Session 24*

Thursday, August 4, 2005

**SESSION 24**  
**HEALTH MONITORING**  
**K. Jata, Chairperson**  
**Cleveland Hall 151**

- 8:30 AM**      **Structural Health Monitoring Strategies for Thermal Protection Structures and Hot Structures with Emphasis on Materials Aspects**  
---**K. V. Jata**, Air Force Research Laboratory, Materials and Manufacturing Directorate, AFRL/MLLP, 2230 Tenth Street, WPAFB, OH 45433
- 9:10 AM**      **TPS Health Monitoring for Space Vehicles**  
---**J. Huang** and J. Ember, Structures Technology, Boeing Phantom Works, 5301 Bolsa Avenue, Huntington Beach, CA 92647
- 9:30 AM**      **Structural Health Monitoring of the Space Shuttle's Wing Leading Edge**  
---**E. I. Madaras** and W. H. Prosser, NASA Langley Research Center, MS231, Hampton, VA 23681; M. R. Gorman, Digital Wave Corp., 11234A Caley Ave., Centennial, CO 80111; G. Studor, NASA Johnson Space Center, Code ES2, 2101 NASA Road 1, Houston, TX 77058
- 9:50 AM**      **Development of a Wireless Active System for TPS Structural Health Monitoring**  
---**V. Giurgiutiu** and B. Xu, University of South Carolina, Department of Mechanical Engineering, Columbia, SC 29208; J. Chung, Global Contours, Ltd.
- 10:10 PM**      **Coffee Break**
- 10:30 PM**      **Integrated Sensing and Material Damage Identification in Metallic and Ceramic Thermal Protection Systems Using Vibration and Elastic Wave Propagation Data**  
---**H. Kess**, T. Johnson, H. Jing, S. Sundararaman, J. White, D. E. Adams, and K. Jata, AFRL/MLLP, Metals, Ceramics, and NDE Division, 2230 Tenth Street, WPAFB, OH 45433
- 10:50 PM**      **Fiber-Optic Sensing for Thermal Protection Structures in Vehicle Health Monitoring**  
---**R. J. Black**, K. Chau, K. Good, M. Hernandez, L. Oblea, and B. Moslehi, Intelligent Fiber Optic Systems Corporation, 650 Vaqueros Avenue, Sunnyvale, CA 94085
- 11:10 PM**      **Damage Evaluation and Analysis of Composite Pressure Vessels Using Fiber Bragg Gratings to Determine Structural Health**  
---**N. Ortyl**, M. Kunzler, and E. Udd, Blue Road Research, 376 NE 219<sup>th</sup> Avenue, Gresham, OR 97030
- 11:30 PM**      **Impact Detection and Acoustic Properties of Thermal Protection System Materials**  
---**S. J. Kuhr**, Anteon Corporation, 5100 Springfield Pike, Suite 509, Dayton, OH 45431-1264; R. Reibel and S. Sathish, University of Dayton Research Institute, 300 College Park, Dayton, OH 45469-0127; K. V. Jata, AFRL/MLLP Materials and Manufacturing Directorate, Wright Patterson AFB, OH 45433
- 11:50 PM**      **Thermal Characterization of TPS Materials**  
---**C. J. Kacmar**, Anteon Corporation Dayton, OH 45409; K. J. LaCivita and K. V. Jata, Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson AFB, OH 45433; S. Sathish, University of Dayton Research Institute, Dayton, OH 45469; D. R. Daniels, Rapiscan Systems, Fairborn, OH 45324
- 12:10 PM**      **Lunch**

**Structural Health Monitoring Strategies for Thermal Protection Structures and Hot Structures with Emphasis on Materials Aspects**

---**Kumar V. Jata**, Air Force Research Laboratory, Materials and Manufacturing Directorate, AFRL/MLLP, 2230 Tenth Street, WPAFB, OH 45433

---Structural health monitoring is a key technology component of the Integrated Systems Health Management (ISHM), and the USAF has many of its Directorates involved in the development of the ISHM capability. One of the major goals of our current research at AFRL/MLLP is to develop structural health monitoring capability for real time interrogation of material and damage state awareness in thermal protection and hot structures. Material systems that are currently being used and the potential materials for future use in the thermal protection or the hot structure components depend on the location of the structural component on the vehicle. For example, the leading edge versus acreage TPS experience has vastly different temperature profiles and thus requires radically different material concepts. Many different materials ranging from metals, ceramics to non-metallics are either currently being used or are potential materials for these structures. After giving a brief introduction to the various potential materials concepts, this talk will discuss possible failure damage modes, sensors and associated capabilities required to perform real time interrogation of materials and damage state awareness, capabilities of current sensors and their limitations.

**TPS Health Monitoring for Space Vehicles**

---**Jerry Huang** and Jonathan Embler, Structures Technology, Boeing Phantom Works, 5301 Bolsa Avenue, Huntington Beach, CA 92647

---Thermal Protection Systems (TPS) are critical to space vehicle safety and operations. Damage to TPS can result in loss of vehicle and crew. Inspection of TPS damage can be time consuming, costly, and, in turn, affect vehicle turn-around time. The Boeing Company is funded by the Air Force Research Lab (AFRL) to evaluate and develop TPS health monitoring technologies for space vehicles such as the Space Operation Vehicle (SOV). These projects have been targeted on developing in-situ sensing and pre or post flight inspection methods with the goal of improving overall vehicle safety and significantly reducing vehicle turn times. A series of bench level experiments was performed to characterize properties of the selected materials and evaluate the candidate sensing techniques for the targeted failure modes. This presentation will provide an overview of Boeing's effort and selected results. Several possible TPS materials and configurations, possible failure modes, and sensing techniques will also be discussed.

### **Structural Health Monitoring of the Space Shuttle's Wing Leading Edge**

---**Eric I. Madaras** and William H. Prosser, NASA Langley Research Center, MS231, Hampton, VA 23681; Michael R. Gorman, Digital Wave Corp., 11234A Caley Ave., Centennial, CO 80111; George Studor, NASA Johnson Space Center, Code ES2, 2101 NASA Road 1, Houston, TX 77058

---It was determined that the loss of the Space Shuttle Columbia resulted from foam debris impacting the Orbiter wing's reinforced carbon-carbon (RCC) leading edge. This led NASA to investigate more thoroughly the effects of impact damage to their thermal protection system. NASA was also tasked with developing methods to evaluate the orbiters while in space so that on-orbit repairs could be made before reentry if required. One method that NASA has been investigating is an automated acoustic based detection system. Such a system would be based in part on methods developed over the years for acoustic emission testing. Impact sensing has been demonstrated through numerous impact tests on both reinforced carbon-carbon leading edge materials as well as Shuttle tile materials mounted on representative aluminum wing structures. A variety of impact materials and conditions have been evaluated including foam, ice, and ablator materials at ascent velocities as well as simulated hypervelocity micrometeoroid and orbital debris impacts. These tests have successfully demonstrated the capability to detect and localize impact events on the Shuttle's wing structure. A first generation impact sensing system was developed and has been deployed on the Shuttle Discovery, the first Shuttle scheduled for return to flight. The system employs wireless modules with accelerometer sensors that were qualified for other applications on previous Shuttle flights. These sensors were deployed on the leading edge spars to detect impacts on the RCC leading edge panels. Improvements to this detection system are under consideration and the system may be extended to monitor other critical Shuttle regions such as the lower wing and nose cone.

### **Development of a Wireless Active System for TPS Structural Health Monitoring**

---**Victor Giurgiutiu** and Buli Xu, Department of Mechanical Engineering, University of South Carolina, Columbia, SC 29208; Jaycee Chung, Global Contours, Ltd.

---Structural health monitoring (SHM) using in-situ active sensors has shown considerable promise in recent years. Small and lightweight piezoelectric wafer active sensors (PWAS), which are permanently attached to the structure, are used to transmit and receive interrogative Lamb waves that are able to detect the presence of cracks, disbonds, corrosion, and other structural defects. Successful demonstrations of active SHM technologies have been achieved for civil and military aircraft components and substructures. The US Air Force is developing the Space Operations Vehicle, which is going to be subject to extreme operational conditions. Of considerable interest is the structural health of the thermal protection system (TPS) which offers the physical protection barrier between the extreme environment and the vehicle structure. The TPS is built to accommodate aerodynamic pressures, as well as thermal conditions found in the cold of space and throughout the heat of reentry. Several TPS panel variants are being considered. This paper will examine how active SHM principles could be applied for the detection and monitoring of critical TPS damage. Several essential aspects are being studied: (a) identification of piezoelectric materials that can survive the harsh environment to which the TPS are exposed; (b) development of active SHM (pitch-catch, pulse-echo, phased-array, electromechanical impedance) that can be applied to the specific constructions; (c) development of self-powering low-power consumption electronics with wireless capability for implementing the active SHM principles, and transmit the diagnostic results. Since the work on this project has just started, the paper focus will be on basic principles and work-in-progress results.

**Integrated Sensing and Material Damage Identification in Metallic and Ceramic Thermal Protection Systems Using Vibration and Elastic Wave Propagation Data**

---**Harold Kess**, Timothy Johnson, Hao Jing, Shankar Sundararaman, Jonathan White, Douglas E. Adams, and Kumar Jata, AFRL/MLL Metals, Ceramics, and NDE Division, 2230 Tenth Street, WPAFB, OH 45433

---Thermal and impact material damage mechanisms in metallic and ceramic thermal protection systems are detected, located, and quantified in this research. First, a virtual force damage identification method is implemented in honeycomb Al and gamma Ti-Al sandwich panels instrumented with a sparse piezo transducer array to identify global impact damage using modal modeling in conjunction with inverse frequency response methods. Measurement repeatability is shown to be an important requirement in this method. Second, phased array beamforming algorithms are used to process active elastic waves in two different equilibrium positions of a gamma Ti-Al sheet to localize simulated thermal damage. Results are shown to be dependent on the equilibrium position considered. Third, a wrapped ceramic tile with a mock strain isolation pad is tested using both standing vibration waves and propagation waves to identify damage to the panel and the pad. Remote actuation and sensing on the bulkhead and the tile backside are shown to be sufficient for detection using transmissibility analysis. Fourth, analytical acoustic transmission models are developed for identifying local changes to material density (and/or modulus) in sandwich metallic thermal protection system panels. These results are supported by preliminary acoustic experiments on a baffled panel.

**Fiber-Optic Sensing for Thermal Protection Structures in Vehicle Health Monitoring**

---**Richard J. Black**, Kelvin Chau, Ky Good, Marco Hernandez, Levy Oblea, and Behzad Moslehi, Intelligent Fiber Optic Systems Corporation, 650 Vaqueros Avenue, Sunnyvale, CA 94085

---Monitoring and evaluation of structural performance plays a key role in reducing the overall operational cost and improving safety of reusable aerospace transportation vehicles. Intelligent Fiber Optic Systems (IFOS) has developed an advanced optical sensing system including High-Temperature Fiber Bragg Grating (HTFBG) sensors to monitor and analyze Thermal Protection Structures (TPS) and Hot Structure Health Monitoring fields to assess structural damage and/or material state conditions. Such HTFBG sensors can be embedded and multiplexed within a Thermal Protection Layer formed by reinforcing fibers and matrix resin. By deploying this sensing technique, vibration and strain can be measured at high speed to detect subtle damages to the aerospace vehicle from liftoff to landing, reducing the cost and time required for structural maintenance. In addition, the IFOS sensing technology can provide a comprehensive monitoring of joints connecting the panels with the structure, panels for temperature leak detection and other structural parameters, as well as the internal states of structural composite at various locations, capable of relaying signals to operators or command center in real time for fast responses. Spin-offs of the technology have diverse applications ranging from weigh-in-motion to pipeline monitoring, civil and marine applications.

**Damage Evaluation and Analysis of Composite Pressure Vessels Using Fiber Bragg Gratings to Determine Structural Health**

---**Nicholas Ortyl**, Marley Kunzler, and Eric Udd, Blue Road Research, 376 NE 219<sup>th</sup> Avenue, Gresham, OR 97030

---With the augmented use of high performance composite materials in critical structures, it has become increasingly important for 'smart' systems to monitor these materials and provide rapid evaluation. Using fiber Bragg gratings embedded into the weave structure of carbon fiber epoxy composites allows the capability to monitor these composites during manufacture, cure, general aging, and damage. Fiber optic sensors allow greater insight into damage progression and can be used to verify analytical models. This paper emphasizes the results of recent work in which multiple arrays of Bragg gratings were wound into composite vessels and monitored while the part was damaged. Based on the response of these sensors, algorithms were developed to identify the location of damage impacts. Results were verified against eddy current and ultrasonic NDE methods. Recent advances in high temperature work at 900°C and above, will also be reviewed.

**Impact Detection and Acoustic Properties of Thermal Protection System Materials**

---**Samuel J. Kuhr**, Anteon Corporation, 5100 Springfield Pike, Suite 509, Dayton, OH 45431-1264; Richard Reibel and Shamachary Sathish, University of Dayton Research Institute, 300 College Park, Dayton, OH 45469-0127; Kumar V. Jata, AFRL/MLLP Materials and Manufacturing Directorate, Wright Patterson AFB, OH 45433

---This paper will discuss the experimental approaches used to measure the acoustic wave propagation characteristics in CMC wrapped tile thermal protection system (CMC+ Foam+ RTV+ SIP+ RTV+ Al) and ceramic foams. Sound velocities and attenuation characteristics were measured in three mutually perpendicular directions on the above materials. Commercially available standard acoustic emission transducers, piezo-wafers and polymer based PVDF (polyvinyl diene fluoride) films were employed in the experiments to acquire the acoustic data. The performance characteristics of these sensors will be discussed in light of detecting impact. Experimental results of the variation in the wave propagation characteristics along different directions will be presented. The role of processing in producing anisotropic acoustic properties in thermal protection system will be discussed.

**Thermal Characterization of TPS Materials**

---**Christopher J. Kacmar**, Anteon Corporation, Dayton, OH 45409; Kenneth J. LaCivita and Kumar V. Jata, Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson AFB, OH; Shamachary Sathish, University of Dayton Research Institute, Dayton, OH 45469; Dan R. Daniels, Rapiscan Systems, Fairborn, OH 45324

---The Thermal Protection System (TPS) used on space shuttles protects the metallic structure from the large amounts of heat created during travel through the atmosphere, both on takeoff and reentry. The high thermo-acoustic loads and impact damage from micro-meteorites can cause disbonds, delaminations, chips, cracks, and other defects in the TPS system. To enhance the durability and damage tolerance new TPS systems with protective layers to the shuttle tile are being developed. This paper explores the use of Pulse Thermography, as a nondestructive technique, to characterize the TPS systems. The TPS materials examined include next generation ceramic composite wrapped TPS tiles, currently used reaction cured glass (RCG) coated tiles, and the non-coated silica substrates. Computed Tomography has also been performed, whenever possible on the tiles. The images of pulse thermography and computer tomography obtained on the same tiles are presented. The advantages of using two techniques to characterize the TPS materials are discussed.

# *Session 25*

Thursday, August 4, 2005

## SESSION 25

### **MATERIALS MICROSTRUCTURE AND DAMAGE MECHANISMS**

Druckenmiller Hall 016

- 8:30 AM**      **Two-Step Monte-Carlo Simulation of Ti-Alloy Microstructures for Studies of Ultrasonic Beam Fluctuations**  
---**A. Li**, R. B. Thompson, F. J. Margetan, and R. Roberts, Iowa State University, Center for Nondestructive Evaluation, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011
- 8:50 AM**      **Laser Measurement of SAM Bulk and Surface Wave Amplitudes for Material Microstructure Analysis**  
---**C. Miyasaka**, K. L. Telschow, and D. L. Cottle, Idaho National Laboratory, Physics Department, Idaho Falls, ID 83415-2218
- 9:10 AM**      **Correlation of Ultrasonic Velocity with Beta-Transus Temperature in Alpha+Beta Titanium Alloys**  
---**A. Kumar**, **T. Jayakumar**, and B. Raj, Indira Gandhi Centre for Atomic Research, Non Destructive Evaluation Division, Kalpakkam, Tamil Nadu, 603102, India
- 9:30 AM**      **In-Situ Observation of Creation and Growth of Internal Damage in Cast Al Using Ultrasonics**  
---**B. Ghaffari**, S. Harris, J. Boileau, and G. Mozurkewich, Ford Motor Company, Research and Advanced Engineering, MD 3083/SRL, P. O. Box 2053, Dearborn, MI 48121-2053
- 9:50 AM**      **Detection of Fatigue Damage Prior Crack Initiation with Scanning SQUID Microscopy**  
---**J. W. Morris**, Jr. and T.-K. Lee, University of California, Berkeley, Department of Materials Science and Engineering, 210 Hearst Memorial Mining Building, Berkeley, CA 94720; J. Clarke and S. Lee, University of California, Department of Physics, Berkeley, CA 94720
- 10:10 AM**      **Coffee Break**
- 10:30 AM**      **The Effects of Heat Treatment and Shot Peening on the Surface Roughness of Inconel-718**  
---**M. J. Johnson**, N. Nakagawa, S. Hentscher, S. Wendt, and D. Raithel, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011
- 10:50 AM**      **A Method to Eliminate Couplant-Dependent Variability in Acoustic Nonlinearity Measurements in Fatigued Components**  
---L. Sun, **S. S. Kulkarni**, B. Moran, S. Krishnaswamy, and J. D. Achenbach, Center for QEFP, Department of Mech. Eng., Northwestern University, IL 60208
- 11:10 AM**      **Surface Texture of Fretting Fatigue Damaged Surfaces of Shot Peened Titanium**  
---**S. A. Martinez** and M. P. Blodgett, Air Force Research Laboratory, Materials and Manufacturing Directorate, 2230 Tenth St., Suite 1, Wright Patterson Air Force Base, OH 45433; S. Sathish, University of Dayton Research Institute, 300 College Park, Dayton, OH 45469-0127; S. Mall, Air Force Institute of Technology, Wright Patterson Air Force Base, OH 45433
- 11:30 AM**      **Detection of Mechanical Damage Using Magnetic Flux Leakage**  
---**A. Rubinshteyn**, V. Babbar, and L. Clapham, Queen's University, Department of Physics, Engineering Physics & Astronomy, Kingston, Ontario, Canada
- 11:50 AM**      **Characterization of Cold Work in Nickel-Base Superalloys by Instrumented Nanoindentation by Instrumented Nanoindentation**  
---**X. Bin**, L. Wang, and S. I. Rokhlin, The Ohio State University, Nondestructive Evaluation Program, Edison Joining Technology Center, 248 Arthur E. Adams Dr., Columbus, OH 43221; P. B. Nagy, University of Cincinnati, Department of Aerospace Engineering and Engineering Mechanics, 731 Rhodes Hall, Cincinnati, OH 45221-0070; M. P. Blodgett, Wright-Patterson AFB, Nondestructive Evaluation, Branch AFRL/MLLP, 2230 10<sup>th</sup> Street, Dayton, OH 45433
- 12:10 PM**      **Lunch**

### **Two-Step Monte-Carlo Simulation of Ti-Alloy Microstructures for Studies of Ultrasonic Beam Fluctuations**

---**Anxiang Li**, R. B. Thompson, F. J. Margetan, and Ron Roberts, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011

---In past work, algorithms have been developed to compute the manner in which a sonic beam becomes distorted when passing through a two-dimensional inhomogeneous metal microstructure. We now take up the problem of generating realistic model microstructures to serve as inputs for the computations. In particular, we consider microstructures similar to those found in certain jet-engine titanium alloys where, during cooling, colonies of alpha-phase (hexagonal) micrograins develop from higher-temperature beta-phase (cubic) macrograins. Here, model microstructures are generated using a 2-step Monte Carlo method based on the Potts model for grain growth. In the first step large, equiaxed beta macrograins are generated having randomly-oriented principal axes. In the second step, micrograins are grown inside the macrograin boundaries, taking into account the 6 possible orientation variants a micrograin can have with respect to its parental macrograin. Stretching of grains, either in step 1 or step 2, can be used to produce elongated microstructures like those seen in practice. Longitudinal wave speeds for the alpha micrograins are calculated from their spatial orientations by solving the Christoffel equation. The simulated microstructures are then passed to the numerical wave-propagation algorithm to study wave-microstructure interactions. Model predictions for P/E back-wall responses and FBH responses are presented.---This material is based upon work supported by the Federal Aviation Administration under Contract #DTFA03-98-D-00008, Delivery Order #0034 and performed at Iowa State University's Center for NDE as part of the Engine Titanium Consortium program, through the Airworthiness Assurance Center of Excellence.

### **Laser Measurement of SAM Bulk and Surface Wave Amplitudes for Material Microstructure Analysis**

---**Chiaki Miyasaka**, Ken L. Telschow, and David L. Cottle, Physics Department, Idaho National Laboratory, Idaho Falls, ID 83415-2218

---Scanning Acoustic Microscopy (SAM) at ultra high frequencies has proven to be a useful tool for investigating materials on the scale of individual grains. This technique is normally performed in a reflection mode from one side of a sample surface. Information about the generation and transmission of bulk acoustic waves into the material is inferred from the reflection signal amplitude. We present an adaptation to the SAM method whereby the acoustic bulk waves are directly visualized through laser acoustic detection. Ultrasonic waves were emitted from a nominal 200 MHz point focus acoustic lens into a thin silicon plate (thickness 75 $\mu$ m) coupled with distilled water. A scanned laser beam detected the bulk and surface acoustic waves at the opposite surface of the thin silicon plate. Distinct amplitude patterns exhibiting the expected symmetry for Silicon were observed that alter in predictable ways as the acoustic focal point was moved throughout the plate. Predictions of the acoustic wave fields generated by the acoustic lens within and at the surface of the Silicon are being investigated through the angular spectrum of plane waves approach. Results shall be presented for plates with (100) and (111) orientations followed by discussion of applications of the technique for material microstructure analysis.

**Correlation of Ultrasonic Velocity with Beta-Transus Temperature in Alpha+Beta Titanium Alloys**

---Anish Kumar, **Tammanna Jayakumar**, and Baldev Raj, Indira Gandhi Centre for Atomic Research, Non Destructive Evaluation Division, Kalpakkam, Tamil Nadu, 603102, India

---Titanium alloys, by virtue of their excellent specific strength and modulus, and better intermediate temperature strength, are preferred structural materials for aerospace applications. Alpha+beta titanium alloys are widely used and accounts for more than 60 % of all titanium tonnage in the market. Beta-transus temperature is one of the important properties of the alpha+beta titanium alloys, which governs the temperature for various thermal and thermo-mechanical treatments. The conventional methods such as dilatometry, calorimetry and multiple specimen heat treatment, for identification of beta-transus temperature are tedious and time consuming. A new methodology has been established for prediction of beta transus temperature in alpha+beta titanium alloys by ultrasonic velocity measurement in a single specimen in one microstructural condition only. Eight different alpha+beta titanium alloys with beta transus temperature in the range of 1050-1250 K, were selected for the present study. One specimen each of these alloys was heat treated at 1273 K (higher than the maximum beta transus temperature in the alpha+beta titanium alloys) for 1 h followed by water quenching. Ultrasonic velocity in these solution annealed specimens exhibited linear relationship with the corresponding beta transus temperature. This linear correlation can be used to determine the beta transus temperature in any unknown alpha+beta titanium alloy, by just one measurement of ultrasonic longitudinal wave velocity in the specimen in solution annealed condition.

**In-Situ Observation of Creation and Growth of Internal Damage in Cast Al Using Ultrasonics**

---**Bitu Ghaffari**, Stephen Harris, James Boileau, and George Mozurkewich, Ford Motor Company, Research and Advanced Engineering, MD 3083/SRL, P. O. Box 2053, Dearborn, MI 48121-2053

---Creation and growth of internal damage during ductile failure was observed utilizing the ultrasonic attenuation caused by scattering from the defects. A focused 100-MHz transducer was used to scan sub-sized specimens of cast aluminum while being tested in a tensile stage. Measurements were made in pulse-echo mode in water with a spatial resolution of 0.1 mm. An accurate measure of attenuation was obtained by comparing a specimen's back-surface echo with that from a defect-free reference specimen. Maps of ultrasonic attenuation at increasing stress levels demonstrate creation and growth of damaged areas as the sample approaches failure.

**Detection of Fatigue Damage Prior Crack Initiation with Scanning SQUID Microscopy**

---**J. W. Morris, Jr.**, and Tae-Kyu Lee,  
University of California, Berkeley, Department of  
Materials Science and Engineering, 210 Hearst  
Memorial Mining Building, Berkeley, CA 94720;  
John Clarke and Seungkyun Lee, University of  
California, Department of Physics, Berkeley, CA  
94720

---The fatigue process can be detected and monitored in the earliest stages of high-cycle fatigue, by the increase in dislocation density and hardness, and in the final stages, through the direct observation of initiated cracks. But there are no probative, non-destructive techniques to follow incipient fatigue through the critical intermediate stage between dislocation saturation and prior to crack nucleation. In this study, we report initial success in using SQUID microscopy for this purpose. Dislocations and microcracks act as pinning sites that impede the motion of magnetic domain walls under an applied magnetic field. It follows that subtle changes in local magnetic behavior follows the reconfiguration of defects that occurs in the intermediate stages of fatigue. These can be detected by mapping the local remanence field of a fatigued specimen. The remanence fields of fatigued ferritic steel specimens were measured using a scanning microscope based on a high transition temperature Superconducting Quantum Interference Device (SQUID). The results show an overall increase of remanence until dislocation density saturates and an additional local remanence increase after saturation during cyclic loading. Because of the combined magnetic and spatial resolution of the SQUID microscope, these local changes of dislocation structures can be detected before a crack actually initiates, and identify the sites where crack nucleation will occur.

**The Effects of Heat Treatment and Shot Peening on the Surface Roughness of Inconel-718**

---**M. J. Johnson**, N. Nakagawa, S. Hentscher,  
S. Wendt, and D. Raithel, Iowa State University,  
Center for NDE, Applied Sciences Complex II,  
1915 Scholl Road, Ames, IA 50011

---It is well known and intuitively obvious that shot peening influences the surface roughness of materials including Inconel-718. It is also well known that surface roughness along with residual stress and cold work (plastic deformation) also influence eddy-current measurements. In order to measure residual stress using nondestructive techniques, a goal of primary importance is the ability to decouple the effects surface roughness and cold work from the eddy-current measurements. Part of the procedure for doing this involves carrying out a stress-relief anneal and water quench; the idea being residual stress is reduced but surface roughness is unaffected. However, recent studies have found that surface topography is affected by this procedure. Surface roughness and eddy-current data (both in two-dimensions) have been gathered for In-718 specimens following a variety of treatments including shot peening and annealing. In addition, a convolution has been carried out such that changes in surface roughness (due to treatments) can be related directly to observed changes in the eddy-current response.---This material is based on work supported by NASA under award NAG-1-029-98.

**A Method to Eliminate Couplant-Dependent Variability in Acoustic Nonlinearity Measurements in Fatigued Components**

---Li Sun, **Salil S. Kulkarni**, Brian Moran, Sridhar Krishnaswamy, and Jan D. Achenbach, Center for Quality Engineering and Failure Prevention, Department of Mechanical Engineering, Northwestern University, IL 60208

---It is well-known that acoustic nonlinearity increases in many metallic components due to increased dislocation densities as fatigue cycling progresses. This suggests that a Structural Health Monitoring system can be developed based on sensors designed specifically to monitor ultrasonic nonlinearity and correlate that to material damage. Such sensors are to be permanently installed on the structure and measurements are made at various stages during the life-cycle of the component. Unfortunately, the bonding of the sensors to the component may degrade with time, leading to changes in the injected fundamental SAW and in turn in the generated second harmonic amplitudes, and this can potentially lead to very large scatter in the measurements. In this paper, a novel two-way measurement method that is insensitive to the couplant/bonding is proposed. Subject to the assumption that the component is the primary source of nonlinearity, it is shown that the proposed technique eliminates the couplant effects between the transducers and the specimen. Nonlinearity measurements on a fatigued aluminum alloy specimen are performed using both conventional and proposed techniques. The comparison is done by calculating the coefficient of variation (COV) of the nonlinearity parameter obtained separately with the two techniques. The COV of the nonlinearity parameter calculated using the proposed technique is approximately half of that calculated using conventional technique. This demonstrates that the proposed technique reduces the variability in the nonlinearity measurements in fatigued components.

**Surface Texture of Fretting Fatigue Damaged Surfaces of Shot Peened Titanium**

---**Sonia A. Martinez** and Mark P. Blodgett, Air Force Research Laboratory, Materials and Manufacturing Directorate, 2230 Tenth St., Suite 1, Wright Patterson Air Force Base, OH 45433; Schamachary Sathish, University of Dayton Research Institute, 300 College Park, Dayton, OH 45469-0127; Shankar Mall, Air Force Institute of Technology, Wright Patterson Air Force Base, OH 45433

---Fretting fatigue damage occurs at the contact between two surfaces, when a static load perpendicular to the interface and a cyclic load parallel to the surfaces are present. The fretting fatigue damage occurring on the surface is known to be responsible for initiation of surface breaking cracks and dramatic reduction of fatigue life of the materials and components. Many premature failures of the engine components of advanced fighter aircrafts have been attributed to fretting fatigue damage. Though fretting fatigue damage occurs at the surface, NDE techniques have limited success in detecting early stages of damage. This paper presents a methodology based on optical profiling of the surface to evaluate the progression of damage in fretting fatigue damaged specimens of shot peened Ti-6Al-4V. Surface topography measurements performed using a white light interference microscope were analyzed to identify the surface texture parameters sensitive to progressive damage. Results of the relation between the number of fretting fatigue cycles, surface texture parameters, residual stress and the changing microstructure are presented. Potential of the optical surface profiling as a nondestructive evaluation tool for characterization of fretting fatigue damage is discussed.

**Detection of Mechanical Damage Using Magnetic Flux Leakage**

---**Alex Rubinshteyn**, Vijay Babbar, and Lynann Clapham, Department of Physics, Engineering Physics & Astronomy, Queen's University, Kingston, Ontario, Canada

---Magnetic Flux Leakage (MFL) signals from pipeline dents have components due both to dent geometry and residual stress. MFL studies of dents were conducted using 1:1, 2:1 and 4:1 aspect ratio indenters with dent depths ranging from 3 to 7 mm. The radial, circumferential and axial components of the MFL dent signals were studied. Signal features that are largely due to residual stress were identified by comparing MFL signals before and after stress-relief annealing. Annealing also allowed MFL features that are largely due to dent geometry to be identified. The experimental work was accompanied by magnetic finite element modeling (FEM), and the causes of the MFL signal features were identified.

