Volume 2, Issue 1 January 2010

PENNSTATE

Structural Health Monitoring

About the Center of Excellence in Structural Health Monitoring

Ben Franklin Technology PArtners
Central and Northern Pennsylvania

The center was founded in 2007 with initial funding from the Ben Franklin Technology Partners.

Vision:

Bring designers and owners of platforms that benefit from structural health monitoring (SHM) technology together with researchers and developers of SHM systems. Grow the Center by building relationships that lead to fruitful multidisciplinary collaborations between industry, academia, and government.

Mission:

Advance the state-of-the-art in SHM to improve public safety, reduce maintenance costs, improve readiness, and foster a paradigm shift in design by leveraging and fostering collaborative R&D efforts between academia, industry, and government entities. Provide a means for transferring technology to member companies, agencies, and institutions.

Objectives:

- Spur the research and development of new SHM technologies
- Transfer SHM technologies to member companies to give them a competitive advantage
- Make PA a hotspot for structural health monitoring, creating a new high tech job market that will provide jobs for residents and draw people and SHM industries to PA
- Train students to provide an outstanding workforce pool in SHM technology areas

Penn State participants are from throughout the College of Engineering and the Applied Research Lab.

For more information on becoming a member contact Cliff Lissenden (*lissenden@psu.edu*) or Ed Smith (*ecs5@engr.psu.edu*).

Inside this edition

Upcoming Events

- SHM Short Course, Penn State, June 23–25, 2010
- Structural Health Monitoring Symposium, United States National Congress on Theoretical and Applied Mechanics, Penn Stater Conference Center, June 28–30, 2010
- The 2010 SHM Meeting, Penn Stater Conference Center, June 30, 2010

ESM Engineering Science and Mechanics · FBS inc. Feature Based Systems · IMPACT · SIEMENS · KCF technologies · GE Sensing & Inspection Technologies · IAI · Sikorsky A United Technologies Company

Structural Health Monitoring

From the Director

First I'd like to wish everyone a happy and productive new year! We look forward to 2010 being a banner year for research and development in structural health monitoring as there are a wide variety of ongoing projects at Penn State and our partner entities, as well as a number of future opportunities for innovative ideas. We are also optimistic about continued improvement of the national and global economies.

We are pleased to welcome two new center members this year; FBS Inc and KCF Technologies. FBS concentrates on ultrasonic guided wave technology transfer and product development. KCF delivers products and technology development to customers in industrial, research, and defense markets in the areas of navigation, energy systems, and devices.

Recent publications indicate the importance of structural health monitoring to the entire constructed infrastructure (aircraft, power generation and distribution, bridges, etc.) for public safety, operating costs, readiness, and design of future structural systems. Boller, Chang, and Fujino edited an *Encyclopedia of Structural Health Monitoring* published by Wiley in March (2960 pages, $1,695). The proceedings of the International Workshop on Structural Health Monitoring held at Stanford University 2009 (edited by Chang) encompass 11 special sessions with the theme of 'from system integration to autonomous systems'. The Rand Corporation published a technical report (authored by J.R. Gebman), "Challenges and issues with the further aging of U.S. Air Force aircraft," that provides: a historical review of technical and institutional developments from 1907-2007, technical challenges for operators, institutional challenges for operators, issues and policy options for effective life-cycle management, and the right pathway for implementing policy options. AMMTIAC Quarterly published two feature articles: "Recent trends in structural health monitoring technologies," (Vol 3, No 4 by H.T. Yolken and G.A. Matzkanin) and "A condition-based maintenance solution for army helicopters," (Vol 4, No 2 by S. Harrigan).

Furthermore, the American Society for Nondestructive Testing (ASNT) is starting to get interested in SHM technologies from engineering, operational, and workforce training points of view. I was invited to give a presentation on SHM technologies at the ASNT Fall Conference in October. Health monitoring of wind turbines is becoming important as more and more turbines are installed. The National Renewable Energy Laboratory hosted two pertinent workshops in 2009, one on wind turbine reliability, and the other on wind turbine condition monitoring. While there are a number of components with reliability concerns, two major ones are gear boxes and blades. Infant mortality and wear-out are both significant issues.

The Penn State-led NSF Engineering Research Center (ERC) pre-proposal on Ultrasound Tool Sets for Health and Infrastructure has been selected for full proposal consideration. The ERC vision is to provide the transformational science and engineering required to dramatically advance current ultrasound technologies, enabling new devices for probing the health of topologically complex and dynamic systems at length scales ranging from microns to kilometers. The proposed program will develop next generation ultrasound toolsets for: ubiquitous ultrasound-based medical care, including sonopills for diagnoses and treatment of cancers in a physician's office, conformable Sonoblankets for inspection of objects with complex shapes, such as wind turbine blades, advanced robotics, welded joints, and human limbs, and extreme environments ultrasound (ExULT) for continuous monitoring of next-generation nuclear power plants and deep-well drilling sites. The testbeds have been chosen to address engineering challenges associated with aggressive miniaturization, complex topologies, and harsh environments. Essential to each of these systems is the ability to integrate optimized piezoelectric materials with innovative transducer fabrication techniques, while providing close-coupled electronics, power management, tailored wave propagation in complex systems, and advanced image re-construction algorithms. The ERC program will advance the state of the art in piezoelectric materials, integrated electronics, as well as acoustics and transducer design.

The Center of Excellence in Structural Health Monitoring (CoE SHM) was initiated with funding from the Ben Franklin Technology Partners as a 3-year program. Ben Franklin is a PA state agency and PA is suffering through a period of economic hardship, so our funding period was cut back to 2.5 years. Thus, we are looking for stable supplemental support for the CoE SHM. If the NSF ERC program is funded, it is our intent to fold the CoE SHM and the Center of Excellence in Piezoelectric Materials and Devices into the ERC, while greatly expanding the membership base. Membership benefits will include:

- Leveraged research funding of $18.5 Million over 5 years (renewable to 10 years)
- Professional short courses
- Industrial advisory board
- Voting rights for center projects
- Non-exclusive rights to intellectual property
- Access to state of the art research facilities
- Industrial mentoring of students and post-docs
- Bi-annual workshop to present new research.

Clearly, SHM encompasses more than the ERC proposed focus on ultrasound research (prognostics, vibration and strain monitoring, and damage modeling to name just a few). We **are not** changing the mission or objectives of the CoE SHM by placing it within the ERC. We **are** providing a stable operating environment for the CoE SHM. If the ERC proposal is funded (3 of 20 proposals are expected to be awarded) the biggest change for CoE SHM members would be a change in the member agreement and dues structure. We are very optimistic about the continued growth of the CoE SHM!

Cliff J. Lissenden

The nature of predictability in systems with evolving damage

Joseph Cusumano jpc3@psu.edu *and*
Francesco Costanzo fxc8@psu.edu

Engineering Science & Mechanics professors Joseph Cusumano and Francesco Costanzo, together with postdoctoral research associate Sergey Abaimov and graduate student Arjun Roy, have carried out research aimed at exploring the nature of predictability in systems with evolving damage. The research was sponsored by Siemens as their membership project for the Ben Franklin CoE in SHM in 2008-2009. New coupled-field continuum models were developed using Hamilton's Principle. These models capture the interaction between meso-scale damage field variables and vibrations in the macroscopic displacements, and can be used to simulate damage evolution all the way from nucleation to failure. Parallel numerical implementations use simulations started from thousands of different random damage initial conditions to demonstrate how initial microstructural uncertainties give rise to probability distributions of failure in space and time. In Figure 1, typical failure time statistics obtained from such simulations are shown for longitudinal vibrations of a bar driven by a periodic end load, with the driving frequency well below the first natural frequency. The coupled-field equations are completely deterministic and were derived from general physical principles without imposing any particular probabilistic structure; nevertheless, we find that they naturally generate Weibull failure time statistics and a log-linear relationship between load and cycles to failure. Furthermore, the simulations yield information on the variability of simulated S-N curves. It was found that the degree of variability (and hence the amount of uncertainty) in the failure times can change significantly (by an order of magnitude) for loading at different frequencies due to different spatial patterns of damage growth. This connection between damage "hot spots" and failure time uncertainty has not been previously noted in the literature.

Short Course

We are preparing to conduct a 3-day short course on structural health monitoring. The course will be led by six Penn State faculty (Joseph Rose, Karl Reichard, Martin Trethewey, Charles Bakis, Francesco Costanzo, and Cliff Lissenden) and includes classroom as well as laboratory components. The course will be free for member companies.

Course Objectives

1. Describe and compare various types of diagnostics for SHM applications.

2. Select a viable SHM methodology for a given application based on available technology.

3. Apply the mechanics of guided waves for SHM applications to detect structural defects.

4. Analyze vibration data from a complex system and use it to predict remaining fatigue life.

Course topics include: SHM overview, SHM framework, material behavior, composite materials, damage mechanics, fatigue life prediction, mechanical testing, ultrasonic guided wave theory and experiments, dynamical systems and vibrations, diagnostics, prognostics, signal analysis, data fusion, classification, system design and implementation. Student feedback from the previous short course was very positive, and we plan to offer the course June 23–25, 2010.