**Characterization of Cold Work in Nickel-Base Superalloys by Instrumented Nanoindentation**

---**Bin Xie**, Lugen Wang, and S. I. Rokhlin, The Ohio State University, Nondestructive Evaluation Program, Edison Joining Technology Center, 248 Arthur E. Adams Dr., Columbus, OH 43221; P. B. Nagy, University of Cincinnati, Department of Aerospace Engineering and Engineering Mechanics, 731 Rhodes Hall, Cincinnati, OH 45221-0070; M. P. Blodgett, Wright-Patterson AFB, Nondestructive Evaluation, Branch AFRL/MLLP, 2230 10<sup>th</sup> Street, Dayton, OH 45433

---Nondestructive evaluation of residual stresses and of residual stress relief in service conditions has great significance for reliability of turbine engine components. It is important to achieve better fundamental understanding of relations between nondestructive signature and material properties such as hardness, plasticity, cold-work and residual stress. In this work a nanoindentation technique is explored to determine the micromechanical properties and their relation to different levels of cold work in Ni based superalloys. Also the relations between inhomogeneities of electrical conductivity in nickel-base superalloys and microscale elasto-plastic properties have been investigated. Results of instrumented nanoindentation measurements of hardness and effective modulus in different Ni based superalloys are reported as it related to above stated applications. Also our recent progress on development of an approach to determine local mechanical properties (Young's modulus  $E$ , yield stress  $f_n$  and strain hardening exponent  $n$ ) from nanoindentation tests as is done from uniaxial tensile/compression experiments is going to be reported. This is based on inversion of nanoindentation data and elasto-plastic properties reconstruction by utilizing finite element simulations and developed explicit scaling functions.

# *Session 26*

Thursday, August 4, 2005

## SESSION 26

### **EDDY CURRENT PROBES AND APPLICATIONS** **Moulton Union Main Lounge**

- 8:30 AM**      **A Comparison of Conventional and Hall-Device-Based Eddy-Current Sensors Using Experimental Measurements and Finite-Element Calculations**  
---M. J. Johnson, J. Henderkott, C. Lee, and J. Knopp, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011
- 8:50 AM**      **Wireless Eddy Current Probe for Engine Health Monitoring (Phase II)**  
---M. S. Reid, B. Graubard, B. Reed, R. J. Weber, J. A. Dickerson, Iowa State University, Electrical and Computer Engineering, 2215 Coover, Ames, IA 50011
- 9:10 AM**      **Eddy Current Flexible Probe for Complex Geometries**  
---C. Gilles-Pascaud and J.-M. Decitre, CEA, CEA Saclay, Service SYSSC batiment 611, 91191 Gif-sur-Yvette, France; G. Cattiaux, IRSN, DES/SAMS, 92262 Fontenay-aux-Roses, France
- 9:30 AM**      **A New Eddy-Current Self-Compensating Probe for Testing Conducting Plates**  
---S. Gratkowski, M. Komorowski, and T. Chady, Electrical Engineering Faculty, Szczecin University of Technology, Szczecin, Poland
- 9:50 AM**      **Surface Flaw Testing of Weld Zone by a New Eddy Current Probe**  
---H. Hoshikawa, Nihon University, Izumicho Narashino, Chiba 275-8575, Japan
- 10:10 AM**      **Coffee Break**
- 10:30 AM**      **A Simple Model for Eddy Current Surface Crack Inspections and Its Application to Weld Inspection**  
---T. Theodoulidis, Department of Engineering and Management of Energy Resources, University of West Macadonia, Greece; J. Bowler, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011
- 10:50 AM**      **Thickness Measurement of Material by Using Pulsed Eddy Current**  
---J. J. Sung, J. E. Jang, and M. K. Kang, Research and Development Center, Sae-an Engineering Corporation, Seoul, Korea; D. M. Suh, Department of Electrical and Broadcast, Kunjang College, Kunsan, Korea
- 11:10 AM**      **Detection Hidden Cracks on Aircraft Lap Joints with GMR Based Eddy Current Technology**  
---J. K. Na and M. A. Franklin, Advanced NDI Wyle Labs, 2700 Indian Ripple Road, Dayton, OH 45440; J. R. Linn, Boeing Company, 707,727,737,757 Service Engineering DNT, Tukwila, WA 98108
- 11:30 AM**      **Comparison of Absolute and Differential ECT Signal Characteristics Generated by Tube Defects Near Support Plate**  
---Y.-K. Shin and Y.-T. Lee, Kunsan National University, School of Electronic and Information Engineering, San 68, Miryang-Dong, Kunsan, Chonbuk, 573-701, Korea
- 11:50 AM**      **Electrical Circuit Model of an Eddy Current System for Computing Multiple Parameters**  
---A. Siddoju, S. Sathish, and R. T. Ko, University of Dayton Research Institute, Center of Materials Diagnostics, Structural Integrity Division, 300 College Park, Dayton, OH 45469-0127; M. P. Blodgett, Air Force Research Laboratory, Metals, Ceramics, and NDE Division, Wright-Patterson Air Force Base, Dayton, OH 45469
- 12:10 PM**      **Lunch**

**A Comparison of Conventional and Hall-Device-Based Eddy-Current Sensors Using Experimental Measurements and Finite-Element Calculations**

---**M J. Johnson**, J. Henderkott, C. Lee, and J. Knopp, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011

---There are a number of fundamentally different approaches to eddy-current nondestructive evaluation. For example, one has the choice of simple induction coils (absolute probes), driver-pickup sensors or probes consisting of Hall or GMR sensors. In addition, there is an increasing availability of pulsed- or transient-based systems. With such a wide variety of techniques it becomes somewhat difficult to carry out a direct performance comparison. By combining model-based predictions with experimental measurements it is possible to go some way towards the development of a tool for determining the optimum configuration for the detection of a particular type of defect. The key is to use experimental measurements in order to determine noise levels and other factors detrimental to detection capability. These figures can then be factored into numerical predictions such that the detectability for other defects can be estimated.---This work was performed at the Center for NDE at Iowa State University with funding from the Air Force Research Laboratory on contract FA 8650-04-C-5228.

**Wireless Eddy Current Probe for Engine Health Monitoring (Phase II)**

---Michael S. Reid, Ben Graubard, Brian Reed, **Robert J. Weber**, and Julie A. Dickerson, Iowa State University, Electrical and Computer Engineering, 2215 Coover, Ames, IA 50011

---This is a continuing project in the development of a wireless eddy current probe (ECP) for on-wing inspection. The first phase prototype, an analog system, was successfully demonstrated in a F100 PW-220 engine without external cabling, except for dc power, at the Air National Guard overhaul facility in Des Moines, Iowa. The second phase of this project is to improve the performance of phase one with a digital wireless eddy current probe system. Phase II will provide improved detection sensitivity, longer battery life, and a smaller package. This will allow for engine preventative maintenance to carry out on-wing inspections, which should reduce the servicing cost. Phase II reduced the driver and sensor circuitry of a commercial eddy current instrument to an integrated circuit. The output of the eddy current probe circuitry is digitized by a dual channel 16-bit A/D converter off chip. An external FPGA provides timing signals for the ECP circuitry and the A/D converter. Additionally, the FPGA controls the calibration of the ECP circuitry and the burst circuitry for the transmitter. Incorporated on the same integrated circuit is a dual-frequency, QPSK, burst transmitter. A receiver built with discrete components will recover and demodulate the dual band signals that will allow a computer to process and display the results.---This work was performed by the Center for NDE and Electrical and Computer Engineering Department at Iowa State University and by Pratt & Whitney with funding from NASA Glenn Research Center under contract number NAS3-98005, task order number 21.

**Eddy Current Flexible Probe for Complex Geometries**

---**Catherine Gilles-Pascaud** and Jean-Marc Decitre, CEA, CEA Saclay, Service SYSSC batiment 611, 91191 Gif-sur-Yvette, France; Gérard Cattiaux, IRSN, DES/SAMS, 92262 Fontenay-aux-Roses, France

---The inspection of nuclear components might be very challenging for NDT when the geometry of a part is complex. In this paper, some developments done in the framework of a joined R&D program between CEA and IRSN are presented. The first application presented is the enhancement of the detection of outer diameter flaw in steam generator tubing in the expansion transition area. The second application studies the feasibility of pipes inspection both from the inner and outer diameter. In both cases, the use of eddy current sensor mounted or etched on a flexible substrate is presented and discussed. It is shown that the flexibility given to the sensors reduces greatly the lift-off noise, optimizes the coupling and thus enhance the detection of flaws. It is also shown that this technology is well adapted to the design of eddy current array probes, which could reduce the inspection time.

**A New Eddy-Current Self-Compensating Probe for Testing Conducting Plates**

---Stanislaw Gratkowski, Mieczyslaw Komorowski, and **Tomasz Chady**, Electrical Engineering Faculty, Szczecin University of Technology, Szczecin, Poland

---Eddy-current methods of non-destructive testing are used extensively for detecting defects in metallic structures. This paper deals with a new eddy-current self-compensating probe for testing conducting plates. The probe was developed at the Szczecin University of Technology, Szczecin, Poland. It consists of two exciting coils connected differentially. Between these coils, around a ferrite core, a signal coil is placed. The system of coils is situated inside an electromagnetic screen made of aluminum. One exciting coil is held in contact with the specimen. Over the second exciting coil there is a compensating replaceable ring made of the same material as that of the specimen. If there is no influence of a defect, the transducer is in equilibrium. The probe can sense only changes in the material under test while canceling out noise and other unwanted signals that affect both fluxes generated by the excitation coils. A simple mathematical model of the probe, as well as results of measurements for different frequencies of the exciting current, are given.

**Surface Flaw Testing of Weld Zone by a New Eddy Current Probe**

---**Hiroshi Hoshikawa**, Nihon University, Izumicho Narashino, Chiba 275-8575, Japan

---Weld zones are difficult to conduct eddy current testing because of large noise generated by the shape variation of the reinforcement. The authors have studied eddy current testing of weld zone using a new probe which generates very small lift-off noise in principle. The probe is comprised of a large tangential exciting coil and a pair of tangential detecting coils arranged in a line on both sides of the exciting coil. The detecting coils pick up parallel component of the eddy current to themselves. Thus the probe detects flaws parallel to the detecting coils in principle. The authors conducted experiments of eddy current testing by the new probe. The probe can detect transversal flaws in weld zone with small noise when the detecting coils are arranged perpendicular to the weld line. The probe can also detect longitudinal flaws by scanning three times along the weld with the detecting coils arranged parallel to the weld line. Thus the new probe has possibility of conducting eddy current testing of weld zone over anti-corrosion painting.

**A Simple Model For Eddy Current Surface Crack Inspections and Its Application To Weld Inspection**

---**Theodoros Theodoulidis**, Department of Engineering and Management of Energy Resources, University of West Macedonia, Greece; John Bowler, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011

---We present a modeling tool for eddy current surface crack inspections based on the combination of an existing thin-skin crack field theory and a general representation for arbitrarily shaped coils above a conductive half-space. The thin-skin model applies to the high frequency regime in which the skin depth is small compared with the crack depth. Therefore, it is well suited for simulating surface crack inspections since the vast majority of these are performed at very high frequencies. Calculation of the coil impedance change due to the crack requires knowledge of the incident magnetic field on the conductor surface in the absence of the crack. This incident field can be calculated either (i) analytically, using closed form expressions that include the effect of tilt and can accommodate, orthogonal, racetrack, and double-D coils as well as ferrite-cored coils; or (ii) numerically in the case of complex coil shapes by utilizing the 2D fast Fourier transform in conjunction with the Biot-Savart law. The result is a reliable representation of eddy current surface crack inspection that is modeled both rapidly and with reasonable accuracy. In the present work, we use a version of the thin-skin model for a long crack and focus our study on probes designed for crack detection in ferritic steel welds.

**Thickness Measurement of Material by Using Pulsed Eddy Current**

---**Je Joong Sung**, Ji Eun Jang, and Moo Kyeong Kang, Research and Development Center, Sae-an Engineering Corporation, Seoul, Korea; Dong Man Suh, Dept. Electrical & Broadcast, Kunjang College, Kunsan, Korea

---The pulsed eddy current system has been developed to control a thickness of cooper tube and submitted the multi-pointing method to select a criteria which could be obtained the thickness by the period of resistivity on the PEC transient signals. Although conventional eddy current testing is powerful method to detect flaws of cooper tube in online processing, it is difficult to measure the thickness of the tube. Eddy current density has changed its magnitude with distance from the surface. Whereas, the PEC has been widely employed for deep depth inspection of structures such as plate, tubes. In this paper, we used the pulsed eddy current technique to overcome the limitation of thickness measurement and studied multi-pointing method to evaluate the thickness with variation of resistivity. Experimental results showed that the thickness could be controlled in range of  $\pm 5 \mu\text{m}$ .

**Detection Hidden Cracks on Aircraft Lap Joints with GMR Based Eddy Current Technology**

---**Jeong K. Na** and Mark A. Franklin, Advanced NDI Wyle Labs, 2700 Indian Ripple Road, Dayton, OH 45440; John R. Linn, Boeing Company, 707, 727, 737, 757 Service Engineering DNT, Tukwila, WA 98108

---Cracks occurring on commercial aircraft fuselage lap joints made of aluminum alloys often caused by scribe lines made during the removal process of moisture sealing materials between two layers. These cracks on thinner bottom layers can be obscured by thicker top plates with paint. A portable GMR (Giant Magnetoresistive) sensor based eddy current system (patent pending) has been developed and tested on several simulated aircraft lap joint samples with EDM notches. Various thicknesses of layers are used to simulate the test as used on different combinations of lap joints. Length and depth of cracks are important factors to be measured quantitatively. Test results are presented to show the relationship between the output signals of GMR system and the two important crack parameters.

**Comparison of Absolute and Differential ECT Signal Characteristics Generated by Tube Defects Near Support Plate**

---**Young-Kil Shin** and Yun-Tai Lee, School of Electronic and Information Engineering, Kunsan National University, San 68, Miryong-Dong, Kunsan, Chonbuk, 573-701, Korea

---Absolute and differential eddy current signals from various defects in the steam generator tube are numerically computed and their signal slope characteristics are investigated. The signal variations due to increased frequencies are also observed. Based on the accumulated knowledge, the analysis of mixed signal is attempted that includes the effect of ferromagnetic support plate. For the signal prediction, axisymmetric finite element modeling is used and this leads us to the slope angle analysis of the signal. Results show that differential signals are useful for locating the position of a defect under the support plate, while absolute signals are easy to presume and interpret even though the effect of support plate is mixed. Combined use of these two types of signals will be helpful to accomplish a reliable inspection.

**Electrical Circuit Model of an Eddy Current System for Computing Multiple Parameters**

---**Ajay Siddoju**, Shamachary Sathish, and Ray T. Ko, University of Dayton Research Institute, Center of Materials Diagnostics, Structural Integrity Division, 300 College Park, Dayton, OH 45469-0127; Mark P. Blodgett, Air Force Research Laboratory, Metals, Ceramics, and NDE Division, Wright-Patterson Air Force Base, Dayton, OH 45469

---An electrical circuit based model for eddy current sensor system has been developed using commercial electrical engineering software. The model allows incorporation of individual characteristics of the signal generator, cable, eddy current sensor and the sample under test. The flexibility allows computation of the most often experimentally measured quantities like, magnitude and phase of the voltage and current, as well as changes in the frequency of the system. Computational results obtained by sweeping the frequency from a few kHz to several hundred MHz, of the magnitude and phase of the voltage, current and the frequency shift under normal and test conditions are presented. Analysis of the sensitivity of each of the measurable eddy current parameters due to change in test conditions are discussed. A comparison between results of computed multiple parameters and experimental measurements are presented.

## *Session 27*

Thursday, August 4, 2005

## SESSION 27

### UT TRANSDUCERS, DEVICES, AND FIELDS Moulton Union Lower Level

- 8:30 AM**      **Aluminum Nitride Piezoelectric Transducers for Ultra-High Temperature Ultrasonics**  
---**J. R. Sebastian**, M. T. Frede, and D. A. Stubbs, University of Dayton Research Institute, 300 College Park, Dayton, OH 45469-0121
- 8:50 AM**      **Residual Bias Phenomenon in Air-Coupled Ultrasonic Capacitive Film Transducers**  
---**S. D. Holland**<sup>1</sup>, J. Song<sup>1</sup>, and D. E. Chimenti<sup>1,2</sup>, Iowa State University, <sup>2</sup>Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011; J. Song<sup>2</sup>, <sup>2</sup>Department of Aerospace Engineering
- 9:10 AM**      **Measurement of Absolute Acoustic Strain by Non-Contact Techniques**  
---**S. B. Jayaraman**, M. K. Pedrick, and B. R. Tittmann, The Pennsylvania State University, Department of Engineering Science and Mechanics, University Park, PA 16802
- 9:30 AM**      **A Preliminary Round-Robin Study of Ultrasonic Phased-Array Transducer Variability**  
---**J. H. Friedl**<sup>1</sup>, R. A. Roberts<sup>1</sup>, F. J. Margetan<sup>1</sup>, J. A. Umbach<sup>2</sup>, A. Degtyar<sup>2</sup>, W. Hassan<sup>3</sup>, F. W. Vensel<sup>3</sup>, and R. B. Thompson<sup>1</sup>, <sup>1</sup>Iowa State University, Center for Nondestructive Evaluation, Ames, IA 50011; <sup>2</sup>United Technologies Pratt & Whitney, East Hartford, CT 06108; <sup>3</sup>Honeywell Engines, Systems & Services, Phoenix, AZ 85034
- 9:50 AM**      **Optimization of Mirrors for the Ultrasonic Inspection of Complex-Shaped Components Using Standard Transducers**  
---**M. Spies**, Physical Basics Department, Fraunhofer Institute for Nondestructive Testing IZFP, 66123, Saarbruecken, Germany; J. Bamberg, Department Materials and Process Engineering, MTU Aero Engines GmbH, 80995 Munich, Germany
- 10:10 AM**      **Coffee Break**
- 10:30 AM**      **Optimization of Transmission Field for DDF-Based Phased-Array Inspection**  
---R. Roberts<sup>1</sup> and **A. Lavrentyev**<sup>2</sup>, and A. Degtyar<sup>2</sup>, <sup>1</sup>Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011; <sup>2</sup>Pratt and Whitney, East Hartford, CT 06108
- 10:50 AM**      **Measurement of Bulk Velocity and Attenuation in Fluids and Particle Suspensions Using the Quasi-Scholte Mode**  
---**F. B. Cegala**, P. Cawley, and M. J. S. Lowe, Imperial College, Department of Mechanical Engineering, Room 564, Exhibition Road, London, SW7 2AZ, United Kingdom
- 11:10 AM**      **Selective Excitation of Lamb-Waves for Delamination Detection in Composites**  
---**G. Petculescu**, S. Krishnaswamy, and J. D. Achenbach, Northwestern University, Catalysis Building, Room 325, 2137 Tech Drive, Evanston, IL 60208-3020
- 11:30 AM**      **Modeling the Beam Fields of Circular and Rectangular, Flat and Focused Transducers Using the Gaussian Beam Superposition Technique**  
---**M. Spies**, Physical Basics Department, Fraunhofer Institute for Nondestructive Testing IZFP, 66123 Saarbruecken, Germany
- 11:50 AM**      **Recent Advances in Modeling All the Components of an Ultrasonic NDE System**  
---**L. W. Schmerr, Jr.**<sup>1,2</sup> and A. Lopez-Sanchez<sup>1,2</sup>, <sup>1</sup>Center for NDE and the <sup>2</sup>Dept. of Aerospace Engineering, Iowa State University, Ames, IA 50011
- 12:10 PM**      **Lunch**

**Aluminum Nitride Piezoelectric Transducers for Ultra-High Temperature Ultrasonics**

---**James R. Sebastian**, Michael T. Frede, and David A. Stubbs, University of Dayton Research Institute, 300 College Park, Dayton, OH 45469-0121

---Oriented polycrystalline films of Aluminum Nitride (AlN), a naturally piezoelectric material, have been successfully used to construct ultrasonic transducers capable of use from room temperature to above 700C at frequencies in the 15-30 MHz range. Anticipated uses emphasize flaw detection and health monitoring in power generation, chemical processing, and other high temperature process equipment. Permanent installation or portable use by inspectors is possible depending on the application; high temperature transducer design is highly application dependent. The sensitivity of these transducers is below that of transducers constructed from commonly used piezoceramics but this disadvantage is partially mitigated by the high excitation voltages tolerated by the transducers.

**Residual Bias Phenomenon in Air-Coupled Ultrasonic Capacitive Film Transducers**

---**Stephen D. Holland**<sup>1</sup>, Junho Song<sup>1</sup>, and D. E. Chimenti<sup>1,2</sup>, Iowa State University, <sup>2</sup>Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011; Junho Song<sup>2</sup>, <sup>2</sup>Department of Aerospace Engineering

---Air-coupled capacitive film transducers made with metallized Mylar films exhibit a phenomenon whereby the films accept and retain a residual electrostatic charge. Charge transfers from the conductive backplate and collects on the non-metallized side of the film. The charged films therefore are electrostatically attracted to the transducer backplate even with no applied voltage bias. These transducers operate by transforming motion of a charged capacitor formed by the backplate and film into a current which appears at the electrodes of the device. Typically, an externally applied bias voltage is needed to charge the capacitor. With the residual bias effect, these air-coupled capacitive film transducers can be used like conventional piezoelectric transducers with no biasing required. We discuss the underlying physics of the residual bias phenomenon, and its implications for the operation of air-coupled film transducers.

### **Measurement of Absolute Acoustic Strain by Non-Contact Techniques**

---**Subash B. Jayaraman**, Michael K. Pedrick, and Bernhard R. Tittmann, Department of Engineering Science and Mechanics, The Pennsylvania State University, University Park, PA 16802

---Some ultrasonic applications require non-contact techniques because the target material is not easily accessible. In such cases laser-based and air-coupled ultrasonic techniques play a major role but commonly significant transmission loss is known to occur especially at higher frequencies. Therefore, it becomes imperative to know the amount of absolute acoustic strain achieved for a given application. In this paper, we report on the use of laser-based techniques to measure absolute strain on the face of vibrating rods excited under various scenarios. These include contact and air-coupled excitation at frequencies at resonance, as well as a factor of 100 below and above the resonance. A variety of materials are considered including Al and steel. The limit of our out-of-plane displacement measurement appears to be about 5 nanometers. Strains as high as  $10^{-6}$  have been obtained. The paper will describe the details of the ultrasonic techniques and some of the applications. The data are compared to theoretical and simulated strain calculations.

### **A Preliminary Round-Robin Study of Ultrasonic Phased-Array Transducer Variability**

---**Jon H. Friedl**<sup>1</sup>, Ronald A. Roberts<sup>1</sup>, Frank J. Margetan<sup>1</sup>, Jeffrey A. Umbach<sup>2</sup>, Andrei Degtyar<sup>2</sup>, Waled Hassan<sup>3</sup>, Frederick W. Vensel<sup>3</sup>, and R. Bruce Thompson<sup>1</sup>, <sup>1</sup>Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011; <sup>2</sup>United Technologies Pratt & Whitney, East Hartford, CT 06108; <sup>3</sup>Honeywell Engines, Systems & Services, Phoenix, AZ 85034

---Phased-array transducers are playing an increasing role in ultrasonic inspections, and methods for comparing the performances of such transducers are needed. In this paper we discuss a preliminary set of performance tests designed to document the operational capabilities of two types of 10-MHz phased array transducers. "Type-I" transducers have 15 elements, including a focused, circular, removable center element (RCE) and 14 outer planar, concentric annular rings. "Type-II" transducers have 110 elements with a compound spherical surface to promote focusing. A series of tests were performed to measure such characteristics as peak response amplitude from a FBH target, center frequency, bandwidth, and beam-diameter at the focus. These could be measured in essentially the same way for both the RCE transducer and the Type-I or Type-II phased elements driven in concert to form a focused beam. Additional tests were specific to either the RCE or the phased array. For phased-arrays, these included an examination of timing variability between individual elements of the array to assess uniformity in manufacturing. Round-robin studies using a fixed test protocol were performed at Iowa State University (Ames, IA), United Technologies Pratt & Whitney (East Hartford, CT), and Honeywell Engines, Systems and Services (Phoenix, AZ). Results of tests on six Type-I and three Type-II transducers will be discussed.---This material is based upon work supported by the Federal Aviation Administration under contract #DTFA03-98-D-00008, Delivery Order #IA029, and performed at Iowa State University's Center for NDE as part of the Engine Titanium Consortium, through the Airworthiness Assurance Center of Excellence.

**Optimization of Mirrors for the Ultrasonic Inspection of Complex-Shaped Components Using Standard Transducers**

---**Martin Spies**, Physical Basics Department, Fraunhofer Institute for Nondestructive Testing IZFP, 66123, Saarbruecken, Germany; Joachim Bamberg, Department Materials and Process Engineering, MTU Aero Engines GmbH, 80995 Munich, Germany

---Ultrasonic inspection of components of complex geometry often suffers from loss of sensitivity, beam distortions and beam misorientations if the transducer is not perfectly matched to the specimen. A procedure which allows to optimize single and multiple element transducers to ensure a proper focusing of the beam field in the range of interest - depending on the specific inspection configuration under concern - has been presented recently. The simulation method is based on delay time calculation for multiple element transducers and employs a superposition technique for beam field calculation. However, the inspection of components with complex shapes can suffer from the fact that the area of interest can not be properly insonified due to restricted access. In such cases the use of mirrors to turn the ultrasonic beam onto the component's surface has proven to be efficient. In this contribution, we report on the optimization of such a mirror - applying the above mentioned simulation approach - where its shape has been designed to compensate the influence of the curved component surface on the ultrasonic beam field and to additionally achieve a focusing of the beam in the area of interest. Simulation as well as experimental results are shown for an engine component, where inspection has been performed applying an unfocused, circular transducer at 25 MHz frequency. The presented approach is particularly useful since commercial off-the-shelf transducers can be applied rather than specifically designed probes. On the other hand, the specifically matched mirrors can usually be easily produced in the machine shop.

**Optimization of Transmission Field for DDF-Based Phased-Array Inspection**

---Ronald Roberts<sup>1</sup> and **Anton Lavrentyev**<sup>2</sup>, and Andrei Degtyar<sup>2</sup>, <sup>1</sup>Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011; <sup>2</sup>Pratt and Whitney, East Hartford, CT 06108

---Phased array based ultrasonic inspections are being used on an ever-wider scale in industrial applications. One of the advantages phased array inspections provide is a dynamic-depth focusing (DDF) allowing an effective extension of focus depth. The use of DDF may potentially lead to decreased inspection times and costs for manufactures while maintaining the required sensitivity. The DDF is based on a dynamic re-focusing on the reception leading to a relatively uniform apparent acoustic field through the focus depth. A further improvement of this uniformity may be achieved by optimizing the acoustic field excited on transmission. This paper discusses various transmission optimization techniques aimed at creating a uniform apparent field and shows corresponding experimental results. Visualization tools for optimizing transmission field are also discussed.

**Measurement of Bulk Velocity and Attenuation in Fluids and Particle Suspensions Using the Quasi-Scholte Mode**

---**Frederic B. Cegala**, Peter Cawley, and Mike J. S. Lowe, Imperial College, Department of Mechanical Engineering, Room 564, Exhibition Road, London, SW7 2AZ, United Kingdom

---Conventional ultrasonic bulk property measurements in test cells are difficult to carry out in in-process applications where stirring mechanisms or other geometrical features are present. The need for precise geometrical alignment of transducers makes test cells expensive and the immediate contact of the fluid and the transducers complicates measurements at high temperatures and in harsh environments. An alternative method for fluid bulk property measurements is to employ a "dipstick" that is inserted into the liquid of interest; a propagating interface wave, called the quasi-Scholte mode, is used to extract the necessary information. The propagation velocity and attenuation of the quasi-Scholte mode is strongly influenced by the properties of the fluid that surrounds the "dipstick". The sensitivity of the quasi-Scholte mode to the liquid parameters is presented. It is shown that small changes in velocity can be monitored successfully by measuring the bulk velocity of distilled water and a 5% ethanol-distilled water mixture over a range of temperatures. Measurements on different silica-suspensions are compared to experiments in a conventional ultrasonic test cell. The results show that the liquid bulk velocity can accurately be retrieved by means of the new approach and errors range within the uncertainties imposed by the experimental setup (0.5%). Initial results of fluid attenuation measurements using both techniques agree well in their qualitative trends but quantitative differences of up to 20% are encountered. The differences have been attributed to geometrical features of the current setup and a new system is being designed. The method is well suited for rapid fluid property measurements in harsh environments or in a bulk sample. The transducers are separated from the measurement area by the "dipstick"; the construction is inexpensive, very easily moved and can be inserted into vessels that contain mechanical stirrers.

**Selective Excitation of Lamb-Waves for Delamination Detection in Composites**

---**Gabriela Petculescu**, Sridhar Krishnaswamy, and Jan D. Achenbach, Northwestern University, Catalysis Building, Room 325, 2137 Tech Drive, Evanston, IL 60208-3020

---It has been shown that many delaminations in layered composites are missed when lower Lamb modes (e.g. s<sub>0</sub>) are used for investigation. This is due to an intrinsic characteristic of the lower modes in layered materials, namely the multiple zero-stress values at specific interfaces within the thickness of the laminate. In order to be able to probe all interfaces within a laminate higher order modes, with a more complex stress-through-thickness distribution, need to be employed. Conventional methods for Lamb-wave generation can only produce distinct lower modes, since only in the low-frequency range where a small number of modes exist they can be separated based on their significantly different group velocities. We are using Lamb-wave sensors which can selectively excite/detect any desired mode by imposing a unique wavelength (more specifically, a narrow-band spatial frequency range). The sensors' design, based on a periodic array of coherent piezoelectric sources, relates directly to the details of the dispersion curves of the substrate material, which need to be determined in advance. We have tested the sensors functionality on Aluminum and further applied the method to carbon-epoxy laminates. Results obtained on the excitation and detection of specific Lamb modes in various carbon-epoxy laminate geometries will be presented. This work is supported by the Federal Aviation Administration.

**Modeling the Beam Fields of Circular and Rectangular, Flat and Focused Transducers Using the Gaussian Beam Superposition Technique**

---**Martin Spies**, Physical Basics Department, Fraunhofer Institute for Nondestructive Testing IZFP, 66123 Saarbruecken, Germany

---Beam field modeling using the superposition of Gaussian beams usually relies on the Gaussian beam coefficients determined by Wen & Breazeale (W&B) for a ten-beam formulation. However, since these coefficients have been determined for a ka-value of 107.8 (wave number times transducer radius), it is in some cases advisable to use other sets of coefficients. This especially holds when the beam fields of focused transducers have to be taken into account. While the usual approach to determine the coefficients is based on a numerically expensive least-squares optimization, an efficient approach can be found in literature, which replaces iterative optimization by a polynomial root-finding problem. It can be applied to field profile data obtained at the near-field length of flat transducers or in the focal point of focused transducers. In this contribution, these reference profiles are determined using the point source superposition technique (GPSS) which is exact as far as the modeling of transducer-generated beam fields is concerned. For modeling rectangular transducers, a formulation has recently been presented in the literature, which reduces the Fresnel field integral to the superposition of a set of two-dimensional Gaussian beams. While the authors rely on the W&B coefficients, the results presented here are obtained employing two different sets of coefficients, individually determined in view of the transducers under concern. To illustrate the efficiency of the extended Gaussian beam superposition technique (GBS) the (monochromatic) beam fields of various commercial transducers are presented in comparison with exact GPSS results.