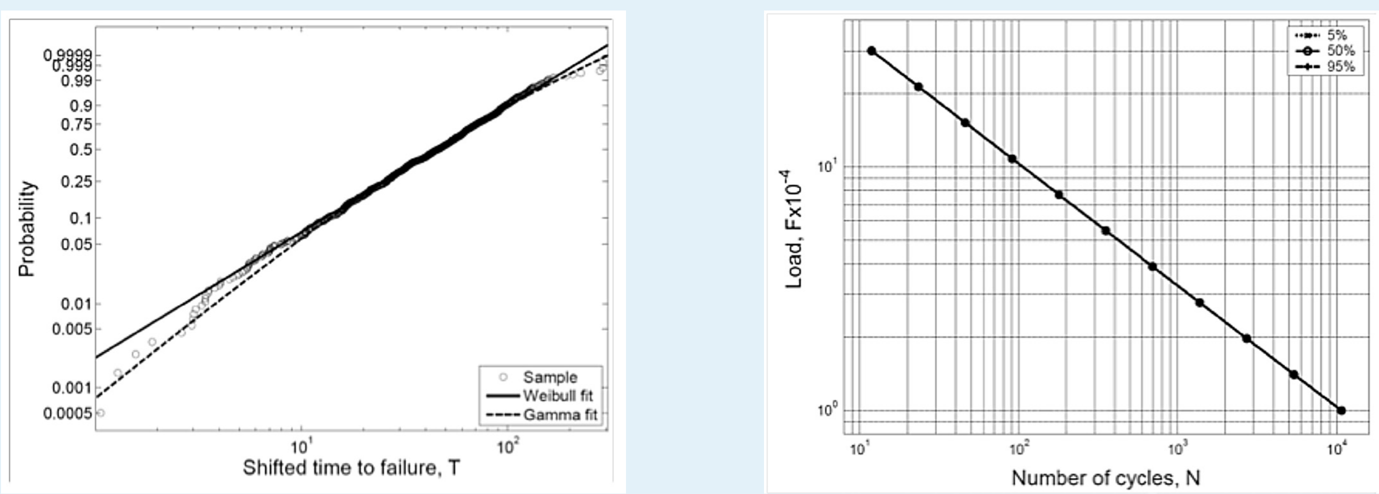

Figure 1. Failure time statistics generated using ensembles of simulations of the coupled-field equations developed as part of the project: (left) Probability of time to failure, showing an excellent fit with a Weibull distribution; (right) A simulated S-N curve, showing a linear log-log relationship between load and number of cycles to failure. Neither of these results are "built in" to the equations, but arise naturally in simulations. For the results shown, low frequency forcing (similar to a cyclic fatigue test) was used, and the only randomness consisted of spatially independent random initial conditions uniformly distributed on $[10^{-6}, 10^{-5}]$. The damage evolution itself was entirely deterministic. The statistics shown were generated using 1000 simulations starting from different random initial damage states.

June 2009 Meeting Summary

The Spring 2009 meeting was held June 12-13 at the Penn Stater Conference Center. The keynote speakers were Stephen Cumblidge from the Pacific Northwest National Laboratory and Thomas Batzinger from GE Global Research. Dr Cumblidge gave an excellent overview of structural health monitoring for the nuclear power generation industry. He discussed the PNNL, Department of Energy, and Nuclear Regulatory Commission interests in SHM, and then described materials degradation and aging management in current plants. Monitoring of new reactors and monitoring needs for advanced reactor designs were described, including wireless communication, power scavenging, and robust materials and electronics. Mr Batzinger discussed transforming inspection of structural components to diagnostics using more autonomous systems from a GE perspective. After an introduction, he eloquently described the challenges of structural health monitoring, the development of technologies at GE, and provided some thoughts on moving forward. Corrosion is pervasive across many industries, including aircraft, nuclear power, pipelines, oil, and chemical, to the tune of $276B/year. In the aircraft industry parts are replaced due to fear of failure, unknown current capability, and fleet statistics rather than known defects. Reduction in component life uncertainty has huge potential cost savings and readiness improvement. SHM provides excellent value for components not accessible for inspection.

Mark Davis (Sikorsky) presented rotorcraft airframe structural integrity monitoring, Weidong Zhu (University of Maryland – Baltimore County) discussed vibration-based structural damage detection, Roger Royer (FBS) described ultrasonic guided wave technology transfer, Elliott Cramer (NASA Langley) gave an overview of the aircraft aging and durability project, George Zhao (Intelligent Automation) discussed a wireless ultrasonic transducer network for SHM applications, Bill Nickerson (Impact RLW) presented SHM sensing and embedded monitoring devices, Igor Alvarado (National Instruments) discussed using COTS technology to create a new generation of SHM systems, and Ron Treusdell (Booz Allen Hamilton) summarized health monitoring and management industry benchmarking. Penn State presenters included: Karl Reichard (ARL) – model-based SHM, Heath Hofmann (EE) – energy harvesting, Joe Cusumano (ESM) – coupled-field modeling and simulation of damage dynamics and failure statistics, Joe Rose and Jaya Koduru (ESM) – new sensors for improved ultrasonic guided wave tomography in SHM, Clark Moose (ARL) – SHM and NDI technologies for wind energy structures, Cliff Lissenden (ESM) – probabilistic fatigue life prediction from guided wave ultrasonic technology SHM, and Tom Shrout (MSE) – Penn State led NSF ERC proposal on ultrasound tool kits for health and infrastructure. PDF files of the presentations are online at www.esm.psu.edu/shm. Greg Johnson gave an aviator's perspective on health monitoring after dinner. The meeting also featured a panel-led discussion on SHM by Cumblidge, Batzinger, Ignacio Perez (Office of Naval Research), and Shweta Sharma (Goodrich) and a tour of some of the laboratory facilities in Earth-Engineering Science building. The advisory board decided to switch to annual meetings with the next one to be held in June 2010.

Probabilistic fatigue life prediction from guided wave ultrasonic technology SHM

Cliff J. Lissenden and Hwanjeong Cho

This center funded project on probabilistic fatigue crack growth modeling enables us to develop SHM strategies that minimize life cycle costs and maximize readiness for service and safety. We are working to develop an ultrasonic guided wave SHM system for characterizing fatigue crack size at a hot spot in a built-up plate structure. While we are working toward a complex multifastener joint, we start with a single plate with a hole. Four piezoelectric wafer active sensors (PWAS) are located around the hole. One PWAS sends a toneburst signal that is received by the other three PWAS. Cycling through all four PWAS in this manner gives 12 signals associated with different guided wave paths. Because of the presence of multiple modes and reflections the signals are fairly complex. The PWAS have detected a crack less than 2 mm long. *Continued on next page…*

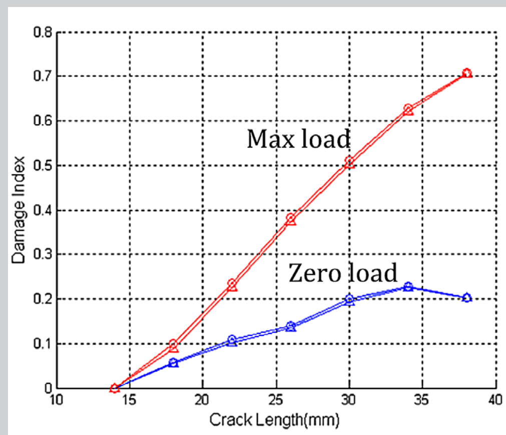

Figure 1. The damage index increases significantly more when the fatigure crack is opened by load (red) than if it is closed (blue).

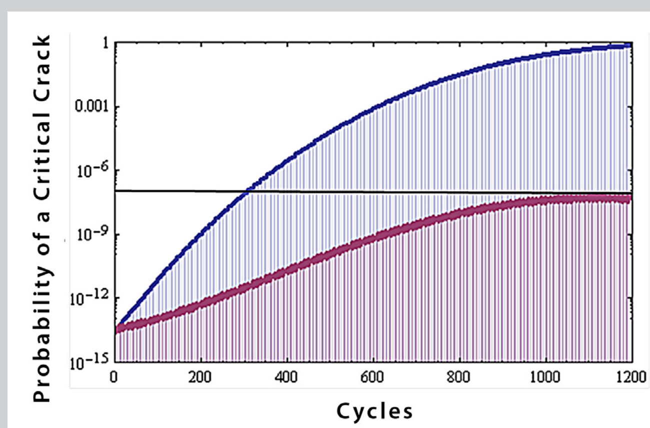

Figure 2. Blue line represents Pr(a > acr) while the red line represents Pr(a > acr) and that the crack has not been detected by the SHM system. The SHM schedule and POD have been selected to provide a reliability of at least 10^{-7}.