**Recent Advances in Modeling All the Components of an Ultrasonic NDE System**

---**Lester W. Schmerr Jr.**<sup>1,2</sup> and Ana Lopez-Sanchez<sup>1,2</sup>, <sup>1</sup>Center for NDE and the <sup>2</sup>Dept. of Aerospace Engineering, Iowa State University, Ames, IA 50011

---We have previously developed an electroacoustic measurement model that contains models of all the components of an ultrasonic flaw measurement system including the electrical and electromechanical components such as the pulser/receiver, cabling, and transducers. These component models can be combined with models of the acoustic/elastic wave propagation and scattering processes present to synthesize the measured output voltage signal. Recently, we have developed a new and highly simplified method for characterizing the transducer in this measurement model. That advance now makes it possible to also more easily simulate the measured output voltage, as we will demonstrate by comparing our model predictions with experimental waveforms. We will also discuss our progress in developing a "virtual" pulser/receiver that is capable of simulating the behavior of a real instrument and the effects of instrument setting on the system response.---This work was supported by the NSF Industry/University Cooperative Research Center at Iowa State University.

# *Session 28*

Thursday, August 4, 2005

## SESSION 28 - POSTERS

**NONLINEAR TECHNIQUES, UT TRANSDUCER AND ARRAYS,  
DETECTION AND SIZING, MATERIAL PROPERTIES, COATINGS AND BONDS,  
VISCOUS MATERIALS, ELECTROMAGNETIC AND THERMAL METHODS,  
DEGRADATION MECHANISMS, NEW TECHNIQUES, FLUORESCENT PENETRANTS**  
Morrell Gymnasium

1:30 PM

### Nonlinear Techniques

#### **Detection of a Closed Crack by Nonlinear Acoustics Using Ultrasonic Transducers**

---S. Hirata and T. Sugiura, Keio University, Mechanical Engineering, 3-14-1 Hiyoshi, Kohoku, Yokohama, Kanagawa 223-8522, Japan

#### **Simulation of Non-Linear Ultrasonic Wave Through an Interface Including Imperfections**

---K. Nakahata, Ehime University, Department of Civil and Environmental Engineering, Ehime, Japan; S. Hirose, Department of Mechanical and Environmental Informatics, Tokyo Institute of Technology, Tokyo, Japan

### UT Transducers and Arrays

#### **Characterization of an Ultrasonic Transducer in a Pulse-Echo Setup**

---A. L. Lopez-Sanchez and L. W. Schmerr, Jr., Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011

#### **Surface Wave Testing of a Flaw by Electromagnetic Acoustic Transducers**

---T. Ohya and T. Sugiura, Keio University, Mechanical Engineering, Yokohama, Kanagawa, Japan

#### **A Spherically Focused Air-Coupled Capacitive-Foil Transducer**

---J. Song<sup>1,2</sup>, S. D. Holland<sup>1</sup> and D. E. Chimenti<sup>1,2</sup>, <sup>1</sup>Iowa State University, Center for NDE, Applied Sciences Complex II, Ames, IA 50011; <sup>2</sup>Department of Aerospace Engineering, Iowa State University, Ames, IA 50011

#### **Flexural Torsional Guided Wave Pipe Inspection**

---Z. Sun, GE Global Research Center KWD-259B, One Research Circle, Niskayuna, NY 12309; L. Zhang and J. L. Rose, The Pennsylvania State University, Engineering Science and Mechanics Department, University Park, PA 16802

#### **Phased Array Inspection of Titanium Disk Forgings Using Mirrors to Compensate for Curved Entry Surfaces**

---H. Friedl, R. A. Roberts, and R. B. Thompson, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011

#### **Use of Expanded Multi-Gaussian Beam Model to Predict Radiation Beam Fields from a Phased Array Ultrasonic Transducer**

---J.-S. Park, H.-J. Kim, and S.-J. Song, Sungkyunkwan University, School of Mechanical Engineering, 300 Chunchun-dong, Jangan-gu, Suwon 440-746, Korea

#### **Particle Size and Concentration Studies of Solid-Liquid Suspensions Utilizing Ultrasonic Backscattering and Attenuation Measurements**

---P. D. Panetta, Pacific Northwest National Laboratory, 902 Battelle Boulevard, Richland, WA 99352

Thursday, August 4, 2005

### Detection and Sizing

#### **Characterization of Subsurface Defects in Ceramic Rods by Laser Scattering and Fractography Methods**

---J. M. Zhang and **J. G. Sun**, Energy Technology Division, Argonne National Laboratory, Argonne, IL 60439; M. J. Andrews, A. Ramesh, J. S. Tretheway, D. M. Longanbach, Caterpillar Inc., Mossville, IL 61552

#### **Hole Enlargement Measurement in Carbon Steel and Seacure Tube**

---**Y. Yu**, N. Nguyen, A. Shatat, and D. Russell, Russell NDE Systems, Inc., 4909 – 75 Avenue, Edmonton, Alberta T6B 2S3, Canada

#### **A Modified Remote Field Eddy Current Method for Imaging Defects in Concentrically Arranged Steel Tubes**

---**G. Miller**, H. Hussin, B. Fernandes, M. Zaid, P. Gaydecki, and F. El-Madaani, University of Manchester, School of Electrical and Electronic Engineering, P. O. Box 88, Manchester M60 1QD, United Kingdom

#### **Reconstruction of Cracks from Eddy Current Signals Using Genetic Algorithm and Fuzzy Logic**

---**R. Sikora** and P. Baniukiewicz, Szczecin University of Technology, Chair of Theoretical Electrotechnics and Computer Science, al. Piastow 17, 70-310 Szczecin, Poland

#### **Circumferential Defect Sizing in Pipe Using an Ultrasonic Guided Wave Focusing Technique**

---**J. Mu**, L. Zhang, and J. L. Rose, Penn State University, Department of Engineering Science and Mechanics, University Park, PA 16802; J. Spanner, Electric Power Research Institute NDE Center, Charlotte, NC 28216

### Material Properties

#### **Estimates of Signal-to-Microstructural-Noise Ratios in Ultrasonic Inspections of Metals**

---**F. J. Margetan**, R. Roberts, and R. B. Thompson, Iowa State University, Center for Nondestructive Evaluation, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50122

#### **Estimation of the Single-Crystal Elastic Constants of Polycrystalline Materials from Back-Scattered Grain Noise**

---**P. Haldipur**, F. J. Margetan, and R. B. Thompson, Iowa State University, Center for NDE Evaluation, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011

#### **Evaluation of Surface Finish in Machined Parts by Ultrasonics**

---**V. Jagasivamani** and A. C. Smith, Hampton University, School of Engineering & Technology, Hampton, VA 23668

#### **Applications of Barkhausen Emission Measurements for Characterization of Surface-Modified Materials**

---D. C. Jiles, C. C. H. Lo, E. R. Kinser, A. J. Barsic, and Y. Melikhov, Iowa State University, Center for NDE, Ames, IA 50011

#### **Multiple Scattering in Polycrystalline Materials**

---**G. Ghoshal** and J. A. Turner, University of Nebraska-Lincoln, Department of Engineering Mechanics, W 317.4 Nebraska Hall, Lincoln, NE 68588-0526

Thursday, August 4, 2005

**Measurement of Ultrasonic and Tensile Properties of Glass-Bead-Filled Polymers**

---**C. D. Thomson**, L. H. Pearson, and J. Johnson, NDE Research and Analysis Group, ATK Thiokol Inc., M/S 245C, P. O. Box 707, Brigham City, UT 84302

**Measurement and Modeling of Ultrasonic Attenuation in Aluminum Rolled Plate**

---**A. Li**, H.-J. Kim, F. J. Margetan, and R. B. Thompson, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011

**Nondestructive Evaluation of Irradiation Brittleness of SQV2A Steel by Using Magnetic Method**

---**M. Shiwa**, C. Weiyang, S. Nakahigashi, I. Komura<sup>1</sup>, NDE Center, Japan Power Engineering and Inspection Corporation, 14-I Benten-cho, Tsurumi-ku, Yokomama, 230-0044, Japan; K. Fujiwara and N. Takahashi<sup>2</sup>, <sup>2</sup>Department of Electrical and Electronic Engineering, Division of Industrial Innovation Sciences, The Graduate School of Natural Science and Technology, Okayama University, 3-1-1 Tsushima, Okayama 700-8580, Japan

**Plastic Foam Porosity Characterization by Air-Borne Ultrasound**

---**H. Hoffrén**, T. Karppinen, and **E. Haeggström**, University of Helsinki, Department of Physical Sciences, Helsinki, Finland

**A New Method for Electromechanical Coupling Factor Determination in Piezoelectric Materials**

---**E. K. Naimi**, Moscow State Institute of Steel and Alloys (Technological University), Physics Department, Moscow, Russia

**Measurement of Ultrasonic Properties in Glass-Bead-Filled Elastic and Viscoelastic Polymers**

---**J. Johnson**, L. H. Pearson, and C. Thomson, ATK Thiokol, Inc., Brigham City, UT 84302

**Coatings and Bonds**

**Interpretation of Back-Scattered Raleigh Surface Wave Signals from Diamond Coating Layers**

---**H.-J. Kim**, S.-J. Song, D.-J. Yang, and W. W. Wu, Sungkyunkwan University, School of Mechanical Engineering, 300 Chunchun-dong, Jangan-gu, Suwon 440-746, Korea

**Damage Monitoring of Thermal Spray Coatings by Laser Based Acoustic Emission**

---**M. Enoki**, The University of Tokyo, Department of Materials Engineering, Tokyo, Japan; K. Tomita, Industrial Technology Center of Fuku Prefecture, Fukui, Japan

**NDE for Characterizing Adhesive Joint Degradation Due to Corrosion**

---**P. Kumar**, J. C. Duke, and M. Hajj, Virginia Tech, Engineering Science and Mechanics, Blacksburg, VA 24061; M. Tillman, Naval Air Development Center, Patuxent River, MD; E. Todorov, Edison Welding Institute, Columbus, OH

Thursday, August 4, 2005

### Viscous Materials

#### **Simulation of the Transient Ultrasonic Waves in Viscoelastic Solid by Using Finite Elements**

---J. He, G. Chen, **X. R. Zhang**, and J. C. Chen, Nanjing University, Institute of Acoustics, #22 Hankou Road, Nanjing, Jiangsu, 210093, China (PRC)

#### **An Experimental Study of the Ultrasonic Properties of High-Viscous Silicone Fluids**

---L. Yu, D. A. Rebinsky, D. Fei, and M. W. Shockley, Caterpillar, Inc., (41) Technical Center – Bldg. E/854, P. O. Box 1875, Peoria, IL 61656-1875

#### **Burning Rate Measurement of Solid Propellant Using Ultrasound-Approach and Initial Experiments**

---S.-J. Song, **J. H. Jeon**, and H.-J. Kim, Sungkyunkwan University, School of Mechanical Engineering, 300 Chunchun-dong, Jangan-gu, Suwon 440-746, Korea; I.-C. Kim and J.-C. Yoo, Agency for Defense Development, Daejeon, Korea

### Electromagnetic and Thermal Methods

#### **Numerical Modeling of Profilometry ECT Signals from Tubesheet and Tube Expansion Area**

---Y.-K. Shin, S.-C. Song, and H.-S. Jung, Kunsan National University, School of Electronic and Information Engineering, San 68, Miryong-Dong, Kunsan, Chonbuk, 573-701, Korea; C.-J. Im, Korea Advanced Inspection Technology, P. O. Box 105, Taejon, 305-600, Korea; S.-S. Kang, Korea Institute of Nuclear Safety, 19, Kusong-Dong, Yusung-Ku, Taejon, 305-338, Korea

#### **Electromagnetic Testing of Magnetic Material by Rotating Uniform Eddy Current Probe**

---H. Hoshikawa, Nihon University, Izumicho Narashino, Chiba 275-8575, Japan

#### **Evaluation of Microstructure of Isothermally Aged 11Cr-3.5W-3Co Steel by Magnetic Coercivity Measurement**

---C. S. Kim, J. H. Kang, and **S. I. Kwun**, Korea University, Division of Materials Science and Engineering, Seoul, Korea; J. W. Byeon, University of Central Florida, Advanced Materials Processing and Analysis Center, Orlando, FL 32816

### Degradation Mechanisms

#### **Irradiation Degradation in Reactor Pressure Vessel Steels by Magnetic Techniques**

---K. Chang, Korea Atomic Energy Research Institute, Yuseon P. O. Box 105, Daejeon 305-600, Korea

#### **Degradation of Light Emitting Diodes Under the Action of Ultrasonic Vibration**

---E. K. Naimi, Moscow State Institute of Steel and Alloys (Technological University), Physics Department, Moscow, Russia; O. I. Rabinovich, Semiconductor Materials and Devices

#### **Tracking Fatigue Damage Development in 7075T6 Aluminum Prior to Crack Formation**

---B. Yoo, J. C. Duke, Jr., and M. Hajj, Virginia Tech, Engineering Science and Mechanics, Blacksburg, VA 24061

Thursday, August 4, 2005

**Evaluation of Thickness Reduction in a Thin Plate Using a Non-Contact Guided Wave Technique**

---I.-K. Park, Seoul National University, Department of Mechanical Engineering, Seoul, 139-743, Korea; H. Kim, Hanyang University, Graduate School, Seoul, 133-7901, Korea; T.-H. Kim, and **Y.-K. Kim**, Seoul National University, Graduate School of Energy and Environment, Seoul, 139-743, Korea; W.-J. Song, Research Institute of Industrial Science and Technology, 32 Hyoja-Dong, Nam-Ku, Pohang, Korea; Y.-S. Cho, Korea Electric Power Research Institute, Daejeon 305-380, Korea

**New Techniques**

**Demonstration of a Multi-Channel Quadrature Interferometer for Remote Detection of Ultrasound**

---**B. F. Pouet**, S. Breugnot, and P. Clemenceau, Bossa Nova Technologies, Venice, CA 90291

**Accurate Defect Location Using a Six-Axis Industrial Robot to Position a Phased-Array Ultrasonic**

---**J. R. Sebastian**, D. S. Erdahl, V. A. Kramb, R. B. Olding, and D. A. Stubbs, University of Dayton Research Institute, 300 College Park, Dayton, OH 45469-0120; P. Collins, American Robot Corporation, 303 Robinson Road, Imperial, PA 15126

**Fluorescent Penetrants**

**UVA-Induced Fade of Penetrant and FPI Indications**

---**R. D. Lopez**, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011

**Study of Thermal Mass Effects on Drying Methods in Preparation for Fluorescent Penetrant Inspection**

---**L. Brasche**, R. Lopez, and D. Eisenmann, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011; K. Griffiths, Rolls Royce, plc., Darby, United Kingdom

**Preliminary Results of Cleaning Process for Lubricant Contamination**

---L. Brasche, R. Lopez, and **D. Eisenmann**, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011

**Engineering Study of Dry Powder Developer Application in FPI**

---**L. Brasche**, R. Lopez, and D. Eisenmann, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011

**Study of Light Level Effects on FPI Performance**

---**L. Brasche**, W. Meeker, R. Lopez, and D. Eisenmann, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011; J. Lively, Pratt & Whitney, P. O. Box 109600, M/S 702-06, West Palm Beach, FL 33410-9600

**3:10 PM**

***Coffee Break***

**Detection of a Closed Crack by Nonlinear Acoustics Using Ultrasonic Transducers**

---**Soshu Hirata** and Toshihiko Sugiura, Keio University, Mechanical Engineering, 3-14-1 Hiyoshi, Kohoku, Yokohama, Kanagawa 223-8522, Japan

---In recent years, diffusion joining and friction stir joining have been used for a solid state bonding which needs high structural safety. These methods are useful in various fields because of many advantages. However they can be affected by impurity of the atmosphere, temperature, and the smoothness of a joining interface etc, so a minute crack may arise in a joining interface. Such a minute crack, if it is closed, cannot be detected by conventional methods that use information on the amplitude of a received signal. Therefore, more attention has been paid to a new method using contact acoustic nonlinearity. This research investigates applicability of this method to detection of minute cracks. Numerical analysis was conducted on the specimen with a minute crack using our FEM program. As an effect of collision of the crack surfaces, a superharmonic wave appeared in received signals. The longer the crack was, the larger the magnitude of the super harmonic wave became. Thus, nonlinear effects can be useful information for detecting minute cracks.

**Simulation of Non-Linear Ultrasonic Wave Through an Interface Including Imperfections**

---**Kazuyuki Nakahata**, Dept. of Civil and Environmental Engineering, Ehime University, Ehime, Japan; Sohichi Hirose, Dept. of Mechanical and Environmental Informatics, Tokyo Institute of Technology, Tokyo, Japan

---Recently, a non-linear ultrasonic method is studied for the detection of imperfections on an interface between metals. A transmitted ultrasonic wave through the interface includes high-harmonic wave components caused by the dynamic interaction of metals. We treat the numerical simulation of the wave propagation through the interface including imperfections. In this study we propose a local imperfection model of the interface whose condition is varied depending on tensile or compressive stress phases. On the other hand, the displacement and stress are continuous on the perfect interface. This model is incorporated into a time domain boundary element method (T-D BEM) and the transmitted waveforms are calculated. From the result of simulations, it is shown that the amplitude ratio of the higher harmonic wave changes according to the initial opening displacement of the imperfection area. At the conference, we will demonstrate the simulation for a sub-harmonic wave as well as the high-harmonic wave using this model.

**Characterization of an Ultrasonic Transducer in a Pulse-Echo Setup**

---**Ana L. Lopez-Sanchez** and Lester W. Schmerr Jr., Center for NDE, Department of Aerospace Engineering, Iowa State University, Ames, IA, 50011

---An ultrasonic transducer plays an important role in both sound generation and reception processes that take place in an ultrasonic NDE measurement system. The transducer effect on an ultrasonic measurement system can be completely characterized in terms of its input electrical impedance and sensitivity. Here, a simplified model-based approach is described to determine both transducer parameters in a pulse-echo setup. The transducer sensitivity obtained using this new approach is compared to the sensitivity determined using a three-transducer method originally developed for lower-frequency acoustic transducers, and which have been used in previous studies. The effect that cabling has at frequencies normally used in NDE is shown in both transducer parameters. Moreover, the influence of the pulser/receiver settings on the transducer impedance and sensitivity is discussed.

**Surface Wave Testing of a Flaw by Electromagnetic Acoustic Transducers**

---**Takeshi Ohya** and Toshihiko Sugiura, Mechanical Engineering, Keio University, Yokohama, Kanagawa, Japan

---For reliable maintenance of engineering structures such as nuclear power plants and pipeline plants, it is important to detect and size flaws, especially close to the surface of the structures. The authors have so far studied quantitative evaluation by electromagnetic acoustic transducers (EMATs). Our FEM-BEM-based numerical simulation of cylindrical or plane waves was in good agreement with experimental results, and our inverse analysis based on this numerical simulation showed possibilities of sizing a flaw with high accuracy. This research investigates quantitative evaluation of a flaw near the surface of a structure by using surface waves transmitted and received by EMATs. Our numerical simulations of the surface waves show effects of a flaw on propagation of the waves and thus on the receiver signals, and give us some correlation between the flaw depth and the receiver signals. Numerical results of the receiver signals agree well with our experimental ones. Thus, surface wave testing by EMATs has good potential of evaluating the depth of a flaw close to the surface of structures.

**Spherically Focused Air-Coupled Capacitive-Foil Transducer**

---**Junho Song**<sup>1,2</sup>, Stephen D. Holland<sup>1</sup>, and D. E. Chimenti<sup>1,2</sup>, <sup>1</sup>Center For NDE, Iowa State University, Ames, IA 50011; <sup>2</sup>Department of Aerospace Engineering, Iowa State University, Ames, IA 50011

---We have developed, fabricated, and tested spherically focused capacitive air-coupled ultrasonic transducers that need no mirror, zone plate, or similar external device. To achieve native focusing, we have employed a flexible copper/polyimide backplate that permits a conformal fit to a spherical fixture whose radius determines the focal length. The backplate is patterned with forty-micron depressions on an 80-micron rectangular grid spacing. A spherically deformed 6-micron aluminized Mylar foil, conforms to the spherical backplate, completing the transducer. Two devices have been tested, one having a 1-cm diameter and a 2.54-cm focus, and another with a 5-cm diameter and 5.1-cm focus. Both devices have frequency spectra centered at 840 kHz with -6 dB points at 310 and 1200 kHz. In the focal plane, the beam diameter is 2.7 mm (1-cm device) and 1.32 mm (5-cm device), when excited with a broadband signal. The focal zone extends from 17 to 32 mm (1-cm device) and from 46 to 57 mm (5-cm device). Both devices' diffraction behavior have been successfully modeled as focused piston radiators.

**Flexural Torsional Guided Wave Pipe Inspection**

---**Zongqi Sun**, GE Global Research Center KWD-259B, One Research Circle, Niskayuna, NY 12309; Li Zhang and Joseph L. Rose, The Pennsylvania State University, Engineering Science and Mechanics Department, University Park, PA 16802

---Flexural torsional guided wave theory has been developed and applied to pipe inspection recently. This paper demonstrates defect detection ability of the flexural torsional modes. Both single defect and multiple defects can be detected. To quantify the defect information locations of defects (both axial and circumferential directions) can be precisely determined with the aid of the phased array focusing. Combined with the longitudinal group of guided waves, the possibility of defect detection has been greatly improved compared to conventional guided wave technique. This new technique has shown the many advantages for pipeline monitoring at many critical but inaccessible areas.

**Phased Array Inspection of Titanium Disk Forgings Using Mirrors to Compensate for Curved Entry Surfaces**

---**Jon H. Friedl**, Ronald A. Roberts, and R. Bruce Thompson, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011

---The phased array implementation of a focused zoned ultrasonic inspection to achieve >3 dB signal-to-noise for #1/2 flat bottom holes (FBH) in titanium beneath curved entry surfaces is reported. Previous work established the ultrasound focusing required to achieve the targeted sensitivity as well as implementing a focused zoned inspection through planar entry surfaces in titanium. This work reports on the design of a set of mirrors to be used with a phased array transducer capable of maintaining the needed focus to the depths required in the forging inspection. It was determined to use phasing of the array to focus over the variable depth of field while using mirrors to, by and large, compensate for a range of entry surface curvatures. While it is theoretically possible to sufficiently phase an array to compensation for surface curvature as well as focus over a variable depth of focus, doing so exceeds the capabilities of most currently available hardware. The performance of the phased array inspection is verified by examining signal-to-noise of #1/2 FBHs contained in curved entry coupons cut from actual forgings.---This material is based upon work supported by the Federal Aviation Administration under contract #DTFA03-98-D-00008, Delivery Order #IA029, and performed at Iowa State University's Center for NDE as part of the Engine Titanium Consortium, through the Airworthiness Assurance Center of Excellence.

**Use of Expanded Multi-Gaussian Beam Model to Predict Radiation Beam Fields from a Phased Array Ultrasonic Transducer**

---Joon-Soo Park, **Hak-Joon Kim**, and Sung-Jin Song, Sungkyunkwan University, School of Mechanical Engineering, 300 Chunchun-dong, Jangan-gu, Suwon 440-746, Korea

---Prediction of radiation beam fields from a phased array ultrasonic transducer is one of fundamental tasks for not only optimization of test conditions but also interpretation of test results. The Rayleigh-Sommerfeld integral (RSI) model has been widely adopted for this purpose. The RSI model, however, suffer from the long calculation time due to its involving an integration over the transducer surface. Very recently, it has been proposed the expanded multi-Gaussian beam (EMGB) model that can take care of such a lengthy calculation problem. The EMGB model is based on the paraxial approximation so that it would loose its accuracy as the increase of steering angle. However, no study has been made on this specific aspect. In this study, we will calculate the radiation beam fields from a phased array transducer at various conditions (steering angle, focal point, wedge, refracted wave type, reflection from the bottom and so on) and compare the results to those obtained by RSI to investigate the boundary of EMGB model in the describing the phased array beam behavior.

**Particle Size and Concentration Studies of Solid-Liquid Suspensions Utilizing Ultrasonic Backscattering and Attenuation Measurements**

---**P. D. Panetta**, Pacific Northwest National Laboratory, 902 Battelle Boulevard, P. O. Box 999, MSIN K5-26, Richland, WA 99352

---On-line, non-invasive measurements of the particle size and concentration of moderate to highly concentrated slurries is required for the efficient process measurement and control for many processes. High concentrations are often found in government applications such as waste remediation for the Department of Energy sites and in industrial applications such as chemical and pharmaceutical manufacturing. However, existing particle sizing methods based on ultrasonic attenuation can become inaccurate for non-dilute suspensions due to the complex interactions particle-particle interactions in the slurries. We are developing two measurements that help to overcome these difficulties, the ultrasonic backscattering and measurements of the diffuse field properties. The backscattering measurement is attractive because viscous, thermal, and inertial effects have small contributions to backscattering. Furthermore, the backscattering theories are simpler than attenuation theories and lend themselves to more stable inversion processes. We have utilize the backscattering, diffuse field and attenuation measurements to isolate the damping, and scattering contributions to the ultrasonic attenuation of solid liquid suspensions. These results provide the basic measurements for comparison with theoretical formulations. Results which elucidate the interrelationship between these energy loss mechanisms will be reported. Where appropriate, experimental measurements will be compared with theoretical predictions.---This work was supported by the Department of Energy, Environmental Management Science Program. Pacific Northwest National Laboratory is operated for the U.S. Department of Energy by Battelle under Contract DE-AC06-76RLO18310.

**Characterization of Subsurface Defects in Ceramic Rods by Laser Scattering and Fractography Methods**

---J. M. Zhang and **J. G. Sun**, Energy Technology Division, Argonne National Laboratory, Argonne, IL 60439; M. J. Andrews, A. Ramesh, J. S. Tretheway, D. M. Longanbach, Caterpillar Inc., Mossville, IL 61552

---Silicon nitride ceramics are leading materials being evaluated for valve train components in diesel engine applications. For these materials, surface and subsurface defects and damage induced by surface machining can significantly affect component strength and lifetime. Because silicon nitride may transmit some light into its subsurface, we have developed an elastic optical scattering technique that uses a low-power laser, special optical components, and digital image processing to provide two-dimensional image data for characterization of subsurface defects and machining damage. In this study, this nondestructive evaluation (NDE) technique has been utilized to analyze eight silicon nitride cylindrical rods subjected to transverse grinding before fracture tests. The fracture origin (machining cracks or inherent material flaws) identified by fractography after fracture testing was correlated with the laser scattering images. The results indicate that the laser-scattering NDE method is able to identify possible fracture origin in the silicon nitride subsurface without the need for destructive fracture tests.

**Hole Enlargement Measurement in Carbon Steel and Seacure Tube**

---**Yuwu Yu**, Noan Nguyen, Ad Shatat, and Dave Russell, Russell NDE Systems, Inc., 4909 – 75 Avenue, Edmonton, Alberta T6B 2S3, Canada

---A novel method is described for identifying and sizing tube support plate (TSP) hole enlargement caused by corrosion or erosion. Finite element simulations and experimental studies performed in this research project have shown that a measurable quantity, detector energy output (DEO), is a linear function of the gap between tube and TSP. DEO can thus be used to quantify the gap. DEO remains a linear function of tube-TSP gap as long as the probe operates in the remote field zone. DEO is calculated from the output signal of a standard RFT probe. The best of our knowledge, this is the first time that the standard RFT technique has been found feasible for inspecting TSP damages. The findings presented in this research work have extended the capabilities of the standard RFT technique beyond its conventional inspection of heat-exchanger tubes.

**A Modified Remote Field Eddy Current Method for Imaging Defects in Concentrically Arranged Steel Tubes**

---**Graham Miller**, Haitham Hussin, Bosco Fernandes, Muhammad Zaid, Patrick Gaydecki, and Fawzi El-Madaani, University of Manchester, School of Electrical and Electronic Engineering, P. O. Box 88, Manchester M60 1QD, United Kingdom

---This paper describes the development of a modified remote field eddy current (RFEC) system for detecting and imaging defects in the outer tube of a concentric steel tube pair. RFEC detection is employed where a receiver coil is displaced from a transmitter coil by a minimum of two pipe diameters. The transmitter and receiver are placed perpendicular to each other in order to reduce cross-talk, with the axis of the transmitter coil parallel to the axis of the tube. This method uses the principle of eddy-current and magnetic coupling, in which the field propagates through the inner steel tube toward the outer steel tube. The field is distorted by defects in the outer section and this change is detected by the receiver. The experimental tubes were approximately 1 metre in length and wall thicknesses of the inner and outer tubes were 2mm and 5mm respectively. The excitation frequency is governed by the wall thickness of the inner tube; typically 125 Hz is employed to ensure that the field is not attenuated by the skin effect of inner tube. By rotating the detection coil around the circumference of the inner tube, it has been possible to generate images of defects on the outer steel tube.

**Reconstruction of Cracks from Eddy Current Signals Using Genetic Algorithm and Fuzzy Logic**

---**Ryszard Sikora** and Piotr Baniukiewicz, Szczecin University of Technology, Chair of Theoretical Electrotechnics and Computer Science, al. Piastow 17, 70-310 Szczecin, Poland

---In this paper the authors present a fast inverse iterative algorithm with a feedback loop designed to reconstruct crack shapes using multifrequency eddy current data. It uses a parametric description of the flaws. Therefore, the algorithm can be applied to recognize natural and regularly-shaped flaws, especially of the profiles close to triangle, rectangle, ellipse and trapezium. The algorithm is not sensitive to signal distortions caused by noise and lift-off fluctuations. The new forward model based on the ANFIS network has been proposed. The optimization problem has been solved by means of genetic algorithms. The recognition process is based on the identification of the whole set of parameters, which describe the flaw. The data used for experiments were achieved from measurements performed on test specimens (Inconel600 plates). The multifrequency eddy current method was applied. The flaws were made by electro discharge machining method. The forward model has been modified in order to achieve a minimal complexity of the forward model and avoid training problems. It has been divided into particular, independent networks. The algorithm has been tested with natural and simulated flaws. Results will be presented in the full version of the paper.

**Circumferential Defect Sizing in Pipe Using an Ultrasonic Guided Wave Focusing Technique**

---**Jing Mu**, Li Zhang, and Joseph L. Rose, Department of Engineering Science and Mechanics, the Penn State University, University Park, PA 16802; Jack Spanner, Electric Power Research Institute NDE Center, Charlotte, NC 28216

---Circumferential defect sizing is studied with an ultrasonic guided wave focusing inspection technique. Differently shaped defects, such as a planar saw cut, a volumetric through-wall hole, and volumetric spherical shape corrosion are studied. A Phased array is used to spin the focal point of the ultrasonic energy around the pipe. The maximum amplitude of the defect echo is recorded with respect to each circumferential focal position. Circumferential lengths of the planar saw cut and volumetric through-wall hole are then measured by comparing the experimental results with numerical calculations obtained through use of the Normal Mode Expansion Method (NME). It is shown that this measurement technique works well with the planar saw cut and volumetric through-wall hole defects. In addition, it is shown that reflections from defects with the same cross sectional area (CSA), but different shapes, might be very different. A 1%CSA through-wall hole can give a substantial reflection, whereas the reflection from a 1%CSA spherical corrosion could be very small. This implies that defect surface shape plays an important role in wave reflection and scattering and must be considered in defect sizing studies.

**Estimates of Signal-to-Microstructural-Noise Ratios in Ultrasonic Inspections of Metals**

---**F. J. Margetan**, Ron Roberts, and R. B. Thompson, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011

---Ultrasonic defect detection in metals is often a hunt for a flaw response in the presence of microstructural noise, with a signal-to-noise ratio (S/N) used to quantify the extent to which the response from a defect or reference reflector stands out above the competing noise. In many cases of practical interest three conditions apply: (1) the defect is small in cross-section compared to the interrogating sound beam; (2) microstructural elements are also small so that the sonic beam cross-section encompasses a significant number of scattering boundaries; and (3) microstructural scattering is weak in the sense that single-scattering events dominate and multiple scattering effects can be ignored. In such cases, independent-scatterer noise models apply and can be used to develop simple, approximate formulas for S/N. For P/E inspections, the formulas relate S/N to the response-weighted volume of the incident sonic pulse. Such formulas have proven useful in designing P/E inspections of jet-engine forgings. After briefly reviewing the P/E case, we introduce generalized versions of the formulas which apply to ultrasonic pitch-catch inspections. The use of the new formulas to assess or optimize inspections is then discussed, including a treatment of phased-array inspections using so-called dynamic depth focusing.---This work was jointly supported by Pratt & Whitney, a United Technologies Company, and by the Federal Aviation Administration under Contract #DTFA03-98-D-00008, Delivery Order #0034 and performed at Iowa State University's Center for NDE as part of the Engine Titanium Consortium program, through the Airworthiness Assurance Center of Excellence.

**Estimation of the Single-Crystal Elastic Constants of Polycrystalline Materials from Back-Scattered Grain Noise**

---**Pranaam Haldipur**, F. J. Margetan, and R. B. Thompson, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011

---Single-crystal elastic stiffness constants are important input parameters for many calculations in material science. There are well established methods to measure these constants using single-crystal specimens, but such specimens are not always readily available. The ultrasonic properties of metal polycrystals, such as velocity, attenuation, and backscattered grain noise characteristics, depend in part on the single-crystal elastic constants. In this work we consider the estimation of elastic constants from UT measurements and grain-sizing data. We confine ourselves to a class of particularly simple polycrystalline microstructures, found in some jet-engine Nickel alloys, which are single-phase, cubic, equiaxed, and untextured. In past work we described a method to estimate the single-crystal elastic constants from measured ultrasonic velocity and attenuation data accompanied by metallographic analysis of grain size. However, that methodology assumes that all attenuation is due to grain scattering, and thus is not valid if appreciable absorption is present. In this work we describe an alternative approach which uses backscattered grain noise data in place of attenuation data. Efforts to validate the method using a pure copper specimen are discussed, and new results for two jet-engine Nickel alloys are presented.---This material is based upon work supported by the Federal Aviation Administration under Contract #DTFA03-98-D-00008, Delivery Order #0034 and performed at Iowa State University's Center for NDE as part of the Engine Titanium Consortium program, through the Airworthiness Assurance Center of Excellence.

**Evaluation of Surface Finish in Machined Parts by Ultrasonics**

---**Vadivel Jagasivamani** and Alphonso C. Smith, Hampton University, School of Engineering & Technology, Hampton, VA 23668

---Evaluation of surface finish and texture in machined parts are useful in several engineering applications. It is well known that the surface features scatter ultrasonics. In this work, ultrasonic scatter is correlated to the surface finish and the orientation of the machining marks. Quantitative relations have been deduced between the surface roughness and surface waviness with the frequency spectrum of scatter set for different scatter conditions. Measurements show promise for this technique to be applied in quantitative assessment of the surface finish which finds applications in quality assurance and reverse engineering operations.

**Applications of Barkhausen Emission Measurements for Characterization of Surface-Modified Materials**

---D. C. Jiles, C. C. H. Lo, E. R. Kinser, A. J. Barsic, and **Y. Melikhov**, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011

---Relationships between magnetic properties and microstructure in surface hardened steel were studied through measurements and model simulations, with the objective of developing techniques for quantitative measurements of case depth of surface hardened steels. The depth profiles of magnetic properties, in particular coercivity and Barkhausen effect signals, were found to correlate with the hardness profile. Simulations were carried out to aid analysis of experimental data using hysteresis models and the stochastic model of domain wall dynamics. Relationships between magnetic properties and microstructure were obtained, which can be used to extract information on pinning site (e.g. dislocation) density from measurement data. Theoretical analysis indicates that the Barkhausen model parameters are inversely proportional to the domain wall pinning. These relationships can be interpreted in terms of the effects of pinning site density on the local pinning field and distance of domain wall jumps which determine the Barkhausen signal activity.---This work was supported by the NSF sponsored Industry/University Cooperative Research Program of the Center for Nondestructive Evaluation at Iowa State University.

**Multiple Scattering in Polycrystalline Materials**

---**Goutam Ghoshal** and Joseph A. Turner, Department of Engineering Mechanics, W 317.4 Nebraska Hall, University of Nebraska-Lincoln, Lincoln, NE 68588-0526

---The scattering of elastic waves in polycrystalline media is primarily due to the orientation distribution of the crystal axes in the grains. This scattering may be used to extract the microstructural parameters of the material such as grain size and grain texture. In particular, ultrasonic backscatter measurements have been especially useful for extracting microstructural information. Backscatter is often modeled analytically using single scattering assumptions. From the theoretical perspective, derivations related to ultrasonic radiative transfer equations (URTE) govern the propagation of diffuse intensities and include all multiple scattering effects. In this presentation, a rigorous connection between the URTE theory and the backscatter experiments is discussed. Specific solutions are obtained for a specimen excited by a normally incident longitudinal wave. Results are compared with previous backscatter theories. The Monte Carlo method is also employed to simulate ultrasonic wave propagation in the media. Numerical results are presented using Monte Carlo simulations at various levels of scattering to observe differences in single and multiple scattering solutions. Numerical simulations based on the Voronoi polycrystal using a finite element solution are presented as well. Relevant applications for materials of common interest are discussed. These results are anticipated to impact ultrasonic NDE of polycrystalline media.--  
-Work supported by US DOE.

**Measurement of Ultrasonic and Tensile Properties of Glass-Bead-Filled Polymers**

---**Clint D. Thomson**, Lee H. Pearson, and Jane Johnson, NDE Research and Analysis Group, ATK Thiokol Inc., M/S 245C, P. O. Box 707, Brigham City, UT 84302

---In this paper, the ultrasonic and tensile properties of glass-bead-filled polymers are presented. The objectives of this study were two-fold: 1) to provide data for the validation of microstructural ultrasonic-wave scattering models; and 2) to assess the sensitivity of ultrasonic measurements in detecting binder and particle-dewetting damage. Two polymer-binder formulations--one elastic and the other viscoelastic--were homogeneously filled with 600  $\mu\text{m}$  glass-beads at volume concentrations ranging from 0-40%, and were molded into dogbone samples. Ultrasonic wavespeeds and attenuation, as well as tensile properties such as stress, strain, and modulus, were then simultaneously measured on strained dogbones using a combined pulse-echo and through-transmission measurement configuration. Correlations were observed between ultrasonic and tensile properties resulting from particle dewetting. Furthermore, in multiple strain cycle tests, it was observed that ultrasonic properties were sensitive to partial particle-binder rewetting, where tensile properties did not exhibit such sensitivity.---This work is funded by AFRL contract # F04611-98-C-0005.

**Measurement and Modeling of Ultrasonic Attenuation in Aluminum Rolled Plate**

---**Anxiang Li**, Hak-Joon Kim, F. J. Margetan, and R. B. Thompson, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011

---When fabricating a new set of calibration blocks for Aluminum 7075 plate inspections, it is advantageous that the new blocks have similar ultrasonic attenuation to existing block sets. This allows the new set to qualify under the same ASTM procedures used for older sets. In the course of surveying candidate materials for possible use as calibration blocks, some interesting attenuation results were observed. When a candidate block was cut from a thick section of rolled plate, measured attenuation values in the rolling or transverse direction were quite sensitive to position in the plate-normal direction. Such variations are presumably tied to microstructural variations within the plate, as revealed by metallography. Some measured attenuation values were found to be in good agreement with predictions of the Stanke-Kino model, while others were not. The measurements and modeling work are reviewed, and additional experiments conducted to clarify certain issues are discussed.---This work was supported by the NSF Industry/University Cooperative Research program.

**Nondestructive Evaluation of Irradiation Brittleness of SQV2A Steel by Using Magnetic Method**

---**Mitsuharu Shiwa**, Cheng Weiyang, Shigeo Nakahigashi, Ichiro Komura<sup>1</sup>, NDE Center, Japan Power Engineering and Inspection Corporation, 14-1 Benten-cho, Tsurumi-ku, Yokomama, 230-0044, Japan; Koji Fujiwara and Norio Takahashi<sup>2</sup>, <sup>2</sup>Department of Electrical and Electronic Engineering, Division of Industrial Innovation Sciences, The Graduate School of Natural Science and Technology, Okayama University, 3-1-1 Tsushima, Okayama 700-8580, Japan

---Irradiation brittleness of SQV2A steel was evaluated by using magnetic methods nondestructively. Thermal aging (TA) and electron beam irradiation (EI) specimens were prepared for the basic examination to evaluate thermal aging effect and irradiation brittleness separately. Electro-magnetic properties and hardness of specimens were measured. The micro-structure of each specimen was observed by transmission electron microscope (TEM). Micro-meter scale Cu precipitations were observed in the case of TA by TEM observation. On the other hand, nano-meter scale Cu precipitations and dislocation around the precipitations were observed in the case of EI. Micro-Vickers hardness decreased with aging temperature and time, and increased with the irradiation dosage. B-H loops changed after thermal aging and electron beam irradiation. Higher harmonics of AC magnetization signals were sensitive to micro-structure changing of both TA and EI specimens. The equivalent operation time (at temperature 573K) of Nuclear Power Plants was correlated by using Larson-Miller parameter, and it is observed that the intensity of the 3<sup>rd</sup> harmonics increased linearly with 100 years of the operation.

**Plastic Foam Porosity Characterization by Air-Borne Ultrasound**

---Hannu Hoffrén, Timo Karppinen, and **Edward Hæggröm**, Department of Physical Sciences, University of Helsinki, Helsinki, Finland

---Porosity influences mechanical, electrical and thermal characteristics of a structure. For instance its hydraulic conductivity is determined by its porosity and pore tortuosity. We are developing an ultrasonic burst-reflection method for estimating porosity and tortuosity of soft solid materials. As a step we report on measurements on polyurethane foams (Sylomer® vibration dampener) with well-defined porosity. This method is based on measuring 245 to 600 kHz ultrasound reflection from the first interface of a solid at two angles of incidence. The reflected sound wave from different foam samples (32% - 64% porosity) was compared to a wave that had traveled from transmitter to detector without reflection. The porosity and tortuosity of the reflector material were obtained from the amplitude change occurring at reflection. The ultrasonically estimated sample porosities coincided within 8% with the porosity estimates obtained by the gravimetric reference method. This parallels the repeatability of the gravimetric method, 8%. The repeatability of the ultrasonic porosity measurements was better than 2%. We aim at an instrument with no moving parts whose sole requirement is that the sample has one flat surface. Currently we apply the method to characterize the structure of other porous materials such as silicon, stone, and wood.

**A New Method for Electromechanical Coupling Factor Determination in Piezoelectric Materials**

---**Eugene K. Naimi**, Physics Department, Moscow State Institute of Steel and Alloys (Technological University), Moscow, Russia

---The major characteristic of any piezoelectric converter is its electromechanical coupling factor  $K_2$ . The various methods of definition  $K_2$  are known. Most widespread is the method, in which  $K_2$  is defined using amplitude-frequency characteristic (resonance response) of the converter in a mode of mechanical vibration generation. In this work the new method for electromechanical coupling factor determination  $K_2$  in piezoelectric materials is offered. In offered method the role of an active element (generator) is given to the piezoelectric quartz, while the researched crystal works as a passive resonator. At a deviation in a resonant length selection of sample by  $\pm 1\%$  the error of  $K_2$  calculated by this method is not more  $\pm 2\%$ . The method was tested on single crystal of  $\text{La}_3\text{Ga}_5\text{SiO}_{14}$  (langasite) with X-crystal cut. Calculated value  $K_2 = (0,24 \pm 0,01)$  is matched to the value  $K_2 = 0,25$  derived by other methods very well.

**Measurement of Ultrasonic Properties in Glass-Bead-Filled Elastic and Viscoelastic Polymers as a Function of Frequency**

---**Jane Johnson**, Lee. H. Pearson, and Clint Thomson, ATK Thiokol, Inc., Brigham City, UT 84302

---Ultrasonic scattering is widely used as a means to characterize materials. This paper presents the ultrasonic inspection results performed on glass-bead-filled polymers at a range of frequencies. In this study elastic and viscoelastic polymers were used as binder systems, glass beads in mono- and trimodal size distributions were used as scattering particles and 250 kHz to 2 MHz was the frequency range. The ultrasonic quantities of interest were velocity and attenuation. The objectives of this study were two-fold: 1) to provide data for the validation of microstructural ultrasonic-wave scattering models; and 2) to assess the sensitivity of ultrasonic measurements to the sample variation given. This work is funded by AFRL contract # F04611-98-C-0005.

**Interpretation of Back-Scattered Raleigh Surface Wave Signals from Diamond Coating Layers**

---**Hak-Joon Kim**, Sung-Jin Song, Dong-Joo Yang, and Wang Wen Wu, Sungkyunkwan University, School of Mechanical Engineering, 300 Chunchun-dong, Jangan-gu, Suwon 440-746, Korea

---Chemical vapor deposit (CVD) diamond coating layer is expected to extend the lifetime of mechanical parts that are used severely abrasive conditions. However, one of the most severe problems is that the delamination between the CVD diamond coating layer and the silicon substrate occurs frequently due to large difference in the material properties such as Young's modulus and thermal expansion coefficient. Therefore, the nondestructive evaluation of adhesive property of CVD diamond coating layer is needed. To address such a need, back-scattered Rayleigh surface wave is currently applied. However, the interpretation of the acquired signal is not easy at all. To take care of such a difficulty, we proposed the time trace angular scan (TTAS) plot and the frequency spectrum angular scan (FSAS) plot to interpret the back-scattered signals from the diamond. Currently, the evaluation of the adhesive property of CVD diamond coating layer is undertaken using the newly proposed plots. In this paper, the concept of the TTAS and FSAS plots and the initial experimental results will be presented to demonstrate the effectiveness of the proposed approach.

**Damage Monitoring of Thermal Spray Coatings by Laser Based Acoustic Emission**

---**Manabu Enoki**, Koichi Taniguchi, and Satoshi Nishinoiri, Department of Materials Engineering, The University of Tokyo, Tokyo, Japan; Koichi Tomita, Industrial Technology Center of Fukui Prefecture, Fukui, Japan

---AE method is a well-known technique for in-situ monitoring of fracture behavior by attaching piezoelectric transducer. However, using piezoelectric transducer for detection of AE signals has several limitations. In recent years, numerous efforts have addressed the substitution of laser-based techniques for ultrasonic nondestructive evaluation in place of conventional piezoelectric transducers. Especially, a laser interferometer can be used to measure a displacement or velocity at materials surface using Doppler-shifted scattered light. It is expected to perform accurate analysis for AE source wave. However, there are few reports referring to the detection of AE signals in the practical materials and testing because of the difficulty of experiments. We developed the AE measurement system with laser interferometer to apply this technique to microfracture evaluation in various materials. This paper demonstrates some AE results from thermal spray coatings at elevated temperature.

**NDE for Characterizing Adhesive Joint Degradation Due to Corrosion**

---**Prakash Kumar**, J. C. Duke, and M. Hajj, Virginia Tech, Engineering Science and Mechanics, Blacksburg, VA 24061; Matthew Tillman, Naval Air Development Center, Patuxent River, MD 20670-1908; Evgueni Todorov, Edison Welding Institute, Columbus, OH 43221

---The development of a nondestructive evaluation method for assessing the extent of adhesive joint degradation due to corrosion will be described. Experimental results for bonded 2024 T3 aluminum degraded in a salt fog environment for 60 days will be presented. Advanced signal analysis has been used to extract physically meaningful information from signals detecting ultrasonic plate wave propagation. This approach offers potential for monitoring of areas where access is limited, or continuous monitoring of critical components is desirable.

**Simulation of the Transient Ultrasonic Waves in Viscoelastic Solid by Using Finite Elements**

---J. He, G. Chen, **X. R. Zhang**, and J. C. Chen, Nanjing University, Institute of Acoustics, #22 Hankou Road, Nanjing, Jiangsu, 210093, China (PRC)

---In this paper, we analyze the transient ultrasonic waves in viscoelastic solids. The relations between the dispersion and attenuation of the waves and the parameters in the general Maxwell model are deduced theoretically. The influences of the relaxation time and strength of the model on the dispersion and attenuation of waves are analyzed in detail. The model parameters such as relaxation time and relaxation strength are recovered from the curves of dispersion and attenuation of the waves by using the simplest general Maxwell model to model viscoelastic solids. Results show that it is efficient method to simulate the transient ultrasound propagating in viscoelastic solids by used finite element method based on the general Maxwell model, when the parameters of the model are known. It is the same the way round. The parameters of the model can be obtained from the transient waveform measured, than can be used to character new viscoelastic solids.

**An Experimental Study of the Ultrasonic Properties of High-Viscous Silicone Fluids**

---**Linxiao Yu**, Douglas A. Rebinsky, Dong Fei, and Michel W. Shockley, Caterpillar Inc., (41) Technical Center – Bldg. E/854, P. O. Box 1875, Peoria, IL 61656-1875

---A recent industrial application created the needs for the ultrasonic properties of high-viscous silicone fluids. In this study, a series of polydimethylsiloxane fluid with a wide range of viscosities were produced first. The ultrasonic properties of these fluids, including ultrasonic attenuation, velocity and dispersion, were then measured. All the measurements were performed using a through-transmission experimental configuration. An analytical relationship used to calculate the fluid attenuation was developed for the through-transmission setup. The measured ultrasonic properties were correlated with the fluid viscosities.

### **Burning Rate Measurement of Solid Propellant Using Ultrasound-Approach and Initial Experiments**

---Sung-Jin Song, **Jin Hong Jeon**, and Hak-Joon Kim, Sungkyunkwan University, School of Mechanical Engineering, 300 Chunchun-dong, Jangan-gu, Suwon 440-746, Korea; In-Chul Kim and Ji-Chang Yoo, Agency for Defense Development, Daejeon, Korea

---Burning rate of solid propellant is one of the crucial properties for the reliable prediction and analysis of the performance of solid propellant rocket. For measurement of burning rate of solid propellant, various methods have been proposed such as the stand burner method, ultrasound, x-ray, microwave, plasma capacitance gage, acoustic emission and so on. Among them, ultrasonic method has a great advantage since it can measure the burning rate in a single test. However, the burning time of the test sample is only about a second and the pressure in the burning chamber usually raises up to 2000psi. So, to measure the burning rate accurately, it is necessary to acquire ultrasonic responses more than 1000 times in one second in high pressure. To take care of such a tough requirement, a specially designed burning chamber and a PC-based ultrasonic testing system have been developed to store whole ultrasonic waveforms and the corresponding pressures with 1 kHz pulse repetition rate during the burning of solid propellant. In addition an analysis program has also been developed to get the burning rate versus pressure curve. Using the fabricated system and the developed program, measurements of burning rate of solid propellants are currently undertaken. In this paper, the approach and the initial experimental results will be presented.

### **Numerical Modeling of Profilometry ECT Signals from Tubesheet and Tube Expansion Area**

---**Young-Kil Shin**, Sung-Chul Song, and Hee-Sung Jung, School of Electronic and Information Engineering, Kunsan National University, San 68, Miryong-Dong, Kunsan, Chonbuk, 573-701, Korea; Chang-Jae Im, Korea Advanced Inspection Technology, P.O. Box 105, Yusung-Ku, Taejon, 305-600, Korea; Sung-Sik Kang, Korea Institute of Nuclear Safety, 19, Kusong-Dong, Yusung-Ku, Taejon, 305-338, Korea

---Steam generator (SG) tubes are expanded in tubesheet holes to be fixed to the tubesheet. Tube expansion is accomplished by rolling or by using explosive or hydraulic methods. One of important requirements in the tube expansion process is to minimize the crevice gap between tubesheet and the transition area of tube diameter. Since SG is set up vertically, the crevice gap becomes packed with magnetite and other byproducts of corrosion. This eventually leads to denting and damages to tubes. Therefore, it is necessary to examine the outcome of a tube expansion process. In this paper, absolute and differential ECT signals are computed by a numerical method for several different locations of tube expansion inside and outside the tubesheet. Signal changes due to magnetic tubesheet and tube expansion are observed and the effects of operating frequencies are investigated. Results show that low frequency is good for detecting tubesheet in both types of signals and high frequency is good for sizing of expanded tube diameter as well as the detection of the transition area of tube diameter. It is also confirmed that the absolute signal has a more adequate signal pattern than the differential signal since the signal variation due to tube expansion is bigger and continuous in the absolute signal.

**Electromagnetic Testing of Magnetic Material by Rotating Uniform Eddy Current Probe**

---**Hiroshi Hoshikawa**, Nihon University, Izumicho Narashino, Chiba 275-8575, Japan

---The authors have studied electromagnetic testing of surface flaws on magnetic material by a rotating uniform eddy current probe. The probe consists of two large exciting tangential coils and a small detecting pancake coil and comprises only air-cored coils. The two exciting coils carrying alternating currents with 90 degrees out of phase each other generate rotating magnetic flux and induce rotating uniform eddy current at the surface of the test material. The detecting coil picks up the magnetic flux perpendicular to the material surface. The probe detects flaws perpendicular to the magnetic flux by magnetic testing because they cause some of the magnetic flux to leak out of the material. The probe detects flaws parallel to the eddy current by eddy current testing because they disturb the circulation of eddy current. Thus the probe detects all flaws in every direction because it rotates the directions of the magnetic flux and eddy current. This presentation reports that an appropriate choice of the test frequency makes the probe detect every flaw despite their direction with almost the same sensitivity. A uniform eddy current probe generates magnetic flux without a hefty exciting magnetic core and makes handheld magnetic flux leakage testing feasible just like eddy current testing. The experimental results have shown that the flaw signals by uniform eddy current probe decays much less by its lift-off from test material than those by a conventional pancake coil probe. Thus uniform eddy current probe can be promising for surface flaw testing of magnetic material through anticorrosion painting.

**Evaluation of Microstructure of Isothermally Aged 11Cr-3.5W-3Co Steel by Magnetic Coercivity Measurement**

---C. S. Kim, J. H. Kang, and **S. I. Kwun**, Division of Materials Science and Engineering, Korea University, Seoul, Korea; J. W. Byeon, Advanced Materials Processing and Analysis Center, University of Central Florida, Orlando, FL 32816

---Magnetic properties (coercivity, remanence) were measured to evaluate the degree of isothermal aging of ferritic 11Cr-3.5W-3Co steel. Isothermal aging was performed at 700°C for up to 4000 hrs to simulate the microstructural degradation resulting from long term exposure at high temperature. Quantitative analysis was performed to determine the size and distribution of the precipitates using electron microscopy (FESEM, AES) and X-ray diffraction. TEM was employed to evaluate the lath and dislocation substructures. The hardness and tensile test were also conducted. The microstructure of as-tempered specimen contained tempered martensite with high dislocation density, martensite laths with small width and fine secondary phases such as M<sub>23</sub>C<sub>6</sub> and MX. As the aging time increased, the lath width increased and the dislocations were recovered. Lath width sharply increased from 0.5 micron to 2.25 micron after initial aging time of 1000 hrs and then saturated afterwards. Aging caused as-tempered carbides (M<sub>23</sub>C<sub>6</sub> and MX) initial coarsening drastically and then induced additional precipitation of Laves (Fe<sub>2</sub>W) phase after a long time. Magnetic coercivity rapidly decreased in the initial aging time of about 1000 hrs and then decreased little afterwards. This decrease of coercivity with aging time is attributed to the decrease of pinning sites such as dislocations and fine precipitates. Consequently, we could evaluate the microstructural changes of isothermally aged 11Cr-3.5W-3Co steel nondestructively using the magnetic coercivity measurement.

**Irradiation Degradation in Reactor Pressure Vessel Steels by Magnetic Techniques**

---**Kee-ok Chang**, Korea Atomic Energy Research Institute, Yuseon P. O. Box 105, Daejeon 305-600, Korea

---Recently, several attempts have been made to apply magnetic techniques in assessing and measuring the mechanical properties of irradiated reactor pressure vessel steels. We were employing the hysteresis loop, Barkhausen Noise and ferromagnetic resonance technique to study the magnetic properties. The specimens employed in the present study were obtained from a reactor pressure vessel surveillance program. The materials were tested in the unirradiated and two different post-irradiation conditions. Saturation magnetization, remanence, coercivity, Barkhausen noise amplitude and ferromagnetic resonance were measured for magnetic parameters, and Vickers microhardness, tensile and Charpy impact tests were performed for mechanical property parameters. After irradiation, hysteresis loops appeared to turn clockwise, resulting in an increase in coercivity, and Barkhausen noise amplitude appeared to decrease after irradiation while all the mechanical property changes followed the same trend as previously our studies. The observed ferromagnetic resonance fields were shifted toward higher resonance fields when they were irradiated. Its intensity decreased and linewidth increased in the irradiation materials. Again, although limited, these magnetic techniques were confirmed to be viable magnetic parameters that can be used in monitoring the mechanical parameter changed due to neutron irradiation.

**Degradation of Light Emitting Diodes Under the Action of Ultrasonic Vibration**

---**Eugene K. Naimi**, Physics Department, Moscow State Institute of Steel and Alloys (Technological University), Moscow, Russia; Oleg I. Rabinovich, Semiconductor Materials and Devices

---The problem of degradation of performance characteristics of commercial Light Emitting Diodes (LED) during their work on different conditions has practical significance. In this report the ultrasonic vibration at frequencies about 100 kHz on spectral characteristics of two types of commercial LEDs: 1) green L-144GD based on GaP; 2) L-383 GD and BL-BB43V4V (green and blue, respectively) based on AlGaInN heterostructures were investigated. Characteristic property of the two previous LEDs is the presence of very strong piezoelectric field (effect). It is detected that after 10 hours of ultrasonic action spectral peak of the first LED type shifts to the short-wave region by 4-6 nm. In the second LED type the shifted spectral peak is observed after 2 hours of ultrasonic action: green LEDs have a shifted spectral peak to the long-wave region by 8-10 nm and blue LEDs - to the short-wave region by 6-8 nm. The broadening of the second LED type are detected at full width at half maximum: for green LEDs it is 20-40 nm and for blue LEDs it is 25-30 nm. The models of LED degradation are suggested and they are based on: 1) an assumption of a junction of N atoms from sites into the interstitial sites under the action of ultrasonic vibrations in GaP LEDs; 2) redistribution of In atoms in quantum-dimensional active regions of AlGaInN LEDs under strong piezoelectric fields induced by ultrasonics.

**Tracking Fatigue Damage Development in 7075T6 Aluminum Prior to Crack Formation**

---**Byungseok Yoo**, J. C. Duke, Jr., and M. Hajj, Virginia Tech, Engineering Science and Mechanics, Blacksburg, VA 24061

---Seemingly identical metal alloy components can exhibit fatigue lives that differ by a factor of 10. Once a reliably detected crack has formed the predictability of its behavior increases as the crack becomes longer. The work reported here uses ultrasonic nonlinear response as a means of tracking damage development prior to the formation of a crack. Novel advanced signal processing makes it possible to perform this tracking in-service. Furthermore this measurement could be used for initial screening of critical components in order to select those with low susceptibility for rapid fatigue degradation. The power of the analysis approach to provide new insight into the material deformation process will be described.

**Evaluation of Thickness Reduction in a Thin Plate using a Non-Contact Guided Wave Technique**

---Ik-Keun Park, Seoul National University, Department of Mechanical Engineering, Seoul, 139-743, Korea; HyunMook Kim, Hanyang University, Graduate School, Seoul, 133-7901, Korea; Tae-Hyung Kim and **Yong-Kwon Kim**, Seoul National University, Graduate School of Energy and Environment, Seoul, 139-743, Korea; Wong-Joon Song, Research Institute of Industrial Science and Technology, 32 Hyoja-Dong, Nam-Ku, Pohang, Korea; Yong-Sang Cho, Korea Electric Power Research Institute, Daejeon 305-380, Korea

---Ultrasonic guided waves are widely being studied and successfully applied to various non-destructive tests with the advantage of a long range inspection. Recently, non-contact methods are also adopted and combined with the guided wave techniques. In this paper, an advanced technique for the nondestructive detection of thinning defects simulating hidden corrosion in thin plates using non-contact guided waves is presented. The proposed approach uses EMAT (Electro-Magnetic Acoustic Transducer) for the non-contact generation and detection of guided plate waves in aluminum plates. Interesting features of the dispersive behavior in selected wave modes are used for the detection of plate thinning. The experimental results show that the mode cutoff measurements provide a qualitative measurement of thinning defects and change in the mode group velocity can be used as a quantitative parameter of thinning depth measurement.