New People

Will McGill is an assistant professor of information sciences and technology at Penn State. His present research spans a wealth of topics within IST and engineering, including advanced uncertainty modeling for both force protection and cyber security problems, studying risk perception of experts and laypeople, and enabling participatory risk and system health management. Prior to joining Penn State, McGill served as an analytical methodologist for the DoD (2007-2008), a consultant risk engineer and uncertainty analyst (2005-2007) and technology surprise analyst for DoD (2004-2005). From 2003-2004, McGill served as the first ASME federal fellow to the Department of Homeland Security; in this role, McGill helped DHS as it sought to understand and apply risk analysis for homeland security problems. McGill began his career in 2001 as a structural engineer with Swales Aerospace, Inc., where he designed and assessed the performance of mechanical and structural systems, and oversaw test plans for environmental testing of structural subsystems. McGill holds a PhD in reliability engineering from the University of Maryland, an MS in aerospace engineering from the University of Maryland and a BS in aerospace engineering from the University of Southern California. In addition, he holds a graduate certificate in composite materials analysis from the University of Delaware and certification in denial and deception analysis from the Foreign Denial and Deception Committee (Office of the Director of National Intelligence). He is a Certified Reliability Engineer with the American Society for Quality and a registered professional engineer in MD and PA.

Sergey Abaimov was a Postdoctoral Scholar in Engineering Science and Mechanics from 11/2008 to 11/2009. His work on the statistical mechanics of damage phenomena, directed by Prof. Joseph P. Cusumano, was supported by a Siemens membership project in the Ben Franklin CoE in SHM. Sergey received his BS and MS degrees, both with honors, from the Moscow Institute of Physics and Technology, and his PhD degree from the University of California, Davis. His current research interests include statistical mechanics of complex systems, damage mechanics, phase transitions, and nucleation.

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Figure 1 shows a damage index (based upon a short time Fourier transform) as a function of fatigue crack length. This is expected to be part of an SHM scheme that enables us to characterize fatigue crack length in complex joints. Current crack size characterization enables us to model fatigue crack growth probabilistically in order to: (1) predict the reliability of the structure as a function of loading cycles as shown in Figure 2, (2) recommend replacement of the component when the probability of fracture becomes too high, (3) develop a monitoring schedule given a probability of detection for the SHM system, (4) determine the minimum probability of detection required for the SHM system given a monitoring schedule and desired lifetime. A Monte Carlo simulation of structural reliability including crack growth and probability of detection is currently being assessed.

Spray-on sol-gel piezoelectric ultrasonic transducers for online health monitoring at high temperatures

Cliff Searfass and Bernhard R. Tittmann brt4@psu.edu

Online monitoring in nuclear plants is critical for effective operations and safety, however it is especially challenging due to the harsh environment and extreme operating conditions. Conventional nondestructive evaluation (NDE) and structural health monitoring (SHM) sensory technologies are greatly challenged by high temperature applications. The most poignant example is piezoelectric materials, which are the active element in most ultrasonic transducers; their functionality is limited by their Currie temperature (in the 150-360°C range for PZT). Identifying active materials for high temperature applications is just the first challenge, coupling transducers to the structure is the next. In response to this national need, new piezoelectric fabrication methods are being developed at Penn State. Spray-on piezoelectrics have been demonstrated to function up to 1000°C. Potential applications for next generation nuclear power plants are many. Light water reactors certainly have needs for on-line health monitoring at high temperature too. The peak-to-peak voltage amplitude received from ultrasonic wave propagation excited by a composite transducer is shown in Figure 1 for temperatures ranging from 0-1000°C. Photo-lithography is being used to deposit electrodes onto the piezoceramic coating to create either a comb transducer with equally spaced rings or an interdigitated transducer with fingers. An example of a transducer is shown in Figure 2.