**Demonstration of a Multi-Channel Quadrature Interferometer for Remote Detection of Ultrasound**

---**Bruno F. Pouet**, Sebastien Breugnot, and Philippe Clemenceau, Bossa Nova Technologies, Venice, CA 90291

---We will display a novel laser interferometer for remote measurement of ultrasound and vibration. This novel interferometer uses a classical interferometric layout combined with multi-channel detection and parallel processing. We will show that the parallel processing can be easily carried out, allowing for high-density multi-channel detection. The optical system is very simple and robust, requiring not stabilization or critical alignment. This novel interferometric scheme fully takes advantage of the random distribution of coherent light scattered by rough surfaces. We will demonstrate that, for a multi-channel detection associated with the proper signal processing, the random distribution of the speckles provides random quadrature that statistically leads to a highly sensitive interferometer and a stable signal. Demonstration will be carried out with the measurement of ultrasounds on unprepared, rough sample surfaces. We will show that this sensitive interferometer is robust, easy to operate and it does not require a controlled environment. The interferometer output signal corresponding to the rectified surface displacement caused by ultrasounds reaching the surface will be displayed in real time on a portable computer. This compact interferometer will allow researchers to perform sensitive remote measurement of ultrasound or vibration independently of the environment, facilitating the transfer from laboratory to factory.

**Accurate Defect Location Using a Six-Axis Industrial Robot to Position a Phased-Array Ultrasonic**

---**James R. Sebastian**, Dathan S. Erdahl, Victoria A. Kramb, Robert B. Olding, and David A. Stubbs, University of Dayton Research Institute, 300 College Park, Dayton, OH 45469-0120; Peyton Collins, American Robot Corporation, 303 Robinson Road, Imperial, PA 15126

---A next-generation inspection system was developed to perform fully automated ultrasonic inspections of in-service turbine engine components. Ultrasonic probe manipulation by a six-axis industrial robot greatly increased the flexibility of the system but presented challenges for accurate probe positioning and defect locating. The implementation of an advanced robot controller improved the motion control accuracy to within the required tolerances for ultrasonic inspection. Objective testing of the robot motion with a variety of metrology devices and the correlation of inspection data from multiple look angles verified that the required accuracy had been achieved.

**UVA-Induced Fade of Penetrant and FPI Indications**

---**Richard D. Lopez**, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011

---In spite of the fact that industry standards don't currently address the issue, one must be aware of the possible consequences of using light sources many times higher than the minimum specified intensity for FPI work. High UVA intensity, coupled with heat and increased air flow, will fade a defect indication to a pale blue in minutes. Experimental work has showed that it is possible to reduce the brightness of an 0.080" long crack indication by half within 5 minutes. Increases in penetrant temperature, or increasing the airflow caused fluorescent penetrant to fade more quickly. Temperature and airflow effects appear to play a greater role than a UVA intensity increase alone.---This material is based upon work supported by the Federal Aviation Administration under Contract #DTFA03-98-D-00008, Delivery Order #0016 and performed at Iowa State University's Center for NDE as part of the Center for Aviation Systems Reliability program in cooperation with partners at Boeing Commercial, Boeing Phantom Works, Delta Airlines, United Airlines, Rolls Royce, General Electric, Pratt & Whitney, Honeywell, D&W Enterprises, and Sherwin.

**Study of Thermal Mass Effects on Drying Methods in Preparation for Fluorescent Penetrant Inspection**

---**Lisa Brasche**, Rick Lopez, and Dave Eisenmann, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011; Keith Griffiths, Rolls Royce, plc., Darby, United Kingdom

---Fluorescent penetrant inspection (FPI) is widely used for aviation and other components for surface-breaking crack detection. As with all inspection methods, adherence to the process parameters is critical to the successful detection of defects. Prior to FPI, components are cleaned using a variety of cleaning methods which are selected based on the alloy and the soil types which must be removed. It is also important that the cleaning process not adversely affect the FPI process. There are a variety of lubricants and surface coatings used in the aviation industry which must be removed prior to FPI. To assess the effectiveness of typical cleaning processes on removal of these contaminants, a study was initiated at an airline overhaul facility. Initial results of the cleaning study for lubricant contamination in nickel, titanium and aluminum alloys will be presented.-  
--This material is based upon work supported by the Federal Aviation Administration under Contract #DTFA03-98-D-00008, Delivery Order #0016 and performed at Iowa State University's Center for NDE as part of the Center for Aviation Systems Reliability program in cooperation with partners at Boeing Commercial, Boeing Phantom Works, Delta Airlines, United Airlines, Rolls Royce, General Electric, Pratt & Whitney, Honeywell, D&W Enterprises, and Sherwin.

**Preliminary Results of Cleaning Process for Lubricant Contamination**

---Lisa Brasche, Rick Lopez, and **Dave Eisenmann**, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011

---Flourescent penetrant inspection is widely used to inspect critical rotating components for the presence of surface breaking defects. Typically these components are made of titanium or nickel and can weigh in excess of several hundred pounds. In preparation for FPI, the parts are cleaned to remove contamination and soil from inservice use. The final step in the cleaning process and prior to FPI, is drying. Two methods are commonly used to dry the part, flash dry and oven dry. Prior studies were completed to assess potential differences between the two drying methods in regards to their effectiveness in preparation for FPI and reported at QNDE. However, the earlier studies were limited to coupons and thus, did not take into consideration potential thermal mass effects. The latest study used a 300 pound nickel engine disk which contained fatigue cracks generated during spin pit testing. The results will be presented and conclusions provided.---This material is based upon work supported by the Federal Aviation Administration under Contract #DTFA03-98-D-00008, Delivery Order #0016 and performed at Iowa State University's Center for NDE as part of the Center for Aviation Systems Reliability program in cooperation with partners at Boeing Commercial, Boeing Phantom Works, Delta Airlines, United Airlines, Rolls Royce, General Electric, Pratt & Whitney, Honeywell, D&W Enterprises, and Sherwin.

**Engineering Study of Dry Powder Developer Application in FPI**

---**Lisa Brasche**, Rock Lopez, and Dave Eisenmann, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011

---For successful inspection, adherence to the established process parameters is critical. As with other methods, this is also true of fluourescent penetrant inspection. A key step in the FPI process is the application of developer which serves to draw the penetrant out of the crack making it more visible under black light. Typical industrial inspection systems utilize a developer chamber or cabinet to apply dry powder to the part surface. Engineering studies have been completed to assess the effectiveness of dry powder application in several typical industrial settings. Laboratory studies have also compared several penetrant/developer combinations. Results of these studies will be presented and conclusions provided.---This material is based upon work supported by the Federal Aviation Administration under Contract #DTFA03-98-D-00008, Delivery Order #0016 and performed at Iowa State University's Center for NDE as part of the Center for Aviation Systems Reliability program in cooperation with partners at Boeing Commercial, Boeing Phantom Works, Delta Airlines, United Airlines, Rolls Royce, General Electric, Pratt & Whitney, Honeywell, D&W Enterprises, and Sherwin.

**Study of Light Level Effects on FPI Performance**

---**Lisa Brasche**, Bill Meeker, Rick Lopez, and Dave Eisenmann, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011; John Lively, Pratt & Whitney, P. O. Box 109600, M/S 702-06, West Palm Beach, FL 33410-9600

---Fluorescent penetrant inspection includes several critical process steps to arrive at an acceptable part for inspection. Upon completion of the part processing, the component is moved to a darkened area and inspected under adequate black light. Current industry specifications define white light levels and minimum black light intensity. However, data supporting the adequacy of these specifications is needed to determine if current parameters are appropriate. POD studies and measurement of indication brightness have been performed to understand the relationship between black light and white light levels. Preliminary results will be presented.---This material is based upon work supported by the Federal Aviation Administration under Contract #DTFA03-98-D-00008, Delivery Order #0016 and performed at Iowa State University's Center for NDE as part of the Center for Aviation Systems Reliability program in cooperation with partners at Boeing Commercial, Boeing Phantom Works, Delta Airlines, United Airlines, Rolls Royce, General Electric, Pratt & Whitney, Honeywell, D&W Enterprises, and Sherwin.

## *Session 29*

Thursday, August 4, 2005

## **SESSION 29**

### ***BENCHMARK STUDIES***

**T. Gray, J. Bowler, and L. Schmerr, Co-Chairpersons**  
**Moulton Union Main Lounge**

- 3:30 PM**      **Simulating the Ultrasonic Experiments of the 2005 Ultrasonic Benchmark Problem**  
---**L. W. Schmerr, Jr.**<sup>1,2</sup>, T. A. Gray<sup>1</sup>, A. Lopez-Sanchez<sup>1,2</sup>, <sup>1</sup>Center for NDE and the <sup>2</sup>Department of Aerospace Engineering, Iowa State University, Ames, IA 50011
- 3:50 PM**      **The 2004 Ultrasonic Benchmark Problem – SDH Response Under Oblique Incidence: Measurements and Patch Element Model Calculations**  
---**C. V. Krishnamurthy**, S. Maddu, and J. V. Vardhan, Centre for Nondestructive Evaluation, Indian Institute of Technology, Chennai, Tamil Nadu, India; K. Balasubramaniam, Department of Mechanical Engineering, Indian Institute of Technology, Chennai, Tamil Nadu, India
- 4:10 PM**      **Results of 2005 UT Modeling Benchmark Obtained with CIVA at CEA: Beam Modeling and Flaws Signal Prediction**  
---**S. Lonné**, M. Cinquin, S. Chatillon, R. Raillon, and S. Mahaut, Commissariat à l’Energie Atomique, SYSSC, Bat 611, CEA Saclay, 91191 Gif sur Yvette Cedex, France
- 4:30 PM**      **Model Predictions to 2005 Ultrasonic Benchmark Problems**  
---**S.-J. Song** and H.-J. Kim, Sungkyunkwan University, School of Mechanical Engineering, 300 Chunchun-dong, Jangan-gu, Suwon 440-746, Korea

**Simulating the Ultrasonic Experiments of the 2005 Ultrasonic Benchmark Problem**

---Lester W. Schmerr Jr.<sup>1,2</sup>, Timothy A. Gray<sup>1</sup>, Ana Lopez-Sanchez<sup>1,2</sup>, <sup>1</sup>Center for NDE and the <sup>2</sup>Dept. of Aerospace Engineering, Iowa State University, Ames, IA 50011

---A set of reference experiments using side-drilled holes and crack-like geometries forms the basis for the 2005 ultrasonic benchmark study. We will model the measured A-scan responses of these reference experiments using a combination of beam and flaw scattering models coupled to an overall ultrasonic measurement model. The beam model will be a multi-Gaussian model. The flaw scattering models will be based on either the Kirchhoff approximation or more exact numerical methods. We will compare the capabilities of these various models for predicting the measured responses and the underlying incident and scattered wave fields.---This work was supported by the NSF Industry/University Cooperative Research Center at Iowa State University.

**The 2004 Ultrasonic Benchmark Problem - SDH Response Under Oblique Incidence: Measurements and Patch Element Model Calculations**

---C. V. Krishnamurthy, Shankar Maddu, and J. Vishnu Vardhan, Centre for Nondestructive Evaluation, Indian Institute of Technology, Chennai, Tamil Nadu, India; Krishnan Balasubramaniam, Department of Mechanical Engineering, Indian Institute of Technology, Chennai, Tamil Nadu, India

---The 2004 ultrasonic benchmark problem requires models to predict, given a reference pulse waveform, the pulse echo response of cylindrical voids of various radii located in an elastic solid for various incidence angles of a transducer immersed in water. We present the results of calculations based on the patch element model, recently developed at CNDE, to determine the response of an SDH in Aluminum for specific oblique incidence angles. Patch element model calculations for a scan across the SDH, involving a range of oblique incidence angles, are also presented. Measured pulse-echo scans involving the SDH response under oblique incidence conditions are reported. In addition, through transmission measurements involving a pinducer as a receiver and an immersion planar probe as a transmitter under oblique incidence conditions are also reported in a defect-free Aluminum block. These pinducer-based measurements on a defect-free block are utilized to characterize the fields at the chosen depth. Comparisons are made between predictions and measurements for the pulse-echo response of a SDH.

**Results of 2005 UT Modeling Benchmark  
Obtained with CIVA at CEA: Beam Modeling  
and Flaws Signal Prediction**

---**Sébastien Lonné**, Marie Cinquin, Sylvain Chatillon, Raphaële Raillon, and Steve Mahaut, Commissariat à l'Energie Atomique, SYSSC, Bat 611, CEA Saclay, 91191 Gif sur Yvette Cedex, France

---The CIVA software developed at the French Atomic Energy Commission (CEA) for processing and simulating NDT data (ultrasonics, eddy-current) includes tools for simulating the whole inspection of a component (possibly made of anisotropic heterogeneous materials and of complex geometry CAD defined) in which virtual defects (calibration reflectors or complex shaped flaws) are positioned. Simulated images are directly comparable with measured ones, as same imaging tools are used for both. The field radiated into the component and generated by refraction by an arbitrary transducer (standard, phased-array) from a coupling medium (immersion, contact) is computed using a model of elastodynamic pencils and accounts for transducer diffraction effects under the approximations of Rayleigh integral formulation. Various scattering theories can be used to compute the beam / defect interaction. In this paper, Kirchhoff's approximation was applied. Reciprocity principle allows us to predict the reception by the transducer of waves scattered by the defect. Results given and discussed are those obtained for the various problems of the 2005 UT benchmark modeling session. These results concern the echographic responses of side drilled holes and different cracks using immersed inspection technique.

**Model Predictions to 2005 Ultrasonic  
Benchmark Problems**

---**Sung-Jin Song** and Hak-Joon Kim, Sungkyunkwan University, School of Mechanical Engineering, 300 Chunchun-dong, Jangan-gu, Suwon 440-746, Korea

---The World Federation of NDE Centers (WFNDEC) has addressed the 2005 ultrasonic benchmark problems including a linear scanning of the side drilled hole (SDH) specimen with oblique incidence with an emphasis on further study on SV-wave response of the SDH versus angles around 60 degrees and responses of a circular crack. To solve these problems, we will adopt the multi-Gaussian beam model and the generalized Rayleigh-Sommerfeld integral as beam models and the Kirchhoff approximation and the separation of variables methods as far-field scattering models. By integration of the models and the system efficiency factor obtained from the given reference experimental setups provided by CNDE into our ultrasonic measurement models, we will predict the responses of the SDH and the circular crack (small cylindrical shape) and summarize the models and predicted results in this paper.

## *Session 30*

Thursday, August 4, 2005

**SESSION 30**  
**NEW SENSORS**  
**Druckenmiller Hall 016**

- 3:30 PM**      **Finite Element Analysis of Capacitive Micromachined Ultrasonic Transducer (cMUT) for NDE Applications**  
---**V. Kommareddy**, M. K. KM, and S. Ramaswamy, Industrial Imaging and Modeling Lab, GE Global Research, Bangalore, India; K. Kishore, Micro and Nano Systems Technologies Lab, GE Global Research, Bangalore, India; J. Barshinger and Y. Fan, Nondestructive Technologies Lab, GE Global Research, Nishkayuna, NY; W.-C. Tian, Micro and Nano Technologies Lab, GE Global Research, Nishkayuna, NY
- 3:50 PM**      **Laser Vibrometric Study of Plate Waves for Structural Health Monitoring (SHM)**  
---**B. Koehler** and J. W. Blakshire, IzfP/FhG, Krueger strasse 22, Dresden, 01326, Germany
- 4:10 PM**      **Multilayer Thin Film Sensors for Structural Health Monitoring**  
---**A. G. Protasov**, National Technical University of Ukraine, Nondestructive Testing Department, Ukraine; Y. G. Gordienko, E. E. Z asimchuk, and G. V. Kurdyumov, Institute of Metal Physics of the National Academy of Sciences, Kiev, Ukraine
- 4:30 PM**      **Embedding Fiber Optic Sensors in FRP Bridge Decks for Building “Smart Materials”**  
---**P. Klinkhachorn**, G. M. Lonkar, and A. S. Mercer, West Virginia University, Lane Department of Computer Science and Electrical Engineering, Morgantown, WV 26506-6109; U. B. Halabe and H. GangaRao, West Virginia University, Department of Civil and Environmental Engineering, Morgantown, WV 26506-6109
- 4:50 PM**      **Mobile Robot Ultrasound Backscatter Algorithm for Automatically Distinguishing Walls, Fences and Hedges**  
---**M. K. Hinders** and W. Gao, College of William an Mary, Applied Science Department, Williamsburg, VA 23187-8795

**Finite Element Analysis of Capacitive Micromachined Ultrasonic Transducer (cMUT) for NDE Applications**

---**Vamshi Kommareddy**, Manoj Kumar KM, and Sivaramanivas Ramaswamy, Industrial Imaging and Modeling Lab, GE Global Research, Bangalore, India; Kuna Kishore, Micro and Nano Systems Technologies Lab, GE Global Research, Bangalore, India; James Barshinger and Ying Fan, Nondestructive Technologies Lab, GE Global Research, Niskayuna, NY; Wei-Cheng Tian, Micro and Nano Technologies Lab, GE Global Research, Niskayuna, NY

---This paper presents numerical results on the 2-D Capacitive Micro-machined Ultrasonic Transducer (CMUT) that can be used to generate sound in air or water, based on FE. CMUTs have become very popular over the last decade because of the comparable bandwidth, sensitivity and dynamic range with its piezoelectric counterparts. The ease of fabrication is an added advantage. The CMUT is a coupled physics problem, which involves solving Electrostatics and Structural interactions simultaneous. A finite-element model of the CMUT is constructed using the commercial code ANSYS. Three different approaches of solving the coupled field problem are discussed and the results are compared for resonance frequency, collapse voltage and electromechanical coupling. The approaches discussed involves TRANS126 element, Fully Coupled Analysis and Reduced Order Modeling (ROM). Also discussed is the effectiveness and scope of each approach when considering material nonlinearity, ambient pressure and pre-stressed condition in the analysis.

**Laser Vibrometric Study of Plate Waves for Structural Health Monitoring (SHM)**

---**Bernd Koehler** and J. W. Blakshire, IzfP/FhG, Krueger strasse 22, Dresden, 01326, Germany

---Economic aspects are not only important in the design and development of technical systems and products but also for their operation. The life cycle costs of a technical system are mainly composed of the in-service usage costs and the maintenance and inspection costs. To lower life cycle costs Structural Health Monitoring (SHM) has gained considerable importance throughout the last few years in fields like aerospace, automotive or civil engineering. Structural Health Monitoring can be understood as an effective means to enhance system reliability, increase efficiency, and decrease life cycle cost of a complex technical system by introducing condition based maintenance and continuous structural integrity monitoring. Lamb waves have been discussed extensively in the past few years as an effective mean for wide area damage detection in plate-like structures. Automatic damage detection systems can be designed exciting and receiving Lamb waves by appropriate built in or surface mounted transducers. The damage is identified by comparing sensor signals before and after the damage event. The difference is the scatter signal originating from the defect. Usually, point like transducers are discussed for Lamb wave excitation in this context. The paper stresses the idea to use the principles of the phased array in this context. The wave fields generated by simple phased arrays are visualized by Laser-vibrometric imaging and the peculiarities in connection with dispersion effects of the plate waves are discussed. Preliminary conclusions about an efficient health monitoring concept are drawn.

### **Multilayer Thin Film Sensors for Structural Health Monitoring**

---**Anatoliy G. Protasov**, Nondestructive Testing Department, National Technical University of Ukraine, Kyiv, Ukraine; Yuri G. Gordienko, Elena E. Z asimchuk, and G. Kurdyumov, Institute of Metal Physics of the National Academy of Sciences, Kiev, Ukraine

---This paper is devoted to the new innovative approach to 'structural health monitoring' within the production and maintenance/servicing aircraft industry. The approach is based on the real-time multiscale monitoring of the smart-designed multilayer thin film sensors ("multiscale smart skin") of fatigue damage with the standard electrical input/output interfaces which can be connected to the embedded and on-board aircraft computers. The "multiscale smart skin" is a thick multilayer (~0.2-0.4 mm) structure which could be rigidly attached (glued, welded or sputtered) to the underlying aircraft component with complex geometry. The first lowest layer is a highly sensitive soft Al single-crystalline film that undergoes the permanent evolution due to external deformation influence from the underlying aircraft component. The second layer is made from different conducting and semiconducting polymer matrix composites (PMCs) with electrical characteristics (resistance, inductance, capacity, etc.) which are highly sensitive to shape changes. The third layer is a terminal, i.e. a multiscale grid of contacts for data acquisition that creates the standard interface for plugging to the embedded or onboard computer systems of an aircraft. The approach provides the optimized composition for the "multiscale smart skin" components, the criteria for the most appropriate method of data acquisition, and detailed descriptions of the requirements in using the "multiscale smart skin" as well. The information from the "multiscale smart skin" response of the actual unpredictable fatigue damage is also discussed, along with the optimal approach for real-time monitoring and adaptation of the data acquisition methods to the available interface and standards. Moreover, the approach supplies the criteria and estimations of reliability and statistical robustness of the health monitoring technique along with the preparation to its practical implementation.

### **Embedding Fiber Optic Sensors in FRP Bridge Decks for Building "Smart Materials"**

---**P. Klinkhachorn**, G. M. Lonkar, and A. S. Mercer, West Virginia University, Lane Department of Computer Science and Electrical Engineering, Morgantown, WV 26506-6109; U. B. Halabe and H. GangaRao, West Virginia University, Department of Civil and Environmental Engineering, Morgantown, WV 26506-6109

---This work aims to analyze the feasibility and effects of embedding Fiber Optic Sensors (FOS) in FRP bridge decks. Embedded FOS lead to the development of "smart materials." Such materials can be developed during the pultrusion process or afterwards. Both the techniques are explored. The first method uses three FRP bridge decks of size 2ft x 1ft manufactured at Bedford Reinforced Plastics. FOS were embedded after pultrusion, while joining the three decks by plyogrip to obtain a deck of size 5.5ft x 1ft. Extrinsic Fabry Perot (EFPI) FOS and a Fiber Bragg Grating (FBG) FOS were embedded in the joints with strain gauge sensors surface mounted above. The specimen was subjected to a cyclic load test for a performance analysis. The second test aimed to embed FOS during the pultrusion process. Both EFPI and FBG FOS were embedded inside FRP components manufactured at Bedford Reinforced Plastics. The embedded FOS were then tested to ascertain the effects of embedding. Results show a correlation between the readings from strain gauges and FOS. Embedding after pultrusion may not be the best way to build "smart materials." A better approach is to embed during pultrusion. Development of such a system is a feasible but challenging task.

**Mobile Robot Ultrasound Backscatter  
Algorithm for Automatically Distinguishing  
Walls, Fences and Hedges**

---**Mark K. Hinders** and Wen Gao, Applied  
Science Department, College of William & Mary,  
Williamsburg, VA 23187-8795

---The goal of our work is to explore the usefulness of air-coupled ultrasound as an imaging sensor for mobile robots. We here present an algorithm to distinguish several kinds of brick walls, picket fences and hedges based on the analysis of backscattered ultrasound echoes. The echo data are acquired by a mobile robot with a 50 kHz ultrasound computer-controlled scanning system packaged as its sensor head. For several locations along a wall, fence or hedge a fan of backscatter ultrasound echoes are acquired and digitized as the transducer is swept over a horizontal arc. Backscatter is then plotted vs. scan angle, with a series of N-peak deformable templates fit to this data for each scan. The number of peaks in the best-fitting N-peak template indicates the presence and location of retro-reflectors, and allows automatic categorization of the various fences, hedges and brick walls.

## *Session 31*

Thursday, August 4, 2005

**SESSION 31**  
**NEW TECHNIQUES AND APPLICATIONS**  
**Cleveland Hall 151**

- 3:30 PM**      **Comparative Study of the Sensitivity of Vibro-Acoustic Modulation and Damping Measurement as NDT Techniques**  
---**P. Duffour**, University College London, Department of Civil & Environmental Engineering, United Kingdom; M. Morbidini and P. Cawley, RCNDE, Imperial College London, London, United Kingdom
- 3:50 PM**      **Electromagnetic-Acoustic Modeling of Fields Induced by Gradient Pulses in Diffusion Tensor Magnetic Resonance Imaging**  
---I. Elshafiey, King Saud University, Electrical Engineering Department, Riyadh, Saudi Arabia; L. **Udpa**, Michigan State University, Electrical Engineering Department, MI 48864-1226
- 4:10 PM**      **Millimeter Wave Nondestructive Detection of Rust in Painted Steel Structures**  
---**S. Kharkovsky** and R. Zoughi, University of Missouri-Rolla, Electrical and Computer Engineering Department, 224 EECH, Rolla, MO 65409
- 4:30 PM**      **Phase Lock-In Reflectometry for Detection and Characterization of Defects Along Wires**  
---**H. Ambalam**, A. Siddoju, R. Reibel, S. Sathish, and B. G. Frock, University of Dayton Research Institute, Center for Materials Diagnostics, Structural Integrity Division, 300 College Park, Dayton, OH 45469-0127

**Comparative Study of the Sensitivity of Vibro-Acoustic Modulation and Damping Measurement as NDT Techniques**

---**Philippe Duffour**, Department of Civil & Environmental Engineering, University College London, London, United Kingdom; Marco Morbidini and Peter Cawley, RCNDE, Imperial College London, London, United Kingdom

---The sensitivities of the conventional damping test and the emerging vibro-acoustic modulation NDT technique have been compared on three types of cracked specimens: (1) a set of mild steel beams cracked in the laboratory, (2) a perspex beam also cracked in the laboratory and (3) an industrial component made of a nickel-based alloy. The latter was forged and cracked in the forging process. The damage severity indexes predicted from the two techniques are compared for each type of specimen. They are also compared with the actual crack size when the specimens could be broken. The results showed very similar performances on the specimens used. Both techniques work best for lightly damped specimens and in setups such that the influence of the support can be minimized. Their sensitivity is severely affected when these two conditions are not satisfied which significantly lower their appeal for many practical situations. The results also show that the correlation between the predicted damage severity and actual crack size was in general fairly poor for both techniques. Some explanation is given as to why this is the case.

**Electromagnetic-Acoustic Modeling of Fields Induced by Gradient Pulses in Diffusion Tensor Magnetic Resonance Imaging**

---Ibrahim Elshafiey, Electrical Eng. Department, King Saud University, Riyadh, Saudi Arabia; **Lalita Udpa**, Electrical Eng. Department, Michigan State University, MI 48864-1226

---Diffusion tensor magnetic resonance imaging (DT-MRI) has recently gained popularity because of its capabilities in axonography of the central nervous system. In this technique, large diffusion gradient pulses are incorporated into the MRI sequence, to enhance sensitivity to random water diffusion in anisotropic biologic tissues. Fast imaging sequences are used to reduce motion induced distortion effects on the diffusion signal. Use of fast sequences however is associated with low signal levels, high acoustic noise, and occasional peripheral nerve stimulation PNS. Eddy current induced by diffusion gradient pulses is also a challenge to DT-MRI. Magnetic field associated with eddy current is a major source of artifacts in scanner images. This research introduces a finite element modeling of electromagnetic and acoustic fields in DT-MRI sequences. The analysis involves three dimensional modeling of the scanner and its interaction with pulses applied to gradient coils. Efficient modeling of induced fields is essential in optimizing parameter settings and improving performance of this imaging modality. This would bring help to many patients, and would also improve our understanding of connectivity in the human brain.

**Millimeter Wave Nondestructive Detection of Rust in Painted Steel Structures**

---**Sergey Kharkovsky** and Reza Zoughi, University of Missouri-Rolla, Electrical and Computer Engineering Department, 224 EECH, Rolla, MO 65409

---Painted steel structures exposed to the elements are susceptible to rusting. Corrosion may cause various mechanical and structural deficiencies such as wall thinning. It is desirable to detect and evaluate the properties of a corroded region early in the corrosion process, fast and in real-time. Microwave nondestructive inspection techniques have shown great potential for this purpose in the past decade. This is in particular true for painted structures, and those covered with other dielectric coatings, in which microwave signals can easily penetrate through the paint or the coating and expose the presence of rust. Similar methods using millimeter wave frequencies are expected to provide higher spatial resolution. Additionally, at these higher frequencies other anomalies associated with the painting process or the age of paint may also be detected. This paper presents the results of an extensive investigation spanning a frequency range of 30-100 GHz and using magnitude- or phase-sensitive reflectometers. Using 2D automated scanning tables, raster images of the rust patches are produced showing the spatial resolution capabilities of these systems. Additionally, attributes of increase in frequency of operation will also be discussed.

**Phase Lock-In Reflectometry for Detection and Characterization of Defects Along Wires**

---**Hari Ambalam**, Ajay Siddoju, Richard Reibel, and Shamachary Sathish, Center for Materials Diagnostics, Structural Integrity Division, University of Dayton Research Institute, 300 College Park, Dayton, OH 45469-0127

---Reflectometry techniques are commonly used to detect electrical discontinuities present along electrical wires. One of the major techniques that have been in use for several decades is the Time Domain Reflectometry (TDR). In TDR an extremely narrow electrical pulse is injected into the wire. As the electromagnetic wave propagates along the wire, the changes in the impedances due to defects partially reflect the signal. The reflected signal is detected at the transmitting end. Analysis of the reflected signal provides information about the characteristics of the defects and its location. However, in detecting and determining exact location of the defect, particularly on dispersive electrical wires, the TDR has several limitations. This paper presents a phase lock-in reflectometry technique, based on the measurement of phase for detection and location of defects in an electrical wire. A tone burst signal of known frequency was propagated through the wire and the reflected signal was compared with the input signal using a lock-in amplifier. An analysis of the phase of the signals in the frequency range of 10-50 MHz was performed to detect opens, shorts as well as changes occurring in the connectors. Results of the analysis of defects on aircraft type of wires, printed circuit boards and flex circuits used in computer hard disk drives are presented. Electrical circuit model developed using PSPICE software for analysis of the reflected wave form and its application to identify and analyze the defects are discussed.