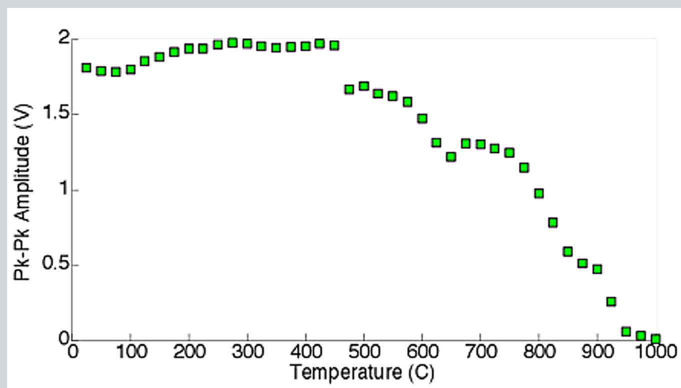


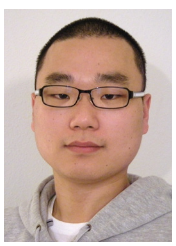
Figure 1. Bismuth titanate-lithium niobate composite transducer voltage as a function of temperature

Figure 2. Functional spray-on bismuth titanate transducer on curved turbine blade fin

Structural Health Monitoring

Student Spotlight

Manton "Matt" Guers is a Ph.D. candidate in Engineering Science and Mechanics. His dissertation advisor is Dr. Bernhard Tittmann, Shell Professor of Engineering Science. Together they are investigating ultrasonic nondestructive evaluation and structural health monitoring techniques for applications in harsh environments. In the work for his dissertation, "Techniques for in-situ ultrasonic monitoring of specimens in the Advanced Test Reactor," Matt is investigating guided waves for sensing dimensional changes in specimens of interest. The work is sponsored by Idaho National Laboratory (INL) in an effort to develop new measurement capabilities for their research facilities. Matt will be spending three months at INL working on his project. He is planning on graduating in August and will be seeking a research position in industry.



Hwanjeong Cho is a graduate student in the Engineering Science and Mechanics department. He is in the Republic of Korea Air Force (ROKAF), South Korea. He majored in weapon systems science for his bachelor's degree at the Republic of Korea Air Force Academy. After he was commissioned as an aircraft maintenance officer in 2002, he served on the flight-line for 6 years including setting up ROKAF's new F-15K aircraft. For his master's thesis he is investigating piezoelectric wafer active sensors (PWAS) to characterize the location and size of fatigue cracks in aluminum plate structures containing fastener holes.

Ronald Then is an undergraduate student majoring in Engineering Science. He acquired laboratory research experience in the summer of 2009 while working on a PA DOT sponsored project to characterize the air void system in fresh concrete using Rayleigh waves. For his honors thesis Ron is part of a team developing a tool that will use circumferential ultrasonic guided waves to characterize the extent of corrosion in steel well casing for gas storage reservoirs. After graduation in Spring 2010, Ron plans to attend graduate school at Penn State.

Intensity Based Structural Health Monitoring

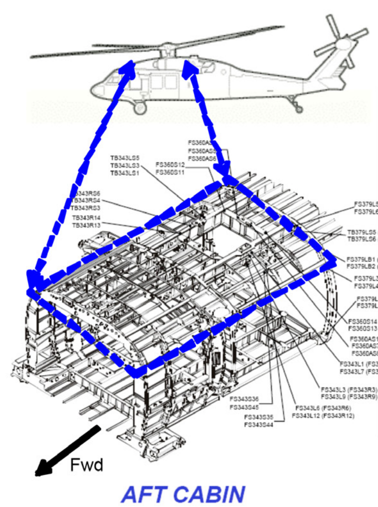
Steve Conlon scc135@arl.psu.edu, Jeff Banks, and Ed Smith

The focus of the research sponsored by the US Army Aviation Applied Technology Directorate is on the implementation of Structural Intensity (SI) sensing for SHM and assessment.

The fundamental mechanisms of structural intensity (or vibrational energy flow) are being investigated computationally and experimentally as they relate to structural damage and its detectability in rotorcraft airframe structures.

FE based computational tools are being used to study sensitivities to relevant airframe damage and optimize sensor / sensing designs. Active excitation damage detection and localization approaches based on both linear and non-linear structural responses, and their associated SI features, are being developed.

The types of representative damage include cracks, delaminations, and degraded riveted joints. Several representative test beds have been developed to correlate and validate the SHM technologies.



UH-60 Blackhawk upper cabin structure located in the PSU CAV lab for SHM research. This test bed allows for the demonstration of developed SHM technologies on a flight grade structure with associated complex structural design features.

Ultrasonic guided wave integrity analysis tool for well casing

Cliff J. Lissenden and Joseph L. Rose

Steel casing enables safe storage and extraction of natural gas from underground reservoirs. The steel casing may be thousands of feet long and is susceptible to corrosion and other types of damage. Maintenance and operations decisions depend on accurate characterization of corrosion. Magnetic flux leakage (MFL) instruments perform satisfactorily for detection, but are not good at characterization of the extent of corrosion. An integrity analysis tool based on ultrasonic guided waves is being developed to work in tandem with a MFL tool. The tool will employ both circumferential and longitudinal guided waves. Finite element modeling of circumferential wave propagation has identified features for characterizing loss of wall thickness due to corrosion. Time of flight measurements can be used to characterize the circumferential extent of corrosion and the amplitude of the analytical envelope obtained from a Hilbert transform can estimate corrosion depth as shown in Figure 1. The design of the fixture to fit inside a well casing and hold the electromagnetic acoustic transducers (EMAT) is shown in Figure 2.

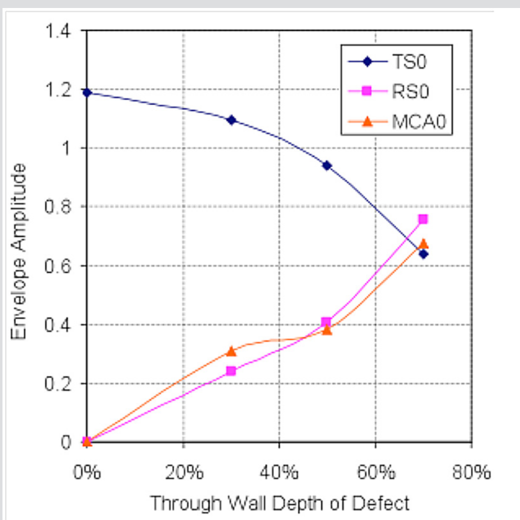


Figure 1. Predicted effect of thickness loss from corrosion on the amplitude of fundamental transmitted (TS0), reflected (RS0), and mode converted (MCA0) modes using 175 kHz excitation.

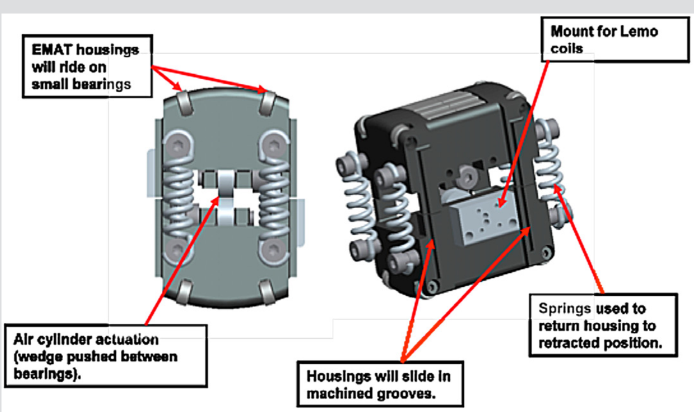


Figure 2. Fixtures are designed to mount EMATs inside a housing that will be towed through a well casing for corrosion monitoring.

Technology evaluation on characterization of the air void system in concrete

Maria Lopez, Cliff Lissenden, Chao Xiao, and Sheng Li

The objective of this PennDOT funded project was to evaluate current technologies that have the potential to characterize the air void system in concrete within the first several hours of placement. This objective was met by a comprehensive technology assessment and literature review, and conducting a laboratory evaluation of two selected technologies: ultrasound and thermography. Experimental results showed that both technologies can capture physical features that are significantly affected by the air void system in concrete.

Results show that ultrasound is able to penetrate fresh concrete as early as 4 hr after placement and that the Rayleigh wave speed is significantly influenced by the air void system (see Figure 1). The key result is that the Rayleigh wave speeds in normal concrete mix with air entrainment and in normal concrete mix without air entrainment are 1017 and 1213 m/s, respectively, 5 hours after placement. The difference of 16 percent is large enough to give Rayleigh waves strong potential to characterize the air void system.

The cool-down of concrete slabs with different mixtures after heat source removal were observed with an IR camera (image shown in Figure 2). The difference in the spatial thermal gradients for concrete with and without air entrainment was found, which appears to be attributable to the air void system. Quadratic polynomials were curve-fitted to the thermal gradients, which correlated well to the data.