# *Session 32*

Thursday, August 4, 2005

## **SESSION 32**

### **X-RAY TECHNIQUES AND APPLICATIONS Moulton Union Lower Level**

- 3:30 PM**      **Energy-Discriminating Linear Detector Array**  
---**F. Hopkins**, B. Ross, T. Gordon, and Y. Du, GE Global Research, Niskayuna, NY 12309
- 3:50 PM**      **Monte Carlo Simulation Tool with CAD Interface**  
---**G.-R. Jaenisch** and C. Bellon, Federal Institute for Materials Research and Testing, Division VIII.3 Nondestructive Testing, Berlin, Germany; M. Zhukovsky and S. Podoliako, Keldysh Institute for Applied Mathematics of Russian Academy of Sciences, Department Electrodynamics and Computational Diagnostics, Moscow, Russia
- 4:10 PM**      **Quantitative Measurements of X-Ray Scattering in Industrial Application from 20 keV to 320 keV**  
---**S. Wendt**, J. Gray and F. Inanc, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011
- 4:30 PM**      **Development in Using High Energy X-Ray Diffraction for Measure Residual Stress**  
---**M. Al-Shorman**, J. Gray, and T. Jensen, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011
- 4:50 PM**      **Impeller Metrology for Pipeline Compressors Using Computed Radiography**  
---**T. Gordon**, G. Nelson, C. Bueno, and D. Noonan, GE Global Research, Nondestructive Technologies, Laboratory, One Research Circle, KWD Room 259A, Niskayuna, NY 12309; S. George, A. Mahesh, and S. Korukonda, GE Global Research, Bangalore, India; F. Fabbri, U. Cantelli, and N. Marcucci, GE Energy Oil & Gas, Firenze, Italy
- 5:10 PM**      **Blob Identification and Characterization in Porous Soil Structures Using 3D Image Analysis and Phosphor Screen Computed Tomography**  
---N. Sheikh, **J. Gray**, T. Jensen, C. Halverston, and D. White, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 School Road, Ames, IA 50011

**Energy-Discriminating Linear Detector Array**

---**Forrest Hopkins**, Bill Ross, Trey Gordon, and Yanfeng Du, General Electric Global Research, Niskayuna, NY 12309

---A team of researchers from General Electric Global Research has produced a new Energy-Discriminating Linear Detector Array (ED LDA) with dynamic selection of X-ray ray path and energy deposition geometries. ED LDAs offer the potential to provide material separation in both digital radiographic and CT imaging that could facilitate the detection of foreign material such as residual core or oxidation in turbine blades or corrosion in pipes and metallic structures. The first embodiment of the new detector approach consists of a scintillation layer coupled to a fiber optic plate, which is bonded to an amorphous silicon panel and oriented in a side-on fashion. The image of the energy deposition pattern in the scintillator can be analyzed in a dynamic, post-acquisition fashion to obtain preferred regions of deposition for optimum separation of low energy x-ray and high energy x-ray attenuation events. This technique has been used successfully to separate low Z material from higher Z material with energy discriminating digital radiography. The flexibility of the technical approach, whereby the depth of the scintillator can be extended in a straightforward manner, provides for high detection efficiency, high resolution ED detectors for source energies from 100keV up to 16MeV.

**Monte Carlo Simulation Tool With CAD Interface**

---**Gerd-Ruediger Jaenisch** and Carsten Bellon, Federal Institute for Materials Research and Testing, Division VIII.3 Nondestructive Testing, Berlin, Germany; Mikhail Zhukovsky and Sergej Podoliako, Keldysh Institute for Applied Mathematics of Russian Academy of Sciences, Department Electrodynamics and Computational Diagnostics, Moscow, Russia

---In radiography, irradiating the object and recording the transmitted radiation gives information about the inner structure of an object. The transmitted radiation consists of a primary and a scattered component. The Monte Carlo method allows the detailed description of the physics of radiation transport. On the other hand, it is necessary to handle complex object geometries to be able to simulate realistic inspection scenarios. Standard Monte Carlo programs like the Monte Carlo n-particle transport code MCNP (Los Alamos National Laboratories) use mainly simple geometrical forms such as parallelepipeds, ellipsoids, or planes to construct complex geometries in a proprietary way. Here a model is presented that combines the Monte Carlo method with the world of CAD. Components are described as closed triangulated surfaces using STL as exchange format, which is supported by all CAD systems. The opportunities of the presented Monte Carlo simulation tool are discussed in terms of various examples and compared to MCNP.

**Quantitative Measurements of X-ray Scattering in Industrial Application from 20keV to 320 keV**

---**Scott Wendt**, Joe Gray, and Feyzi Inanc, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011

---Effects of X-ray scattering processes are well known in radiography and other x-ray methods; however, there are a considerable number of parameters that complicate the practical description of scattered radiation. While the well known Compton scattering formula is widely referenced, it doesn't lend itself to providing insight to the generation of a typical scattering field seen in an inspection chamber. We present recent results on x-ray scattering measurements in the energy range from 20 keV through 320 keV. A key result is that scattering is controlled by four separate parameters, the volume of the material illuminated, the distance of the detector from the scatter sources, the x-ray optical length of the material and the shape of the part. It is important to note that the methodology used to measure the scattering contribution to a detector signal is very important. Quantitative measurements illustrating the result of the effects of these parameters will be presented. Of particular note is the result that at high energies the scattering can be 4-6 times that intensity of the direct flux. This has a profound impact on the loss of contrast of features in the image. We have also measured scattering spectra and can show that the energy of the scattered radiation is only marginally shifted to lower energies. This has bearing on the effectiveness of lead screens reducing scatter and having the result of better image contrast.---This material is based upon work supported by the Federal Aviation Administration under Contract #DTFA03-98-D-00008, Delivery Order #0012 and performed at Iowa State University's Center for NDE as part of the Center for Aviation Systems Reliability program.

**Development in Using High Energy X-Ray Diffraction for Measure Residual Stress**

---**M. Al-Shorman**, J. Gray, and T. Jensen, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011

---We are developing high energy diffraction, between 50 and 150 KeV, method for use in measuring internal strain of moderately sized objects. Traditional x-ray strain measurements are limited to a few microns depths due to the use of Cu  $K\alpha$  and Mo  $K\alpha$  radiation. The high energy that we are using allows for greater penetration. We have completed demonstrations of high energy diffraction in aluminum through 150 micron Ni layers. Due to the very small diffraction angle, less than 5 degrees, this represents several centimeters of Ni. We have also developed a simulation program for modeling the effect of monochromator slit alignment, detector collimator configurations and several scanning means. We will present recent results on the development of this new tool and on x-ray diffraction measurement at high energy, typically in the range of 60-100 keV.---This work was performed at the Center for NDE at Iowa State University with funding from the Air Force Research Laboratory on contract FA 8650-04-C-5228.

**Impeller Metrology for Pipeline Compressors Using Computed Radiography**

---**Trey Gordon**, Garth Nelson, Cliff Bueno, and Dan Noonan, GE Global Research, Nondestructive Technologies Lab, One Research Circle, KWD Room 259A, Nishkayuna, NY 12309; Sheri George, Asati Mahesh, Sanghamithra Korukonda, GE Global Research, Bangalore, India; Marco Fabbri, Ugo Cantelli, and Nicola Marcucci, GE Energy Oil & Gas, Firenze, Italy

---A team of researchers from GE Global Research and GE Energy has developed a new method to quantitatively measure critical features in pipeline turbine impellers using computed radiography (CR). This capability is required during the design and manufacturing processes to optimize the efficiency of impeller performance. For the impeller used in this study, it is critical to dimension the key features of throat distance, leading edge profile, blade thickness, and exit angle with non-destructive methods with an accuracy of 5 mils. Many imaging modalities were investigated, but it was determined that CR was an optimal solution with its large area coverage, simplicity, and high spatial resolution. A novel phantom was developed in conjunction with a unique image processing algorithm chain to determine the accuracy of feature sizing with CR. The phantom is an 11.25" diameter, 0.375" thick stainless steel disc with 4-6 raised features, oriented in such a way as to test multiple object orientations in one CR image. In CR tests with this phantom at 43" source to detector distance, a measurement repeatability of 99.9% (1 mil) was demonstrated. Challenges to the impeller metrology such as object positioning, image magnification and part geometry issues will also be discussed.

**Blob Identification and Characterization in Porous Soil Structures Using 3D Image Analysis and Phosphor Screen Computed Tomography**

---N. Sheikh, **J. Gray**, T. Jensen, C. Halverston, and D. White, Iowa State University, Center for NDE, 1915 Scholl Road, Ames, IA 50011

---Blob identification finds its application in various fields and in a variety of datasets whether they belong to medical sciences, geology, engineering or non destructive evaluation. Blob identification algorithm introduced by us consists of a series of sweeps through a 3D dataset and assessing whether a voxel's neighbors are above a threshold. An entire connected region is identified as a blob and added to a list of blob structures. Erosion and dilation operations are used to separate weakly connected blobs. Analysis functions produce information about the shape of the blobs and assemble statistical information about the distribution of the size and shapes. As an application soil samples used in foundation material in civil structures is analyzed for the size of blobs and the number and location of blob regions. This algorithm can be enhanced to study interconnectivity and constrictions in soil network. We present recent studies using a large area CsI phosphor screen 3D CT system. The image is acquired from a cooled 14 bit CCD camera with 3k X2k pixels. This system allows the generation of CT scans at 150 micron voxel sizes for objects up to 15' is size.---This material is based on work supported by NASA under award NAG-1-029-98.

# ***FRIDAY***

Session 33 – Probability of Detection and Detection Reliability .....	205
Session 34 – NDE for Process Control .....	210
Session 35 – NDE for Coated Materials and Material Damage .....	216
Session 36 – UT Flaw Detection and Characteri- zation .....	222

# *Session 33*

Friday, August 5, 2005

## SESSION 33

### **PROBABILITY OF DETECTION AND DETECTION RELIABILITY** **Moulton Union Main Lounge**

- 8:30 AM**      **A Statistical Model to Adjust for by Flaw-Sizing Bias in the Computation of Probability of Detection**  
---**Y. Wang**<sup>1</sup> and W. Q. Meeker<sup>2</sup>, Iowa State University, <sup>1</sup>Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011; <sup>2</sup>Department of Statistics, 304C Snedecor Hall, Ames, IA 50011
- 8:50 AM**      **Model-Assisted POD for Ultrasonic Detection of Cracks at Fastener Holes**  
---**C. A. Harding**, G. R. Hugo, and S. J. Bowles, Maritime Platforms Division, Defence Science and Technology Organisation, Fishermans Bend, Victoria, Australia
- 9:10 AM**      **On Mathematical Methods to Determine POD**  
---R. J. Fokkink and M. Ouwehand, Delft University of Technology, Delft Institute of Applied Mathematics, The Netherlands; **N. Portzgen** and C. Wassink, Röntgen Technische Dienst b.v., Development Department, Delftweg 144, 3046 NC Rotterdam, The Netherlands
- 9:30 AM**      **Use of Physics-Based Models to Guide the Extrapolation of Aircraft Engine Ultrasonic POD Data to Small Flaw Sizes**  
---**R. B. Thompson**, T. A. Gray, and W. Q. Meeker, Iowa State University, Center for NDE, Applied Sciences Complex II, 1915 Scholl Road, Ames, IA 50011
- 9:50 AM**      **Probability of Detection Estimation for Hit/Miss Data When Detection Cannot be Attributed to Specific Flaws: An Exploratory Data Analysis**  
---**F. W. Spencer**, Independent Surveillance Assessment & Statistics Department, Sandia National Laboratories, Albuquerque, NM 87185-0829
- 10:10 AM**      **Coffee Break**
- 10:30 AM**      **SIMULTSONIC: A Simulation Tool for Ultrasonic Inspection**  
---A. Krishnamurthi, S. Karthikeyan, and **C. V. Krishnamurthy**, Centre for Nondestructive Evaluation, Department of Mechanical Engineering, Indian Institute of Technology, Chennai, Tamil Nadu, India; K. Balasubramaniam, Department of Mechanical Engineering, Indian Institute of Technology, Chennai, Tamil Nadu, India
- 10:50 AM**      **Finite Difference Simulation of Ultrasonic NDE Methods for the Detection and Sizing of Stress Corrosion Cracking (SCC)**  
---**N. Portzgen** and C. Wassink, Development Department, Röntgen Technische Dienst b.v., Delftweg 144, 3046 NC Rotterdam, The Netherlands; M. Fingerhut and M. Tomar, Pipeline Integrity Services, RTD Quality Services USA LP, Houston, TX 77099
- 11:10 AM**      **Cost Benefit Analysis Incorporating Probabilistic Risk Assessment for Structural Health Monitoring**  
---**J. C. Aldrin**<sup>1</sup>, E. A. Medina<sup>2</sup>, and J. Knopp<sup>3</sup>, <sup>1</sup>Computational Tools, Gurnee, IL; <sup>2</sup>Austral Engineering and Software, Inc., Dayton, OH; <sup>3</sup>NDE Branch, Materials and Manufacturing Directorate, U.S. Air Force Research Laboratory, Wright-Patterson AFB, OH 45433-7817
- 11:30 PM**      **Adjourn**

**A Statistical Model to Adjust for by Flaw-Sizing Bias in the Computation of Probability of Detection**

---**Yurong Wang**<sup>1</sup> and William Q. Meeker<sup>2</sup>, Iowa State University, <sup>1</sup>Center for NDE, 1915 Scholl Road, Ames, IA 50011; <sup>2</sup>Department of Statistics, 304C Snedecor Hall, Ames, IA 50011

---There is an important need to quantify the probability of detection of (POD) in both production quality control and in-service reliability for parts that degrade over time. The standard assessment method, known as ahata, uses a linear regression models to relate NDE signal response to flaw or defect size. Bias in flaw sizing will cause bias in estimates of POD. This paper describes two statistical models for adjusting for bias in POD estimates that is caused by flaw sizing errors. The models are fit by using the method of maximum likelihood. We present the results of simulation studies that show how the use of our models will eliminate flaw-sizing bias.

**Model-Assisted POD for Ultrasonic Detection of Cracks at Fastener Holes**

---**Cayt A. Harding**, Geoffrey R. Hugo, and Susan J. Bowles, Maritime Platforms Division, Defence Science and Technology Organisation, Fishermans Bend, Victoria, Australia

---To reduce the cost of conducting experimental probability of detection (POD) trials, DSTO is currently developing methods for assessing POD that utilize models to account for factors that influence the inspection reliability. Model-assisted POD has the potential to significantly reduce the cost of POD trials, as well as provide alternative methods for validating reliability when conventional POD trials are not feasible. An initial target application is ultrasonic detection of cracks emanating from fastener holes. Electric-discharge machining (EDM) is frequently used to produce artificial defects for NDE procedure development and evaluation. However, a realistic measure of POD for ultrasonic methods can only be obtained using specimens containing genuine fatigue cracks, which are very expensive to produce, and it is often impractical to introduce fatigue cracks into representative structure. A key objective of DSTO research is to model the differences between the ultrasonic responses from EDM notches compared to fatigue cracks, including scatter due to natural variation in fatigue cracks and effects of crack closure. Experimental results for laboratory specimens containing both fatigue cracks and EDM notches, as well as representative aircraft structure containing EDM notches will be presented.

**On Mathematical Methods to Determine POD**

---R. J. Fokkink and M. Ouwehand, Delft University of Technology, Delft Institute of Applied Mathematics, The Netherlands; **Niels Portzgen** and Casper Wassink, Röntgen Technische Dienst b.v., Development Department, Delftweg 144, 3046 NC Rotterdam, The Netherlands

---The reliability of a nondestructive inspection method is most often quantified by a POD curve, which gives the probability of detecting a flaw versus its size. Often the uncertainty of the POD curve is expressed by a confidence interval on the POD at certain fixed sizes of the flaw, the lower limit of which benchmarks the accuracy of the equipment. The POD curve and the confidence intervals are determined by a priori mathematical and physical assumptions. In this paper we study the implications of these assumptions. We compare various methods to determine POD curves and we compare these from a mathematical point of view. It is observed that a maximum likelihood fit on the POD curve may not agree with the confidence intervals, which can be explained mathematically. We study how various mathematical methods may lead to various accuracy levels. In the real world a POD curve depends on material and field conditions. We study the physical distribution of the flaws using NDT qualification data from inspections of pipeline girthwelds.

**Use of Physics-Based Models to Guide the Extrapolation of Aircraft Engine Ultrasonic POD Data to Small Flaw Sizes**

---**R. B. Thompson**, T. A. Gray, and W. Q. Meeker, Iowa State University, Center for Nondestructive Evaluation, 1915 Scholl Road, Ames, IA 50011

---In the determination of POD by techniques such as  $A\text{-hat}$  versus  $A$ , the slope of a plot of log (flaw response) versus log (flaw size) is determined empirically by a regression analysis. This often works quite well. However, in the analysis of ultrasonic data obtained in the detection of naturally-occurring, hard-alpha inclusions in titanium alloys, a very low slope has been obtained. Physically, this is presumably the result of the complex morphology of the flaws, which leads to a very weak dependence of flaw response of flaw area. In the context of the POD analysis, this low slope of the regression line implies that very small flaws would produce a significant response, and hence a POD curve that retains a relatively large value at these small flaw sizes. However, the detection of such small flaws generally does not occur in the field. In this paper, the causes of this apparent inconsistency are identified and a procedure to correct for it is presented. The essential idea is that there is a change in slope of the regression line when flaw sizes become sufficiently small that one enters the Rayleigh scattering regime. Hence the slope of the mean flaw response line must be much steeper in this regime than it is for the larger flaw sizes, as is derived from the regression analysis. Procedures are presented to use quantitative understanding of the physics of the Rayleigh scattering regime to make the appropriate correction.

**Probability of Detection Estimation For Hit/Miss Data When Detection Cannot be Attributed to Specific Flaws: An Exploratory Data Analysis**

---**Floyd W. Spencer**, Independent Surveillance Assessment & Statistics Department, Sandia National Laboratories, Albuquerque, NM 87185-0829

---A post inspection characterization of test specimens may uncover multiple flaws present at specific inspection sites. However, the results of the nondestructive evaluation are in the form of hit or miss for the site rather than for the individual flaws present at the site. In this paper we explore several approaches to estimation of an underlying probability of detection curve when the detection results are site specific but not individual flaw specific. Binary regression is used with several candidate explanatory flaw characteristic variables. The flaw characteristics considered are the "largest flaw" present at the site, and the sum of flaw lengths. Each of these variables is combined with the categorical variable - "number of flaws" in the binary regression analysis. A third statistical model in which the individual flaws are treated independently, each governed by the same underlying probability of detection curve, is developed. In this model a miss at a site implies all of the flaws at the site were missed and a hit at the site implies only that at least one of the flaws was detected. The approaches are compared and discussed in the context of estimating a POD curve for a specific eddy current bolt-hole inspection procedure.

**SIMULTSONIC: A Simulation Tool for Ultrasonic Inspection**

---Adarsh Krishnamurthi, Soumya Karthikeyan, and **C. V. Krishnamurthy**, Centre for Nondestructive Evaluation, Department of Mechanical Engineering, Indian Institute of Technology, Chennai, Tamil Nadu, India; Krishnan Balasubramaniam, Department of Mechanical Engineering, Indian Institute of Technology, Chennai, Tamil Nadu, India

---A simulation program SIMULTSONIC is under development at CNDE to help determine and/or help optimize ultrasonic probe locations for inspection of complex components. SIMULTSONIC provides a ray-trace based assessment initially followed by a displacement or pressure field-based assessment for user-specified probe positions and user-selected component. Immersion and contact modes of inspection are available in SIMULTSONIC. The code written in Visual C++ operating in Microsoft Windows environment provides an interactive user interface. In this paper, the application of SIMULTSONIC to the inspection of very thin-walled pipes (with 450 um wall thickness) is described. The weldment (TIG type) of a thin-walled pipes needs to be inspected for poor or lack of welding across the wall thickness over the entire circumference. Ray trace based assessment was done using SIMULTSONIC to determine the standoff distance and the angle of oblique incidence for a immersion mode focused transducer. A 3-cycle Hanning window pulse was chosen to represent the probe signal and appropriate plane-wave transmission and reflection coefficients were used to account for changes in signal amplitude as the rays undergo multiple transmissions and reflections. Experiments were carried out to validate the simulations. The A-scans and the associated B-Scan images obtained through simulations show good correlation with experimental results, both with the arrival time of the signal as well as with the signal amplitudes. The scope of SIMULTSONIC to deal with parametrically represented surfaces will also be discussed.

**Finite Difference Simulation of Ultrasonic NDE Methods for the Detection and Sizing of Stress Corrosion Cracking (SCC)**

---**Niels Portzgen** and Casper Wassink, Development Department, Röntgen Technische Dienst b.v., Delftweg 144, 3046 NC Rotterdam, The Netherlands; Martin Fingerhaut and Munendra Tomar, Pipeline Integrity Services, RTD Quality Services USA LP, Houston, TX 77099

---Although solutions for detection and sizing of longitudinal and circumferential cracks in pipeline walls exist, reliable detection and sizing of SCC in pipelines has been a challenge for Non Destructive Evaluation (NDE) for many years. Detection and sizing are impeded by the fact that SCC can have very irregular morphology and can occur in random orientations. NDE as an industry on the other hand has suffered from the emerging of many new UT techniques and a difficult jargon, making easy understanding of the actual problems and solutions impossible for an outsider (i.e. the pipeline operator). This paper presents a novel approach to provide insight into the capabilities of common NDE methods using finite difference simulation software developed by RTD. Simulations are performed on the most common morphologies of SCC using the most commonly used in-the-ditch NDE methods. Using the parameters of the actual inspection procedure a picture is painted of what works and doesn't work about the most common ways of accessing SCC.

**Cost Benefit Analysis Incorporating Probabilistic Risk Assessment for Structural Health Monitoring**

---**John C. Aldrin**<sup>1</sup>, Enrique A. Medina<sup>2</sup>, and Jeremy Knopp<sup>3</sup>, <sup>1</sup>Computational Tools, Gurnee, IL, <sup>2</sup>Austral Engineering & Software, Inc., Dayton, OH, <sup>3</sup>NDE Branch, Materials and Manufacturing Directorate, U.S. Air Force Research Laboratory, Wright-Patterson AFB, OH 45433-7817

---Prior work has addressed the development of a strategy and software framework for integrating various nondestructive evaluation (NDE) design and product life management tools into a design platform enabling analysis of tradeoffs in NDE design and product life cycle outcomes such as reliability and cost. This effort builds upon this design platform to enable cost benefit analysis of structural health monitoring (SHM) systems. Probabilistic models incorporating probability of detection functions are developed to represent SHM systems. Consideration in the SHM model design is also given to address the use of secondary in-field and depot inspections, track repairs and removal from service due to SHM indications, and address the potential for SHM system degradation over time. The capability to perform Monte Carlo simulations is also provided in the software framework to explore the sensitivity of performance measures such as cost and reliability with respect to SHM system parameter variability and uncertainty in the economic service life model. A discussion is presented concerning the near and long-term costs and benefits of the SHM systems through both a qualitative survey and quantitative case studies that use the probabilistic model to provide key insight into the potential opportunities and challenges of SHM applications.

# *Session 34*

Friday, August 5, 2005

## SESSION 34

### NDE FOR PROCESS CONTROL

Druckenmiller Hall 016

- 8:30 AM**      **Recent Developments in On-Line Assessment of Steel Strip Properties**  
---**P. Meilland**, MCE, Arcelor Research S.A., B.P. 30320, 57283 Maizières-lès-Metz Cedex, France; **J. Kroos**, Quality Management, Salzgitter A.G., 38223 Salzgitter, Germany; **O.-W. Buchholtz**, WKZ-Auto, ThyssenKrupp Stahl, Kaier-Wilhelm-Strasse 100, 47166 Duisburg, Germany; **H. Hartmann**, FQZ-Brandenburg, Industriepark EKO, Strasse 20, 15890 Eisenhuettenstadt, Germany
- 8:50 AM**      **Capacitive Measurement of Paint Thickness**  
---**M. G. Neu**, Dassault Aviation, DGOI CDE, 1 avenue du Parc, 95100 Argenteuil, France; **M. T. Kinsella**, Dassault Falcon Jet, Teterborough, France; **M. F. Tixador** and **M. A. Perin**, Fogale Nanotech, Nimes, France
- 9:10 AM**      **Utilization of Electrical Impedance Tomography to Detect Internal Anomalies in Southern Pine Logs**  
---**P. H. Steele**, J. E. Cooper, and **B. K. Mitchell**, Mississippi State University, Department of Forest Products, Box 9820, Mississippi State, MS 39762
- 9:30 AM**      **Use of Digital Radiography Data for Quantitative Analysis in Design and Manufacturing Engineering**  
---**R. M. McGee**, The University of Michigan, Nuclear Engineering and Radiological Sciences, 2245 Placid Way, Ann Arbor, MI 48105; **S. J. Hollister**, The University of Michigan, Departments of Biomedical Engineering, Surgery, and Mechanical Engineering, Ann Arbor, MI 48105
- 9:50 AM**      **Quantitative Defect Prediction in Die-Casting Using X-Ray Computed Tomography and Numerical Simulation**  
---**H. Badarinarayan** and **K. Sasaki**, H. America Ltd., R&D, 34500 Grand River Avenue, Farmington Hills, MI 48335; **N. Sadaoka**, Digital Engineering Group, Hitachi Ltd., Power and Industrial Systems, 832-2, Horiguchi, Hitachinake-shi, Ibaraki-ken, 312-8507, Japan
- 10:10 AM**      **Coffee Break**
- 10:30 AM**      **Vibrothermography of Resistance Spot Welds: Resonance Enhancement and Quantitative Performance**  
---**C. J. Dasch**, General Motors R&D Center, MC 480-106-224, 30500 Mound Road, Warren, MI 48090
- 10:50 AM**      **Non-Contact Thickness and Profile Measurements of Rolled Aluminum Strip Using EMAT**  
---**A. Aruleswaran** and **A. Hobbis**, Rolling Process Group, Novelis Inc., Novelis Global Technology Research Center, P. O. Box 8400, 945 Princess Street, Kingston, Ontario K7L 5L9, Canada
- 11:10 AM**      **The Measurement of Oil Film Thickness in Ball Bearings Using Ultrasound**  
---**J. Zhang** and **B. W. Drinkwater**, University of Bristol, Department of Mechanical Engineering, Bristol, United Kingdom; **R. S. Dwyer-Joyce**, University of Sheffield, Department of Mechanical Engineering, Sheffield, United Kingdom
- 11:30 AM**      **Metallurgical and Ultrasonic Inspections of Steel Resistance Spot Welds**  
---**T. J. Potter**, **B. Ghaffari**, and **G. Mozurkewich**, Ford Motor Company, Research and Advanced Engineering, MD 3083/SRL, P. O. Box 2053, Dearborn, MI 48121-2053; **F. Reverdy** and **D. Hopkins**, Lawrence Berkeley National Laboratory, One Cyclotron Road, MS46A-1123, Berkeley, CA 94720
- 12:10 PM**      **Adjourn**

### **Recent Developments in On-Line Assessment of Steel Strip Properties**

---**Philip Meilland**, MCE, Arcelor Research S.A., B.P. 30320, 57283 Maizières-lès-Metz Cedex, France; Joachim Kroos, Quality Management, Salzgitter A.G., 38223 Salzgitter, Germany; Otto-Wolfgang Buchholtz, WKZ-Auto, ThyssenKrupp Stahl, Kaier-Wilhelm-Strasse 100, 47166 Duisburg, Germany; Hansjoerg Hartmann, FQZ-Brandenburg, Industriepark EKO, Strasse 20, 15890 Eisenhuettenstadt, Germany

---On-line non-destructive assessment of steel strip properties is a subject of growing interest amongst European manufacturers. They come in with substantial advantages, as they provide information all along the products length or surface, without slowing down the production. However their outputs are not always easy to understand and relate to the metallurgical phenomena, which drive the products' quality. Also, such outputs may also be sensitive to mechanical and thermal perturbations. Several attempts were recently undertaken by Arcelor, Salzgitter and TKS, with support from the European Community, to assess in particular the mechanical properties of flat carbon steel strips at the exit of galvanizing lines. We review here the works undertaken within different consortiums, with techniques based on magnetic properties. We include results from laboratory characterizations to assess the robustness of their outputs to perturbations as well as an overall assessment from on-line trials in plant conditions.

### **Capacitive Measurement of Paint Thickness**

---**M. G. Neau**, Dassault Aviation, DGOI CDE, 1 avenue du Parc, 95100 Argenteuil, France; M. T. Kinsella, Dassault Falcon Jet, Teterborough, France; M. F. Tixador and M. A. Perin, Fogale Nanotech, Nimes, France

---The measurement of paint thickness on composite material parts (carbon fibres and epoxy resin) is a relevant challenge. Aircraft manufacturers are interested in this measurement for thunder related behaviour of the plane structures. As well known, a structure too well insulated would not play the role of a lightning conductor, therefore leading to severe damages. For civil aircraft, the outside appearance has to be irreproachable and paint thickness may sometimes overpass the safety threshold. Thus, despite the metallic grid layered on the composite part to improve the conductivity, the thickness of the paint has to be precisely evaluated and kept under given brackets to ensure the plane safety. The Paintscope, developed by FOGALE, in partnership with DASSAULT AVIATION, is based on capacitive measurements. Several probe designs have been tested, and finally a rather easy handling portable equipment has been prototyped. The measurements on representative samples have been confronted to destructive testing (micrographies) in order to correlate the data provided by the developed prototype and the real paint thickness. Results are discussed and compared to high frequency ultrasonic measurements.

**Utilization of Electrical Impedance Tomography to Detect Internal Anomalies in Southern Pine Logs**

---**Philip H. Steele**, Jerome E. Cooper, and Brian K. Mitchell, Department of Forest Products, Mississippi State University, Box 9820, Mississippi State, MS 39762

---Machine vision companies and forest products researchers have pursued development of log scanners capable of imaging interior defects of saw logs. With this information sawing strategies can be applied that are known to increase lumber value by 10%. The most effective available technologies are too slow (CT scanning) and/or too expensive (NMR), or difficult of application (ultrasound). An Electrical Impedance Tomography (EIT) application has recently been developed to allow detection and visualization of anomalies in pine logs. The Through-Log Density Detector (TLDD) is an EIT application patented in the U.S. in 2004. The TLDD detects areas of differential density internal to logs, cants or trees. To-date the TLDD has been tested in the static mode with electrodes stationary and moved manually. Fabrication of a dynamic laboratory prototype is underway and expected to be completed by March of 2006. Tests of the TLDD show that it accurately detects knots in southern pine logs if these occur in the mature wood. The high moisture content of juvenile wood obscures the knots located in the first 10 rings or so of the log. However, it is believed that knot location in the mature wood is adequate to substantially increase lumber value.

**Use of Digital Radiography Data for Quantitative Analysis in Design and Manufacturing Engineering**

---**Robert M. McGee**, The University of Michigan, Nuclear Engineering and Radiological Sciences, 2245 Placid Way, Ann Arbor, MI 48105; Scott J. Hollister, The University of Michigan, Department of Biomedical Engineering, Surgery, and Mechanical Engineering, Ann Arbor, MI 48105

---Industrial radiographic inspections using film or image intensifiers are traditionally used for qualitative inspections of manufactured components. With advancements in computer technology and radiation detection, industrial computer axial tomography (CT) can now rapidly produce digital images of manufactured components with high levels of dimensional accuracy. These digital images can then be used by multiple engineering disciplines for a wide range of quantitative studies. Design Engineers can use digital images to perform Computer Aided Engineering (CAE) on components of interest. Durability studies which normally take weeks or even months can be performed on standard computer workstations in hours. Stress, strain and temperature analysis can be performed using the digital image of the component, regardless of the geometric complexity of the part. The results of a blind study conducted by the authors on an automotive transmission case are presented. Manufacturing Engineers can use digital images as a gage to compare the 'as built' component to a digital master in order to perform dimensional analysis as well as defect detection. This report presents a study where an internal characteristic of a fully assembled transmission was dimensioned to 0.0003 inch using a CT image produced by a 9MeV linear accelerator.

**Quantitative Defect Prediction in Die-Casting Using X-Ray Computed Tomography and Numerical Simulation**

---**Harsha Badarinarayan** and Kaname Sasaki, Hitachi America Ltd., R&D, 34500 Grand River Avenue, Farmington Hills, MI 48335; Noriyuki Sadaoka, Digital Engineering Group, Hitachi Ltd., Power and Industrial Systems, 832-2, Horiguchi, Hitachinake-shi, Ibaraki-ken, 312-8507, Japan

---This paper deals with the quantification of defects that occur during the die-casting process of a Copper motor rotor. Defects (porosities) were observed on the part after casting and X-ray CT was used as a Non-Destructive Evaluation (NDE) technique to quantify the amount (volumetric) of porosity that occurred in the part. The X-ray CT used in this study had an energy source of 6 MeV since the specimen (Copper) has a high density. The size of the voxel data obtained from the X-ray CT scan was of the order of 0.4 mm, but we can handle data with a finer resolution due to the fact that our software can deal with sub-voxel data. As a complement to the X-ray CT technique, mold flow simulation was also carried out to numerically determine the porosity in die-cast copper rotors. We show volumetric data comparison between X-ray Computed Tomography (X-ray CT) and simulation about defects inside of casting. Finally, in order to validate the results obtained from the X-ray CT and simulation analysis, the rotor was cut to get the cross-sectional information of the porosity distribution. Results obtained from destructive analysis closely match with those obtained from the NDE techniques mentioned above, thus it can be concluded that X-ray CT can be effectively used as a NDE technique.

**Vibrothermography of Resistance Spot Welds: Resonance Enhancement and Quantitative Performance**

---**Cameron J. Dasch**, General Motors R&D Center, MC 480-106-224, 30500 Mound Road, Warren, MI 48090

---The use of vibrothermography to test resistance spot welds is examined quantitatively. Vibrothermography uses ultrasound to frictionally heat the area around a spot weld and produce a transient "hot" ring. The thermal ring quickly decays into a spot. It has been previously suggested that this ring size might be used to measure the weld size. Using a novel arrangement with clamps around the weld to produce a resonant cavity, infrared images of the weld can be obtained with ultrasonic excitation pulses as short as 35 ms and with energy as low as a few joules. These early-arrival thermal images are compared to ultrasonic pulse/echo images of the same welds to elucidate the weld features that give rise to the thermogram. It is found that any joined interface is sufficient to produce the frictional heating. This is a problem for testing welds in galvanized steel where cold/soldered welds cannot be distinguished from good welds and where expulsions can produce very strong signals.

**Non-Contact Thickness and Profile Measurements of Rolled Aluminum Strip Using EMAT**

---**A. Aruleswaran** and A. Hobbis, Rolling Process Group, Novelis Inc., Novelis Global Technology Research Center, P. O. Box 8400, 945 Princess Street, Kingston, Ontario K7L 5L9, Canada

---Novelis Inc. is a multinational company engaged in all aspects of aluminum rolling and rolled products. Accurate measurement of aluminum strip thickness and profile for quality assessment is a high priority for Novelis. This paper presents the findings of trials to measure the thickness and profile of aluminum strip using a send-receive, radially polarized Electromagnetic Acoustic Transducer (EMAT). A broadband EMAT system, developed at Warwick University with a centre frequency of approximately 5MHz and frequency content up to 12MHz was used. The resultant ultrasonic waveforms have been processed using Fourier analysis. Aluminum alloy samples in the thickness range between 0.28mm to 2.8mm have been measured using this non-contact approach, at stand-offs of up to 2mm. Measurements across the strip width with an offline measurement system were carried out successfully to evaluate the thickness profile. Some of the experiments and results obtained are described in detail.

**The Measurement of Oil Film Thickness in Ball Bearings Using Ultrasound**

---**Jie Zhang** and Bruce W. Drinkwater, Department of Mechanical Engineering, University of Bristol, Bristol, United Kingdom; Rob S. Dwyer-Joyce, Department of Mechanical Engineering, University of Sheffield, Sheffield, United Kingdom

---A condition monitoring system capable of providing early warning of bearing lubrication failure has been developed. Apparatus is described in which a 6016 deep groove ball bearing can be controllably tested under various operating conditions. A measurement system has been developed to monitor the thickness of the oil-film in the ball bearing using a high frequency broadband (50 MHz) ultrasonic transducer mounted in the outer raceway. Typically the oil-films are between 0.27 to 1.25 micro-meter in thickness and so are significantly smaller than the ultrasonic wavelength. The thickness is extracted via a quasi-static spring model. The measurement conditions are extremely challenging as, in addition to the difficulties associated with measuring thin films, the lubricated 'contact' region is of the order of 100 micro-meter in length and the bearing operates at high speed. The measurement system described uses accurate triggering and rapid data capture to overcome these problems. Importantly, 10-100 ultrasonic pulses are used to characterize each lubricated region and hence improve the accuracy of the thickness measurement. Experiments are described in which the loading conditions and rotational speed are varied. The ultrasonically measured oil-film thicknesses obtained are shown to agree well with the predictions from classical elastohydrodynamic lubrication theory.

**Metallurgical and Ultrasonic Inspections of Steel Resistance Spot Welds**

---Timothy J. Potter, **Bita Ghaffari**, and George Mozurkewich, Ford Motor Company, Research and Advanced Engineering, MD 3083/SRL, P. O. Box 2053, Dearborn, MI 48121-2053; Frederic Reverdy and Deborah Hopkins, Lawrence Berkeley National Laboratory, One Cyclotron Road, MS46A-1123, Berkeley, CA 94720

---Metallurgical examination of steel resistance spot welds has been used to gauge the capabilities of two different ultrasonic inspection techniques. Several spot welds were scanned ultrasonically and the A-scan corresponding to each scan pixel was analyzed to assess the weld state. One technique relied on fitting the A-scan echoes to a template and utilizing the amplitude of the echo from the weld faying surface, normalized by the amplitude of the front-surface echo, to produce a C-scan of the weld interface. In the other method, the Fourier transform of each A-scan was taken to calculate the ratio of the Fourier peaks corresponding to single-sheet and double-sheet thicknesses. Image processing was applied to these ratio maps to extract the largest contiguous area of high ultrasonic transmission indicative of the weld state. The specimens were subsequently sectioned, polished and etched, allowing the fully-welded, zinc-brazed, and un-welded areas of each weld to be distinguished. These sections were then compiled to construct a map of the weld faying surface for comparison with the ultrasonic maps. The C-scans obtained through the Fourier-peak technique better matched the metallurgical maps, while the fitted-amplitude method consistently overestimated the size of the welds.

# *Session 35*

Friday, August 5, 2005

## SESSION 35

### ***NDE FOR COATED MATERIALS AND MATERIAL DAMAGE*** **Cleveland Hall 151**

- 8:30 AM**      **Dispersion Characteristics for Axial Rayleigh Wave Dispersion for Coated Cylindrical Geometry**  
---**M. A. Hussain**, M. A. Doxbeck, and J. Frankel, US Army RDECOM ARDEC AETC, WS&T, AMSRD-AAR-AEW-TA, B115, 1 Buffington Street, Watervliet, NY 12189-4000
- 8:50 AM**      **Quality Assessment of Refractory Protective Coatings Using Multi-Frequency Eddy Current MWM-Arrays**  
---V. Zilberstein, L. Evans, C. Huguenin, D. Grundy, I. Shay, and **N. Goldfine**, JENTEK Sensors, Inc., 110-1 Clematis Avenue, Waltham, MA 02453-7013; C. Mulligan, US Army Armament Research, Development & Engineering Center, Benét Laboratories, Watervliet, NY 12189-4050
- 9:10 AM**      **Optical Coherence Tomography for Inspection of Highly Dispersive Ceramic Media: Glass Powders and Plasma Sprayed Coatings**  
---**J. Veilleux** and M. I. Boulos, University of Sherbrooke, Department of Chemical Engineering, Sherbrooke, Québec, Canada; C. Moreau, D. Lévesque, and M. Duffour, Industrial Material Institute, National Research Council Canada, Boucherville, Québec, Canada
- 9:30 AM**      **Acoustic Evaluation of the Integrity of Thin Film Structures**  
---**J. Du** and B. R. Tittmann, The Pennsylvania State University, Department of Engineering Science and Mechanics, University Park, PA 16802
- 9:50 AM**      **Ultrasonic Resonance in Thin Two-Layer Dynamic Systems**  
---**B. Lanyon**, S. Dixon, and G. Rowlands, University of Warwick, Department of Physics, Coventry, CV4 7AL, United Kingdom
- 10:10 AM**      **Coffee Break**
- 10:30 AM**      **High Resolution Materials Characterization of Critical Geometries Using a Pulsed Phase Locked Loop Instrument**  
---**M. J. McKenna**, E. V. Malyarenko, J. E. Lynch, A. Achanta, and J. S. Heyman, Luna Innovations-Hampton Roads, 130 Research Drive, Hampton, VA 28666
- 10:50 AM**      **Thermo-Elastic Characterization of Heat Damage in Carbon Fiber Epoxy Composites**  
---**S. Sathish** and R. Reibel, Structural Integrity Division, University of Dayton Research Institute, Dayton, OH 45469; J. Welter and C. Buynak, Metals, Ceramics, and NDE Division, Air Force Research Laboratory, Wright-Patterson Air Force Base, Dayton, OH 45433-7817
- 11:10 AM**      **Assessment of the Structural Irregularity and Damage Evaluation Routine (SIDER) Capability to Locate Impact Damage on an A-320 Vertical Stabilizer**  
---**R. M. Crane**, Structures and Composites Division, Naval Surface Warfare Center, West Bethesda, MD 20817-5700; C. P. Ratcliffe, Mechanical Engineering Dept., United States Naval Academy, Annapolis, MD 21402; D. S. Forsyth, Institute for Aerospace Research, National Research Council Canada, Ottawa, ON K1A 0R6, Canada
- 11:30 AM**      **Application of Eddy Current Techniques for Orbiter Reinforced Carbon-Carbon Structural Health Monitoring**  
---**B. Wincheski**, Structures and Materials, NASA Langley Research Center, Hampton, VA 23681; J. Simpson, Lockheed Martin Space Operations, Hampton, VA 23681
- 12:10 PM**      **Lunch**

**Dispersion Characteristics for Axial Rayleigh Wave Dispersion for Coated Cylindrical Geometry**

---**Moayyed A. Hussain**, Mark A. Doxbeck, and Julius Frankel, US Army RDECOM ARDEC AETC, WS&T, AMSRD-AAR-AEW-TA, B115, 1 Buffington Street, Watervliet, NY 12189-4000

---We discuss the effect of curvature on the dispersion characteristics of axial Rayleigh waves on coated cylindrical geometries. Interior/bore coatings are essential for extending the life of a tube in harsh environments and repeated thermal cycles. The Laser Wave system is generally suitable for a straight specimen and the theory for Rayleigh wave dispersion, in the presence of strong and weak bonds, is well understood for coated samples. For the purpose of extending our present dispersion analysis, we present the theory for a cylindrical geometry with and without a coating. The results show that the effect of the curvature is quite pronounced in the kilohertz range. The dominant frequencies of the acoustic signal are dependent on the pulse duration of the laser system, and are in the megahertz range for our setup. This allows us to make only slight modification in the dispersion calculation for evaluation of coating and bond properties of cylindrical samples. Analysis has been carried out for a set of canonical problems, starting with the Pochhammer's solution and progressing towards more realistic solutions. Further, the specimen will be subject to high temperatures, in an attempt to study the effect of temperature on the propagation of Rayleigh velocities.

**Quality Assessment of Refractory Protective Coatings Using Multi-Frequency Eddy Current MWM-Arrays**

---Valadimir Zilberstein, Leslie Evans, Carolene Huguenin, David Grundy, Ian Shay, and **Neil Goldfine**, JENTEK Sensors, Inc., 110-1 Clematis Avenue, Waltham, MA 02453-7013; Christopher Mulligan, US Army Armament Research, Development & Engineering Center, Benét Laboratories, Watervliet, NY 12189-4050

---The demands to increase range, rate of fire, and muzzle velocity have resulted in increased wear and erosion problems in gun tubes coated with aqueous electroplated chromium. To increase the service life of gun tubes and address the environmental considerations associated with electroplating, dry physical vapor deposition (PVD) processes such as cylindrical magnetron sputtering (CMS) are being developed to deposit refractory metal coatings. Quantitative Nondestructive Evaluation of coatings deposited by CMS is crucial to the continued development and statistical process control of these emerging manufacturing processes. The use of a suitable device for coating thickness measurement and verification of deposited microstructure will prove highly beneficial for ensuring the quality and durability of these coatings. In this paper, we present absolute property coating characterization results for Ta multilayer coatings. These measurements were performed by a Meandering Winding Magnetometer (MWM<sup>®</sup>) eddy-current sensor and MWM-Array with grid methods. The MWM technology enables measurement of the coating thickness, the absolute electrical conductivity, the permeability of the underlying steel substrate, and the sensor lift-off. The electrical conductivity of the coating is of particular interest since it indicates the phase composition, i.e., the ratio of the intended  $\alpha$ -Ta phase to that of the undesirable  $\beta$ -Ta phase. The coating thickness correlates to the throwing power and deposition uniformity of the CMS system, and the sensor lift-off can be related to the surface roughness of the deposited coating. The use of this method for characterization of as-deposited coatings, as well as potential applications of this technique for in-service inspection will be discussed.

**Optical Coherence Tomography for Inspection of Highly Dispersive Ceramic Media: Glass Powders and Plasma Sprayed Coatings**

---**Jocelyn Veilleux** and Maher I. Boulos, Department of Chemical Engineering, University of Sherbrooke, Sherbrooke, Quebec, Canada; Christian Moreau, Daniel Lévesque, and Marc Duffour, Industrial Material Institute, National Research Council Canada, Boucherville, Quebec, Canada

---Optical coherence tomography (OCT) is evaluated as a promising technique for microstructure characterization of plasma sprayed ceramic coatings. OCT combines the principles of low coherence interferometry and optical heterodyne detection to obtain both a high sensitivity to weakly backscattered light and a high axial resolution. It thus can be used to accurately locate interfaces where the refractive index changes abruptly within translucent materials. As a preliminary study for the present work, OCT is used to collect B-scan images of different spherical glass powders with mean diameter ranging from 10 to 150 microns. The interferograms forming the B-scans are then analyzed individually to successfully gather information related to powder diameter. In particular, it will be shown that appropriate peak distance measurements on the interferograms provide a good approximation of the particle size distribution. The relationship between the light penetration depth in the glass powders and the particle diameter will also be discussed based on the Mie diffusion theory. Thereafter, OCT images of plasma sprayed ceramic coatings will be shown and different approaches for establishing correlations between the microstructure and relevant OCT interferogram parameters will be presented.

**Acoustic Evaluation of the Integrity of Thin Film Structures**

---**Jikai Du** and Bernhard R. Tittmann, Department of Engineering Science and Mechanics, the Pennsylvania State University, University Park, PA 16802

---Soft thin films are of central importance in a variety of fields ranging from semiconductor devices to optical components. With any deposited film, functional characteristics of the film depend critically upon its properties and adhesion to the substrate. However, reliable assessment of such characteristics has remained a complex problem. This paper explores the potential offered by high frequency acoustic microscopy for nondestructive, qualitative and quantitative characterization of thin (micron and submicron) films. Wave propagation modeling in soft thin film samples shows that multiple modes of surface waves can exist in soft thin film structures. Interface weakness modeling indicates that surface wave velocities are sensitive to interface conditions and that different modes have different levels of sensitivity to bond strength. Our new acoustic microscope experimental system will be able to measure experimental dispersion curves more accurately, and measure the surface wave velocity as a function of frequency in the 100 MHz to 1000 MHz range.

### **Ultrasonic Resonance in Thin Two-Layer Dynamic Systems**

---**B. Lanyon**, S. Dixon, and G. Rowlands, Department of Physics, University of Warwick, Coventry, CV4 7AL, United Kingdom

---Ultrasonic measurement of polymer cure has been demonstrated to be a method that can provide material property information for coatings or bonding applications. Often the polymer thickness required in real applications is significantly less than typical ultrasonic wavelengths that may be practically available or suitable. The cure behavior of thin layers will be different to thicker samples as the reaction is usually exothermic and strongly influenced by heat flow in the system. By applying a thin layer of polymer in the thickness range 10-100 microns to an aluminium substrate with thickness of approximately 1mm we are able to monitor the effects of adhesive cure on the resonant modes of this two layer system. We describe a simple model that does not take into account ultrasonic attenuation and then an improvement to this model that does take into account ultrasonic attenuation in the polymer through viscoelastic behavior and compare the results of both models to experimental data. Experimental results show good correlation with the models and help to explain the complex behavior observed even when using the simpler model. The potential to extract the ultrasonic properties of the polymer layer from these measurements is discussed.

### **High Resolution Materials Characterization of Critical Geometries Using a Pulsed Phase Locked Loop Instrument**

---**Mark J. McKenna**, Eugene V. Malyarenko, J. Edward Lynch, Anjani Achanta, and Joseph S. Heyman, Luna Innovations-Hampton Roads, 130 Research Drive, Hampton, VA 28666

---As materials become more complex, there is an increasing need for precise, high resolution measurements to characterize strength and damage in the materials. One such example is the adhesive bond strength in composites and lap joints on aircraft structures. Another critical need is for measurements of the stiffness or crack detection in railroad tracks. One technique which has been used for such high resolution measurements is the pulsed phase locked loop ultrasonic instrument as developed by Luna Innovations. With the high resolution for measurements of changes in the ultrasonic velocity to parts per million, this instrument allows for precise nonlinear phase measurements. For the determination of the adhesive bond strength, a low-level load derivative is determined. Results will be presented which clearly differentiate between good quality and poor quality adhesive bonds for the materials and geometries tested. The measurements also can be used to predict the overall bond strength. Comparable measurements using guided waves on a railroad track can detect cracks on the underside of the track or changes in the support structure for the track itself. This device can be thought of as a traveling strain-gauge for rail performance assessment. Development of a new digital pulsed phase locked loop instrument which offers greater output power, greater stability and sensitivity will be discussed.

**Thermo-Elastic Characterization of Heat Damage in Carbon Fiber Epoxy Composites**

---**Shamachary Sathish** and Richard Reibel, Structural Integrity Division, University of Dayton Research Institute, Dayton, OH 45469; John Welter and Charles Buynak, Metals, Ceramics, and NDE Division, Air Force Research Laboratory, Wright-Patterson Air Force Base, Dayton, OH 45433-7817

---Several nondestructive evaluation techniques are in use to inspect heat damage in organic matrix composites. Majority of the techniques can detect major damage like cracking, delamination and blistering. An NDE technique sensitive to early stages of heat damage ("incipient" damage) is still elusive. This paper presents, a novel non-contact NDE method, based on detection and measurement of heat developed during the propagation of an acoustic wave through the material. Temperature changes in burn damaged regions, in a composite panel were measured. A correlation between heat exposure time and the temperature change due to acoustic wave propagation was established. Thermo-elasticity theory was used, to gain an understanding, of the relation between changes in the material property due to heat damage and temperature changes due to propagating acoustic wave. Advantages and limitations of the technique are discussed.

**Assessment of the Structural Irregularity and Damage Evaluation Routine (SIDER) Capability to Locate Impact Damage on an A-320 Vertical Stabilizer**

---**Roger M. Crane**, Structures and Composites Division, Naval Surface Warfare Center, West Bethesda, MD 20817-5700; Colin P. Ratcliffe, Mechanical Engineering Dept., United States Naval Academy, Annapolis, MD 21402; David S. Forsyth, Institute for Aerospace Research, National Research Council Canada, Ottawa, ON K1A 0R6, Canada

---The U.S. Navy is currently involved in the development of several large area composite structures for fleet implementation. Techniques to provide rapid nondestructive inspection of large area composite structural components are required for these applications. An inspection technique, Structural Irregularity and Damage Evaluation Routine, SIDER, has been developed by the Navy to rapidly locate areas of stiffness variation that result from processing anomalies and in-service damage. SIDER was used to locate impact damage created on an A320 vertical stabilizer. Various impact energy levels were used, from 50 J, simulating barely visible impact damage, to 120 J, simulating significant impact damage. The entire structure was inspected using SIDER as well as conventional ultrasonic and thermographic techniques. A comparison of the capability of each of these techniques to locate the impact damage will be presented. In addition, results from the use of MEMs sensors to perform the SIDER inspection is presented.

**Application of Eddy Current Techniques for Orbiter Reinforced Carbon-Carbon Structural Health Monitoring**

---**Buzz Wincheski**, Structures and Materials, NASA Langley Research Center, Hampton, VA 23681; John Simpson, Lockheed Martin Space Operations, Hampton, VA

---The development and application of advanced nondestructive evaluation techniques for the Reinforced Carbon - Carbon (RCC) components of the Space Shuttle Orbiter Leading Edge Structural Subsystem (LESS) was identified as a crucial step toward returning the shuttle fleet to service. In order to help meet this requirement, eddy current techniques have been developed for application to RCC components. Eddy current technology has been found to be particularly useful for measuring the protective coating thickness over the reinforced carbon-carbon and for the identification of near surface cracking and voids in the RCC matrix. Testing has been performed on as manufactured and flown RCC components with both actual and fabricated defects representing impact and oxidation damage. Encouraging initial results have lead to the development of two separate eddy current systems for in-situ RCC inspections in the orbiter processing facility. Each of these systems has undergone blind validation testing on a full scale leading edge panel, and recently transitioned to Kennedy Space Center to be applied as a part of a comprehensive RCC inspection strategy to be performed in the orbiter processing facility after each shuttle flight.

# *Session 36*

Friday, August 5, 2005

## SESSION 36

### **UT FLAW DETECTION AND CHARACTERIZATION Moulton Union Lower Level**

- 8:30 AM**      **Bispectral Analysis of Ultrasonic Inter-Modulation Data for Improved Defect Detection**  
---**A. J. Hillis**, S. A. Neild, B. W. Drinkwater, and P. D. Wilcox, University of Bristol, Department of Mechanical Engineering, Queens Building, University Walk, Bristol BS81TR, United Kingdom
- 8:50 AM**      **Circumferential Guided Waves for Defect Detection in Coated Pipe**  
---**W. Luo**, J. L. Rose, and J. V. Velsor, The Pennsylvania State University, Department of Engineering Science & Mechanics, University Park, PA 16802; J. Spanner, NDE Center, Science & Technology Development, EPRI, Charlotte, NC 28221
- 9:10 AM**      **A Study on the Time Reversal Technique for Ultrasonic Guided Waves Inspection of Pipes**  
---**H.-J. Kim**, S.-J. Song, and J.-H. Seo, Sungkyunkwan University, School of Mechanical Engineering 300 Chunchun-dong, Jangan-gu, Suwon 440-746, Korea; R. B. Thompson, Iowa State University, Center for NDE and Department of Aerospace Engineering, Ames, IA 50011; J.-H. Kim and H.-S. Eom, Korea Atomic Energy Research Institute, Daejeon, Korea
- 9:30 AM**      **Rail Defect Detection Using Ultrasonic Surface Waves**  
---**R. S. Edwards**, S. Dixon, X. Jian, and Y. Fan, University of Warwick, Department of Physics, Coventry CV4 7AL, United Kingdom
- 9:50 AM**      **The Reflection of Ultrasound at Oblique Incidence Angle from Partially Contacting Rough Surfaces and from Real Fatigue Cracks**  
---**D. Liaptsis**, B. W. Drinkwater, and R. Thomas, University of Bristol, Department of Mechanical Engineering, Bristol, BS8 1TR, United Kingdom
- 10:10 AM**      **Coffee Break**
- 10:30 AM**      **Spiral Creeping Waves in Ultrasonic Angled-Beam Shear Wave Inspection of Fastener Holes in Multilayer Structures**  
---**J. C. Aldrin**<sup>1</sup>, J. Knopp<sup>2</sup>, D. Judd<sup>3</sup>, J. R. Mandeville<sup>3</sup>, and E. Lindgren<sup>3</sup>, <sup>1</sup>Computational Tools, Gurnee, IL; <sup>2</sup>NDE Branch, Materials and Manufacturing Directorate, U.S. Air Force Research Laboratory, Wright-Patterson AFB, OH; <sup>3</sup>SAIC Ultra Image Int., New London, CT 06320
- 10:50 AM**      **Inspection Using Shear Wave Time of Flight Diffraction (S-TOFD) Technique**  
---G. Baskaran and R. C. Lakshmana, Indian Institute of Technology Madras, Department of Applied Mechanics, Chennai 600036, Tamil Nadu, India; **K. Balasubramaniam**, and C. V. Krishnamurthy, Indian Institute of Technology Madras, Department of Mechanical Engineering, Chennai 600036, Tamil Nadu, India
- 11:10 AM**      **Time Domain Analysis of Subharmonic Ultrasound for Practical Crack Sizing**  
---**K. Yamanaka**, R. Sasaki, T. Ogata, Y. Ohara, and T. Mihara, Tohoku University, Department of Materials Processing, Sendai, Miyagi, Japan
- 11:30 AM**      **Flow Shape Reconstruction by Three-Dimensional Linearized Inverse Scattering Method**  
---**M. Yamada** and H. Miyakoshi, Tohoku University, Department of Civil Engineering, Graduate School of Engineering, Sendai, Japan
- 11:50 PM**      **Adjourn**

**Bispectral Analysis of Ultrasonic Inter-Modulation Data for Improved Defect Detection**

---**Andrew J. Hillis**, Simon A. Neild, Bruce W. Drinkwater, and Paul D. Wilcox, University of Bristol, Department of Mechanical Engineering, Queens Building, University Walk, Bristol BS81TR, United Kingdom

---This paper describes the use of the ultrasonic inter-modulation technique for damage detection. This technique can offer potentially far greater sensitivity than linear acoustical methods, and is extremely simple to implement. The specimen is excited by two continuous sinusoidal ultrasonic signals at different frequencies (F1 and F2) and the resultant vibration signal is captured for interrogation. The presence of damage is indicated by the generation of frequency components in the signal power spectrum at the sum and difference frequencies of the excitation ( $F2 \pm F1$ ). The vibration signal of an intact specimen would contain only the driving frequencies F1 and F2. The early detection of damage requires the discrimination of very low amplitude signal components from the background signal noise. A sensitive signal processing technique, known as bispectral analysis, is described which has the property of suppressing signal noise, permitting the detection of much smaller nonlinear effects. This approach is demonstrated experimentally on samples containing fatigue cracking. A model is also presented which highlights the benefits of the bispectrum approach and potentially allows for characterization of the nonlinearity.

**Circumferential Guided Waves for Defect Detection in Coated Pipe**

---**Wei Luo**, Joseph L. Rose, and Jason V. Velsor, Department of Engineering Science & Mechanics, The Pennsylvania State University, University Park, PA 16802; Jack Spanner, NDE Center, Science & Technology Development, EPRI, Charlotte, NC 28221

---Circumferential guided wave propagation behavior in a viscoelastic multi-layered hollow cylinder is studied to provide a baseline for further studies on wave scattering, defect detection, classification, and sizing analysis in tar coated gas pipelines. Theoretical work was carried out by developing the appropriate dispersion curves and wave structures for circumferential guided waves in a pipe coated with a viscoelastic material (such as coal tar or diffusion bonded epoxy)utilizing a matrix technique. Parameters that affect wave attenuation were investigated with some initial guidelines being established for improved penetration power. Some factors affecting wave attenuation, as well as their relationships with viscoelastic coating properties, were discovered by a parametric study. Low frequencies are suggested from both attenuation and detection depth points of view. Under this guidance, experiments utilizing a linear transducer array were conducted at a low frequency range for successfully detecting delamination and volumetric defects in tar coated pipe. It is of interest eventually to be able to calculate the reflected and transmitted guided wave scattering field from 3 dimensional defects in a tar coated pipe. Mixed mode conversion from longitudinal to shear horizontal and vice versa is expected, that with proper handling could become beneficial in defect classification and sizing analysis. In order to move in that direction, the first step is to generate dispersion curves for tar coated pipe. Values are then used in the wave scattering computational model. Even without the wave scattering analysis that is useful in defect classification and sizing, the dispersion curves reported here provide insight into attenuation effects and ways to improve propagation distance.

**A Study on the Time Reversal Technique for Ultrasonic Guided Waves Inspection of Pipes**

---**Hak-Joon Kim**, Sung-Jin Song, and Jung-Ho Seo, Sungkyunkwan University, School of Mechanical Engineering, 300 Chunchun-dong, Jangan-gu, Suwon 440-746, Korea; R. B. Thompson, Iowa State University, Center for NDE and Department of Aerospace Engineering, Ames, IA 50011; Jae-Hee Kim and Heung-Sup Eom, Korea Atomic Energy Research Institute, Daejeon, Korea

---For the long range inspection of pipes using array transducer, it is quite often adopted a phase tuning method to generate ultrasonic guided waves of the particular modes. The phase tuning method is able to control the wave modes but not to focus waves on the defects. Therefore, it is strongly desired to have a technique not only for phase tuning but also for focusing on the defects. To address such a need, in this study, we will adopt the time reversal technique that is claimed to be very robust to focus ultrasonic waves on the defect. Previously, we have proposed a numerical approach to simulate ultrasonic guided waves propagation with time delay in a pipe using array transducers. Thus, based on the previously proposed approach, we will simulate the ultrasonic guided waves propagation to and scattering from artificial defects without time delay. Based on the simulated results, we calculate the appropriate time delay using the time reversal technique and re-generate ultrasonic guided waves with the calculated time delay. In this paper, we will also present the comparison to the result obtained by the phase tuning method.

**Rail Defect Detection Using Ultrasonic Surface Waves**

---**Rachel S. Edwards**, Steve Dixon, Xiaoming Jian, and Yichao Fan, Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom

---Current testing of the rail network is limited in terms of both speed of testing and accuracy of detecting surface defects such as gauge corner cracking. By using ultrasonic surface waves generated and detected in a pitch-catch manner we can detect such defects with a much higher accuracy. We use electro-magnetic acoustic transducers (EMATs) to generate and detect the ultrasound. These have the advantage of being non-contact and require no couplant. It is not sufficient to merely detect the presence of a defect, hence accurate calibration of the system is required. We present measurements on calibration samples giving the response of the system to defects of different depths and angle to the sample surface. Further experiments have been performed on rail samples containing real defects, both longitudinal and transverse. Using the change in signal amplitude and frequency content we are able to give a depth and position for these defects, and these are compared with more established measurement methods. An enhancement of the signal when the detecting EMAT is close to the defect is also discussed.

**The Reflection of Ultrasound at Oblique Incidence Angle From Partially Contacting Rough Surfaces and from Real Fatigue Cracks**

---**Dimosthenis Liaptsis**, Bruce W. Drinkwater, and Ruth Thomas, Department of Mechanical Engineering, University of Bristol, Bristol, BS8 1TR, United Kingdom

---The ultrasonic reflection coefficient of solid-solid interfaces such as those found in fatigue cracks is known to be functions of compressive loading. In this paper the limitations of the use of quasi-static spring model of such interfaces are investigated. Specifically, the combined effects of crack face roughness and closure on ultrasonic detectability at oblique incidence are considered. Experimental results are described in which the pitch-catch reflection coefficients of compressively loaded solid-solid interfaces were measured over a range of frequencies (3-30 MHz) and at both 45° and 60° incident angles. The results obtained were compared with a quasi-static spring model predictions. This enabled the region of validity of these models to be defined for these interfaces. In addition the non-specular scattering of ultrasonic waves from the same interfaces was measured. As the spring model predicts only specular reflection, these measurements were used to assess the validity of this modelling approach. Reflection coefficients were also measured from real fatigue cracks under compressive loading. These results are discussed and the implications for modelling the inspection of real fatigue cracks are highlighted.

**Spiral Creeping Waves in Ultrasonic Angled-Beam Shear Wave Inspection of Fastener Holes In Multilayer Structures**

---**John C. Aldrin**<sup>1</sup>, Jeremy Knopp<sup>2</sup>, Dave Judd<sup>3</sup>, John R. Mandeville<sup>3</sup>, and Eric Lindgren<sup>3</sup>,  
<sup>1</sup>Computational Tools, Gurnee, IL, <sup>2</sup>NDE Branch, Materials and Manufacturing Directorate, U.S. Air Force Research Laboratory, Wright-Patterson AFB, OH <sup>3</sup>SAIC Ultra Image Int., New London, CT 06320

---NDE procedures using ultrasonic angled-beam shear wave methods with automated scanning systems have been validated for the detection of cracks at fastener sites in multilayer aircraft structures. However, there is some uncertainty concerning the reliability of these methods to detect cracks with varying angular position around the fastener hole. In addition, advanced NDE techniques that locate and size cracks at fastener sites are desired to improve decision-making concerning maintenance actions and to provide data for prognostics programs. Of particular interest toward gaining a better understanding of this complex 3D ultrasonic scattering problem is the spiral creeping wave, which propagates around the fastener hole and originates from the incident shear wave. Analytical models are first used to provide insight into the propagation of spiral creeping waves around cylindrical holes. To focus spiral creeping waves to a point of interest, consideration must be given to the incident angles and time delays across the beam to address differences in wave speed and propagation distance. Preliminary experimental data demonstrates the presence of spiral creeping waves in angled-beam inspection and the potential benefit in detecting cracks of varying angle location. Lastly, hybrid numerical methods are proposed as measurement models for 3D scattering from holes with cracks.

**Inspection Using Shear Wave Time of Flight Diffraction (S-TOFD) Technique**

---G. Baskaran and Rao C. Lakshmana, Department of Applied Mechanics, Indian Institute of Technology Madras, Chennai 600036, Tamil Nadu, India; **Krishnan Balasubramaniam** and C. V. Krishnamurthy, Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036, Tamil Nadu, India

---Ultrasonic Time of Flight Diffraction (TOFD) for sizing defects is based on the time of flight of the longitudinal diffracted echo(es) that is (are) generated when a longitudinal wave is incident on a crack tip. TOFD technique so far have been commonly applied for the inspection of thick sections (>15 mm). This paper focuses the applications of the less used SHEAR WAVE diffracted echo(es) from the defect tips, in a TOFD mode, to inspect thin sections and for near surface defects. The application of ray based model to select experimental parameters will also be discussed. Experimental result for simulated and realistic defects in thin samples will be presented.

**Time Domain Analysis of Subharmonic Ultrasound for Practical Crack Sizing**

---**Kazushi Yamanaka**, Ryouta Sasaki, Toshihiro Ogata, Yoshikazu Ohara, and Tsuyoshi Mihara, Department of Materials Processing, Tohoku University, Sendai, Miyagi, Japan

---Cracks can be detected by ultrasound if they are open. However, their detection is not easy when closed by residual stresses or interfacial oxides, causing a fundamental problem in ultrasonic testing. Subharmonics with half the input frequency are potentially useful in evaluation of such cracks, because it opens and measures them. Theories accounting for the effect of crack closure have been developed and their validity proved by comparison with experiments on a well-defined fatigue cracks. In practical applications e.g. in aged atomic power plants, subharmonics will improve the accuracy of crack sizing in a configuration similar to the time-of-flight diffraction (TOFD) method. If the amplitude is high, subharmonic signals will be detected earlier than a TOFD signal generated at open crack tip, and the depth of the closed crack can be accurately measured. When the crack has an irregular shape, as is the case for stress corrosion cracks, a phased array has been constructed with filtering at subharmonic frequency. For cracks smaller than the wavelength, resonant vibration will be excited at subharmonic frequency due to the standing Rayleigh wave on the crack face, which is also useful for crack sizing. Such novel approaches will significantly reduce the sizing error problem.

**Flow Shape Reconstruction by Three-Dimensional Linearized Inverse Scattering Method**

---**Masaki Yamada** and Hiroyuki Miyakoshi,  
Dept. of Civil Engineering, Graduate School of  
Engineering, Tohoku University, Sendai, Japan

---Geometrical characteristic of flaw in a structural component is fundamental information for repair and maintenance. The linearized inverse scattering method in this study is one of the imaging methods and reconstructs the shape of flaw in solid. This method is based on the Born and Kirchhoff approximations for unknown displacements in the integral representations of the scattered waves. The performance of two and three-dimensional inversion formulae have been validated by numerically simulated data, and it is shown that the two-dimensional inversion formulae reconstruct the shape of flaw model by experimentally measured ultrasonic waveforms. But experimental shape reconstruction by three-dimensional inversion formulae has not been notified yet. In this study, we prepare cement-based material specimens that include three-dimensional flaw models and experimentally measure backscattered waveforms from all directions surrounding the flaw model. Wave data are fed into inversion formulae after data processing, the performance of the three-dimensional shape reconstructions are confirmed.

# ***AUTHORS INDEX***

***QNDE 2006 is planned for the  
Portland Hilton  
Portland, Oregon  
July 30-August 4, 2006***

## AUTHORS INDEX

Abram, E. R., 43  
Achantá, A., 219  
Achenbach, J. D., 149, 161  
Adams, D. E., 142  
Addison, Jr., R. C., 91\*  
Ahmed, T., 24  
Aldrin, J. C., 9, 98, 100, 209, 225  
Alers, G. A., 90, 106  
Alers, R. B., 106  
Algernon, D., 8  
Alkuwari, R., 129  
Allison, S., 65  
Almond, D. P., 25, 26  
Al-Shorman, M., 203  
Ambalam, H., 200  
Anastasi, R. F., 131  
Andrews, M. J., 172  
Apelian, D., 45  
Aruleswaran, A., 214  
Arunachalam, K., 41  
Asemota, E., 117  
Ashbaugh, M., 23  
  
Babbar, V., 150  
Badarinarayan, H., 213  
Baek, E., 29  
Balasubramaniam, K., 31, 133, 135,  
192, 208, 226  
Balcom, B. J., 111  
Bamberg, J., 68, 160  
Baniukiewicz, P., 174  
Barden, T. J., 25, 26  
Barnard, D. J., 13  
Barshinger, J., 195  
Barsic, A. J., 176  
Baskaran, G., 31, 226  
Baum, G. A., 125  
Baumann, J., 26  
Bellon, C., 202  
Belvin, W. K., 138  
Benitez, D., 16, 17  
Benoist, P., 10, 96  
Benz, J., 23  
Benzerrouk, S., 45

Bescond, C., 107  
Beshears, R. D., 68  
Black, R. J., 142  
Blackshire, J. L., 113, 129  
Blakshire, J. W., 195  
Blodgett, M. P., 89, 101, 105, 107,  
149, 150, 156  
Blouin, A., 77, 78  
Boehnlein, T. R., 101  
Boileau, J., 147  
Bonavolontà, C., 37  
Bossi, R. H., 12  
Bostrom, A., 28  
Boudraa, M., 117  
Boulos, M. I., 218  
Bowler, J. R., 98, 99, 154, 191\*  
Bowler, N., 39\*, 43, 137  
Bowles, S. J., 206  
Brar, A. S., 67  
Brasche, L., 76\*, 77, 78, 188, 189,  
190  
Bray, D. E., 108  
Breugnot, S., 124, 187  
Bridge, B., 82  
Brown, C. E., 125  
Buchholtz, O.-W., 211  
Bueno, C., 204  
Burdekin, F. M., 114  
Burke, S. K., 99  
Busse, G., 47  
Buynak, C., 220  
Byeon, J. W., 184  
  
Calmon, P., 10, 35  
Cantelli, U., 204  
Casula, O., 96  
Cattiaux, G., 96, 153  
Cawley, P., 25, 26, 80, 81, 101, 161,  
199  
Cegala, F. B., 161  
Cepel, R., 136  
Cetrangolo, G., 70  
Chady, T., 85, 153  
Chaffai-Gargouri, S., 73

Chang, K.-O., 136, 185  
Chatillon, S., 73, 193  
Chau, K., 142  
Chen, F., 47  
Chen, G., 19, 182  
Chen, J. C., 46, 182  
Chen, P., 7, 8  
Chernovsky, A., 130  
Chimenti, D. E., 1\*, 96, 158, 170  
Chinn, D. J., 122  
Chiou, C.-P., 128  
Cho, H., 36  
Cho, Y.-S., 186  
Chohan, F. Y., 75  
Choi, Y. H., 119  
Choquet, M., 125  
Chung, J., 141  
Cinquin, M., 193  
Clapham, L., 150  
Clarke, J., 148  
Clemenceau, P., 124, 187  
Cochran, S., 117  
Collins, P., 187  
Concordia, M., 9  
Cooney, A., 113, 129  
Cooper, J. E., 212  
Cottle, D. L., 146  
Cramer, K. E., 25  
Crane, R. M., 220

Daniels, D. R., 144  
Dasch, C. J., 213  
De Moura, E. P., 85  
Decitre, J.-M., 153  
Degtyar, A., 159, 160  
DeNale, R., 110  
Deydier, S., 35  
Dickerson, J. A., 152  
Didion, C., 93  
DiMambro, J., 23  
Dixon, S., 45, 219, 224  
Do, T., 123  
Doering, D., 47  
Doering, E. R., 68  
Dogandzic, A., 9  
Doxbeck, M. A., 217

Drai, R., 117  
Drake, T. E., 123  
Drinkwater, B. W., 94, 112, 214, 223,  
225  
Du, J., 218  
Du, Y., 202  
Dubois, M., 121\*, 123  
Duffour, M., 218  
Duffour, P., 26, 199  
Duke, Jr., J. C., 65, 181, 186  
Dumas, P., 95  
Dwyer-Joyce, R. S., 214

Edwards, R. S., 45, 224  
Eichenberger, J., 38  
Eisenmann, D., 188, 189, 190  
El-Madaani, F., 17, 18, 173  
Elshafiey, I., 199  
Embler, J., 140  
Endo, H., 119  
Engstrand, C., 36  
Enoki, M., 181  
Enokizono, M., 102, 137  
Eom, H.-S., 224  
Erdahl, D. S., 187  
Evans, L., 217

Fabbri, M., 204  
Fair, G. E., 14, 34  
Fan, Y., 195, 224  
Fatemi, M., 46  
Favro, L. D., 23, 24  
Fei, D., 182  
Fernandes, B., 10, 16, 18, 173  
Ferreira, W. M., 85  
Fingas, M. F., 125  
Fingerhaut, M., 209  
Fokkink, R. J., 207  
Forgues, S., 107  
Forsyth, D. S., 220  
Franca, D. R., 77, 78  
Frankel, J., 217  
Franklin, M. A., 155  
Frede, M. T., 67, 158  
Friedl, J. H., 159, 171  
Frishman, A. M., 106

Fromme, P., 31  
Fu, F., 98, 99  
Fujiwara, K., 178  
Fukutomi, H., 30

Gagarin, N., 80  
Gallagher, S., 117  
Gammell, P. M., 86  
GangaRao, H. V. S., 70, 71, 196  
Gao, H., 35, 113, 114  
Gao, W., 197  
Gaydecki, P., 10, 16, 17, 18, 114,  
173  
Gebhardt, W., 93  
Generazio, E., 2  
George, S., 204  
Ghaffari, B., 147, 215  
Ghasr, M. T., 41  
Ghoshal, G., 177  
Gilles-Pascaud, C., 153  
Giurgiutiu, V., 141  
Goldfine, N., 112, 217  
Goncalves, L. L., 85  
Gonella, S., 38  
Good, K., 142  
Gordienko, Y. G., 196  
Gordon, T., 202, 204  
Gorman, M. R., 141  
Gosse, J. H., 12  
Gossellin, S. R., 90  
Gratkowski, S., 153  
Graubard, B., 152  
Gray, J., 203, 204  
Gray, T., 191\*, 192, 207  
Greenleaf, J. F., 46  
Griffiths, K., 188  
Grundy, D., 217  
Guers, M. J., 114

Haeggström, E., 69, 71, 179  
Hajj, M., 181, 186  
Halabe, U. B., 70, 71, 196  
Haldipur, P., 175  
Halverston, C., 204  
Han, X., 21\*, 23, 24  
Hanagud, S., 111

Harding, C. A., 206  
Harold, D., 65  
Harris, G. R., 86  
Harris, S., 147  
Hartmann, H., 211  
Hassan, W. T., 89, 95, 159  
Hauck, E. T., 35, 66  
Hayashi, T., 73, 116  
He, C., 66, 86  
He, J., 182  
Henderkott, J., 152  
Hentscher, S., 148  
Hernandez, M., 142  
Hesse, D., 81  
Heyman, J. S., 219  
Hillis, A. J., 223  
Hinders, M. K., 6, 197  
Hirao, M., 133, 134  
Hirata, S., 168  
Hirose, S., 29, 168  
Hobbis, A., 214  
Hodges, K. L., 25  
Hoffman, J., 98  
Hoffrén, H., 179  
Holland, S. D., 96, 158, 170  
Hollister, S. J., 212  
Holmes, C., 94  
Homma, C., 26  
Hopkins, D., 215  
Hopkins, F., 202  
Hoshikawa, H., 154, 184  
Hosten, B., 14  
Hou, Y., 24  
Howard, D. R., 22  
Howell, P. A., 25  
Howse, S. A., 68  
Hsu, D. K., 13, 36  
Huang, J., 140  
Huang, R., 74  
Hubbard, C. R., 104  
Huber, R. D., 122  
Hugo, G. R., 206  
Huguenin, C., 217  
Hussain, M. A., 217  
Hussin, H., 10, 16, 17, 18, 173

Im, C.-J., 183  
Im, K.-H., 36  
Inanc, F., 120, 203  
Islam, M. S., 24

Jackson, T. G., 125  
Jacobs, L. J., 19, 84  
Jaenisch, G.-R., 202  
Jagasivamani, V., 176  
Jan, J. E., 155  
Jarzynski, J., 19  
Jata, K. V., 139\*, 140, 142, 143, 144  
Jayakumar, T., 102, 105, 147  
Jayaraman, S. B., 159  
Jensen, T., 203, 204  
Jeon, J. H., 183  
Jeong, H., 72  
Jeong, H. J., 119  
Jezzine, K., 30  
Jian, X., 224  
Jiao, J., 86  
Jiles, D. C., 78, 90, 176  
Jing, H., 142  
John, R., 104  
Johnson, J., 177, 180  
Johnson, K. I., 90  
Johnson, M. J., 148, 152  
Johnson, T., 142  
Jones, R., 6  
Judd, D., 9, 225  
Jung, H.-K., 119  
Jung, H.-S., 183

Kacmar, C. J., 144  
Kaiser, D., 123  
Kalyanasundaram, P., 102  
Kam, T. Y., 37  
Kamitsuji, R., 29  
Kang, J. H., 184  
Kang, M. K., 155  
Kang, S. C., 119  
Kang, S.-S., 183  
Karpowicz, N., 130  
Karppinen, T., 69, 71, 179  
Karthikeyan, S., 208  
Kazantsev, D., 120

Kephart, J., 46  
Kerans, R. J., 14, 34  
Kess, H., 142  
Kharkovsky, S., 41, 200  
Kim, B. C., 136  
Kim, C. S., 184  
Kim, C.-H., 119  
Kim, H.-J., 28, 171, 178, 180, 183, 193, 224  
Kim, H.-M., 186  
Kim, I.-C., 183  
Kim, J.-H., 224  
Kim, T.-H., 186  
Kim, Y.-K., 186  
Kinsella, M. T., 211  
Kinser, E. R., 176  
Kishore, K., 195  
Kita, A., 123  
Klein, M., 38  
Kline, R. A., 36  
Klinkhachorn, P., 70, 71, 196  
KM, M. K., 6, 32, 195  
Knight, B., 22  
Knopp, J. S., 9, 98, 100, 152, 209, 225  
Ko, R. T., 101, 156  
Koehler, B., 74, 118, 195  
Koike, M., 119  
Kommareddy, V., 6, 32, 195  
Komorowski, M., 153  
Komsky, I. N., 48, 126  
Komura, I., 178  
Konstantinidis, G., 112  
Koponen, T., 69  
Korukonda, S., 204  
Kramb, V. A., 187  
Krishnamurthi, A., 208  
Krishnamurthy, C. V., 31, 133, 135, 192, 208, 226  
Krishnaswamy, S., 49, 110, 126, 135, 149, 161  
Kroos, J., 211  
Kropf, M. M., 49  
Kruger, S. E., 124  
Kuhr, S. J., 143  
Kulkarni, S. S., 149

Kumar, A., 147  
Kumar, P., 181  
Kumar, P. P., 133, 135  
Kunzler, M., 143  
Kurdyumov, G., 196  
Kuroda, H., 84  
Kurtis, K. E., 19  
Kwan, C., 114  
Kwun, S. I., 184

LaCivita, K. J., 144  
Lafond, E. F., 125  
Lakshmana, R. C., 31, 226  
Langenberg, K. J., 118  
Lanyon, B., 219  
Lavrentyev, A., 160  
Le Ber, L., 10, 73  
Lee, C., 88, 106, 152  
Lee, C. R., 37  
Lee, S., 148  
Lee, S. J., 78  
Lee, S. L., 136  
Lee, T.-K., 148  
Lee, Y.-T., 156  
Lees, B., 117  
Lefebvre, J. H. V., 7  
Leonard, K. R., 6  
Leppanen, M., 71  
Lévesque, D., 107, 218  
Leymarie, N., 35  
Lhémery, A., 30  
Lhota, J. R., 24  
Li, A., 146, 178  
Li, W., 23  
Li, X., 130  
Liaptsis, D., 225  
Licht, R., 93  
Lilley, C. M., 135  
Lin, S., 30  
Lindgren, E., 9, 225  
Linn, J. R., 155  
Lipetsky, K. G., 110  
Lively, J., 190  
Liyang, S., 72  
Lo, C. C. H., 90, 176  
Longanbach, D. M., 172

Lonkar, G. M., 71, 196  
Lonné, S., 193  
Lopato, P., 85  
Lopez, R. D., 78, 188, 189, 190  
Lopez-Sanchez, A., 162, 169, 192  
Lord, M., 107, 124  
Lowe, M. J. S., 80, 81, 161  
Lu, J., 23  
Luangvilai, K., 84  
Ludwig, R., 45  
Lunin, V. P., 118  
Luo, W., 93, 94, 223  
Lupien, V., 95  
Lynch, J. E., 219  
Lyons, R., 112

Ma, J., 81  
Madaras, E. I., 107, 128, 131, 141  
Maddu, S., 192  
Maestas, J., 123  
Mahaut, S., 10, 193  
Mahesh, A., 204  
Mall, S., 149  
Malyarenko, E. V., 219  
Mandache, C., 7  
Mandeville, J. R., 225  
Marcucci, N., 204  
Margetan, F. J., 146, 159, 175, 178  
Maris, H., 122  
Martin, R. W., 107  
Martinez, S. A., 149  
Maruvada, S., 86  
Mastikhin, I., 111  
Matlage, P., 90  
Matsui, T., 119  
Mazlumi, F., 40  
McGee, R. M., 212  
McGinnis, M. J., 20  
McKenna, M. J., 219  
Medina, E. A., 209  
Meeker, W. Q., 69, 190, 206, 207  
Meilland, P., 211  
Meksen, T. M., 117  
Melapudi, V. R., 41, 128, 129  
Melikhov, Y., 78, 90, 176  
Mengeling, V., 35

Mercer, A. S., 196  
Merrey, C., 65  
Michaels, J. E., 48, 92  
Michaels, T. E., 48, 92  
Mihalache, O., 100  
Mihara, T., 226  
Mijarez, R., 10, 114  
Miller, G., 10, 16, 17, 18, 173  
Mills, P., 80  
Mitchell, B. K., 212  
Mitri, F. G., 46  
Miura, T., 84  
Miyakoshi, H., 227  
Miyasaka, C., 146  
Moini, R., 40  
Monchalín, J.-P., 107, 124, 125  
Moran, B., 149  
Morbidini, M., 25, 26, 199  
Moreau, A., 108  
Moreau, C., 218  
Morra, M., 90  
Morris, Jr., J. W., 148  
Moslehi, B., 142  
Mozurkewich, G., 147, 215  
Mu, J., 174  
Müller, W., 118  
Mulligan, C., 217  
Murase, M., 73, 116  
Murashima, S., 75  
Murphy, R. K., 9, 98  
Murray, T. W., 122

Na, J. K., 155  
Nagao, M., 116  
Nagy, P. B., 3, 88, 89, 101, 103\*,  
150  
Naimi, E. K., 179, 185  
Nair, N. V., 129  
Nakagawa, N., 88, 106, 148  
Nakahata, K., 168  
Nakahigashi, S., 178  
Nakamura, N., 134  
Nalladegga, V., 67  
Namkung, M., 107  
Neal, S. P., 136  
Neau, M. G., 211

Neild, S. A., 223  
Nelson, G., 204  
Nelson, T. R., 129  
Néron, C., 125  
Newaz, G. M., 23, 24  
Nguyen, N., 173  
Niho, H., 133  
Nishimizu, A., 119  
Nishinoiri, S., 181  
Nitta, H., 134  
Noonan, D., 204

O'Keefe, M., 41  
Oblea, L., 142  
Ochiai, M., 84  
Ogata, T., 30, 226  
Ogi, H., 133, 134  
Ohara, Y., 226  
Ohya, T., 169  
Oka, M., 102, 137  
Olding, R. B., 187  
Onodera, T., 84  
Ortyl, N., 143  
Osakata, F., 84  
Oskard, M., 80  
Osterkamp, M., 123  
Ouwehand, M., 207

Padioleau, C., 125  
Palmer, D., 41  
Panetta, P. D., 87\*, 90, 106, 172  
Park, C. B., 80  
Park, I.-K., 73, 186  
Park, J.-S., 171  
Park, J.-W., 36  
Parthasarathy, T. A., 14, 34  
Pearson, L. H., 177, 180  
Pedrick, M. K., 159  
Peluso, G., 37  
Pepe, G. P., 37  
Peri, F., 138  
Perin, M. A., 211  
Pessiki, S., 20  
Petculescu, G., 126, 161  
Pfleiderer, K., 47  
Podoliako, S., 202

Popovics, J. S., 20, 70  
Portzgen, N., 207, 209  
Potter, T. J., 215  
Pouet, B. F., 124, 187  
Powers, P. E., 129  
Prosser, W. H., 141  
Protasov, A. G., 196  
Punurai, W., 19  
Pyatkin, V., 120

Qiao, Y., 110  
Qu, J., 19, 84  
Quek, S., 17

Rabinovich, O. I., 185  
Raillon, R., 193  
Raithel, D., 148  
Raj, B., 102, 105, 147  
Ram, B. C., 135  
Ramakrishnan, S., 129  
Ramaswamy, S., 6, 32, 195  
Ramesh, A., 172  
Rao, B. P. C., 102  
Ratcliffe, C. P., 220  
Rebello, J. M. A., 85  
Rebinsky, D. A., 182  
Redo, A., 130  
Reed, B., 152  
Reibel, R., 143, 200, 220  
Reid, M. S., 152  
Reverdy, F., 215  
Richter, J. D., 131  
Riddell, W. T., 46  
Ridgway, P. L., 125  
Rieder, H., 93  
Ring, A. P., 90  
Ringermacher, H. I., 22, 127\*  
Roberts, A. R., 25  
Roberts, R. A., 92, 96, 146, 159,  
160, 171, 175  
Rokhlin, S. I., 11\*, 34, 150  
Rose, J. L., 35, 66, 93, 94, 113, 114,  
170, 174, 223  
Ross, B., 202  
Rothenfusser, M., 26  
Rowlands, G., 219

Roy, M., 70  
Rubinshteyn, A., 150  
Rudd, K. E., 6  
Russell, D., 173  
Russo, R. E., 125  
Ruzzene, M., 38, 111  
Ryden, N., 80

Sabbagh, E. H., 9, 98  
Sabbagh, H. A., 9, 98  
Sadaoka, N., 213  
Sadeghi, S. H. H., 40  
Salov, G., 120  
Sarangan, A. M., 129  
Saranpaa, P., 69  
Sasaki, K., 213  
Sasaki, R., 226  
Sathish, S., 67, 101, 107, 143, 144,  
149, 156, 200, 220  
Sattar, T. P., 82  
Satzger, W., 68  
Schlicker, D., 112  
Schmerr, Jr., L. W., 28, 72, 74, 162,  
169, 191\*, 192  
Schmitz, V., 118  
Schubert, F., 74  
Scott, M. L., 80  
Scully, J. R., 4  
Sebastian, J. R., 67, 158, 187  
Sedov, A., 74  
Seebo, J., 128  
Seo, J.-H., 224  
Serimaa, R., 69  
Sharma, V. K., 111  
Shatat, A., 173  
Shay, I., 112, 217  
Sheikh, N., 204  
Shen, Y., 88, 106  
Shepard, M. J., 104  
Shepard, S. M., 24  
Shi, Z., 38  
Shijiu, J., 72  
Shin, Y.-K., 156, 183  
Shiwa, M., 178  
Shockley, M. W., 182  
Siddoju, A., 156, 200

Sienicki, T., 38  
Sikora, R., 174  
Simonetti, F., 81, 101, 116  
Simpson, J., 221  
Sivakumar, M. S., 135  
Smith, A. C., 176  
Smith, J., 38  
Snyder, J. E., 90  
Sohn, Y., 49  
Sollier, T., 10  
Solodov, I., 47  
Song, G., 86  
Song, J., 96, 158, 170  
Song, M. H., 119  
Song, S.-C., 183  
Song, S.-J., 28, 36, 119, 171, 180,  
183, 193, 224  
Song, W.-J., 73, 186  
Song, Y., 66  
Spanner, J., 174, 223  
Spencer, F. W., 208  
Spies, M., 93, 118, 160, 162  
Sposito, G., 101  
Steele, P. H., 212  
Stor-Pellinen, J., 71  
Stubbs, D. A., 158, 187  
Studor, G., 141  
Stuk, G., 130  
Sugiura, T., 168, 169  
Suh, D. M., 155  
Sun, J. G., 23, 172  
Sun, L., 149  
Sun, Z., 170  
Sundararaman, S., 142  
Sung, J. J., 155  
Sung, Q., 16  
  
Tabib-Azar, M., 42  
Tada, T., 133  
Takagi, T., 119  
Takahashi, N., 178  
Taniguchi, K., 181  
Tansel, I. N., 7, 8  
Telschow, K. L., 146  
Theodoulidis, T., 98, 99, 154  
Thiruvanukkarasu, S., 102

Thomas, M., 123  
Thomas, R., 225  
Thomas, R. L., 23, 24  
Thompson, R. B., 1\*, 128, 146, 159,  
171, 175, 178, 207, 224  
Thomson, C. D., 177, 180  
Tian, J., 133  
Tian, W.-C., 195  
Tillman, M., 181  
Tittmann, B. R., 49, 159, 218  
Tixador, M. F., 211  
Todorov, E., 181  
Tomar, M., 209  
Tomita, K., 181  
Torres, V., 16, 17  
Tretheway, J. S., 172  
Tsuchida, Y., 102, 137  
Tsuchihashi, K., 84  
Tuncer, E., 43  
Turner, J. A., 177  
  
Uchimoto, T., 119  
Udd, E., 143  
Udpa, L., 41, 128, 129, 199  
Udpa, S. S., 41, 128, 129  
Ueda, M., 100  
Umbach, J. A., 159  
Ume, I. C., 123  
  
Vaidyanathan, S., 102  
Valentino, M., 37  
Van Velsor, J., 66  
Vardhan, J. V., 192  
Veilleux, J., 218  
Velsor, J. V., 223  
Vensel, F., 95, 159  
Vieira, A. P., 85  
Viens, M., 134  
  
Walker, J. L., 131  
Wang, C.-Y., 29  
Wang, L., 150  
Wang, X., 86  
Wang, Y., 69, 206  
Wang, Z., 134  
Washabaugh, A., 112

Wassink, C., 207, 209  
Weber, R. J., 42, 152  
Weiying, C., 178  
Welter, J., 220  
Wendt, S., 148, 203  
White, D., 204  
White, J., 142  
White, J. S., 130  
Wiggenhauser, H., 8  
Wilcox, P. D., 47, 94, 112, 223  
Williamson, S., 130  
Wincheski, B., 221  
Winfree, W. P., 25, 128, 129, 131  
Wu, B., 86  
Wu, J., 8  
Wu, W. W., 180  
  
Xie, B., 150  
Xu, B., 141  
  
Yadegari, A. M., 40  
Yakushiji, T., 102, 137  
Yamada, M., 227  
Yamaguchi, T., 100  
Yamanaka, K., 226  
Yamashita, T., 100  
Yan, F., 35  
Yang, D.-J., 180  
Yang, I.-Y., 36  
Yawn, K., 123  
Yenilmez, A., 7, 8  
Yibo, L., 72  
Yim, H., 29  
Yoo, B., 186  
Yoo, C. S., 136  
Yoo, J. Y., 119  
Yoo, J.-C., 183  
Yu, F., 88, 89  
Yu, L., 182  
Yu, Y., 173

Zagbai, T., 28  
Zaid, M., 10, 16, 17, 18, 173  
Zalameda, J. N., 25  
Zasimchuk, E. E., 196  
Zeng, Z., 23  
Zenzinger, G., 68  
Zhang, B., 9  
Zhang, F., 135  
Zhang, J., 214  
Zhang, J. M., 172  
Zhang, L., 94, 170, 174  
Zhang, X., 125  
Zhang, X. R., 182  
Zhang, X.-C., 130  
Zhao, G., 114  
Zhao, Z., 82  
Zhou, Y., 126  
Zhu, J., 20  
Zhu, Y., 66  
Zhukovsky, M., 202  
Zilberstein, V., 217  
Zimdars, D., 130  
Zimmer, A., 118  
Zoughi, R., 40, 41, 200