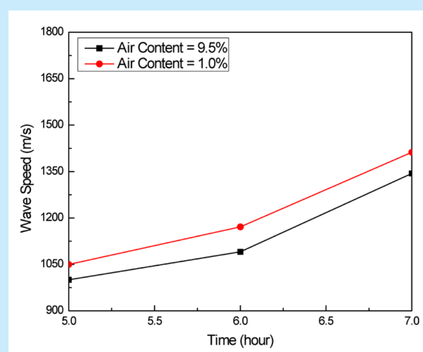
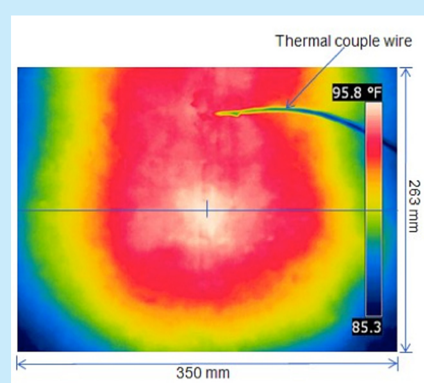


Figure 1. Rayleigh wave speed for air entrained concrete (9.5%) and normal mix concrete (1.0% air) as a function of time after placement. Air voids reduce wave speed.

Figure 2. Thermal image from IR camera for air entrained concrete (2 hr after concrete placement, 1 min after removal of heat source).



Members

Sikorsky Aircraft Corporation is a world leader in the design, manufacture and service of military and commercial helicopters; fixed-wing aircraft; and spare parts; in maintenance, repair and overhaul services for helicopters and fixed-wing aircraft; and civil helicopter operations. Sikorsky helicopters are used by all five branches of the United States armed forces, along with military services and commercial operators in 40 nations. Our well known rotary wing products include the BLACK HAWK, SEAHAWK, H-53 and Schweitzer light helicopters. Our fixed wing aircraft include Schweitzer reconnaissance airplanes as well as the PZL Mielec Sky Truck and Dromader airplanes. Sikorsky Aerospace Services provides full-spectrum service solutions to fixed and rotary wing, commercial and military customers worldwide. SAS comprehensive support is designed to minimize operator downtime, improve ease of use, and reduce cost of ownership. From newly engineered logistics programs to industry-recognized maintenance, repair and overhaul services and parts requisition, Sikorsky Aerospace Services keeps you flying.

Intelligent Automation, Inc. (IAI) is a woman owned firm founded in 1987. Headquartered in Rockville, Maryland and with over 100 researchers and technical staff, IAI has maintained its character as a diverse R&D "think tank." Our current areas of research, applications, and products focus on distributed intelligent systems, networks, signal processing, controls, robotics, artificial intelligence, communications, health monitoring, electro-mechanical systems, forensics, and educational & training technology. Key application areas include defense, transportation, law enforcement, space, communications, and training. IAI has twice been honored with the prestigious "Tibbetts Award" from the Small Business Administration and the Small Business Technology Council for excellence in technology research and commercialization.

Impact Technologies, LLC is a engineering services and product development firm that deploys solutions to monitor systems, autonomously analyze data, estimate health, and predict future capability. Impact has existing products and continued new developments in the areas of structural health management, smart sensing devices, advanced vibration detection software, oil quality monitoring, electronic component test and prognostics, actuation component fault detection, adaptive control algorithms, and a range of design, maintenance planning, and logistics tools. The broad range of these offerings and customized solution approach has assisted many DoD and industrial users to optimize the utilization of their aircraft, shipboard, ground vehicle, and land-based equipment assets with realizable cost benefit, safety enhancements, and readiness/availability improvements. Impact-RLW Systems' family of intelligent sensor products and wireless network technology complements Impact's core competencies in diagnostics, prognostics, and condition-based maintenance software, systems, and enterprise management tool sets. Impact Technologies maintains offices in Rochester, New York, State College, Pennsylvania, and Atlanta, Georgia.

GE Sensing & Inspection Technologies is part of GE Enterprise Solutions, a $5 billion business helping customers compete and win in a changing global environment by combining the power of GE's unique expertise and intelligent technology to drive customers' productivity and profitability. GE Sensing & Inspection Technologies is a leading innovator in advanced measurement, sensor-based and inspection solutions that deliver accuracy, productivity and safety to its customers. The company designs and manufactures sensing instruments that measure temperature, pressure, moisture, gas and flow rate for demanding customer applications. It also designs, manufactures and services inspection equipment, including radiographic, ultrasonic, remote visual and eddy current, that monitors and tests materials without disassembly, deforming or damaging them. Its products are used in a wide range of industries, including oil and gas, power generation, aerospace, transportation and healthcare. The company has 4,700 employees at more than 40 facilities in 25 countries worldwide.

Siemens Energy Systems is the world's leading supplier of a complete spectrum of products, services and solutions for the generation, transmission and distribution of power and for the extraction, conversion and transport of oil and gas. It develops and builds fossil fueled power plants and power generating components as well as wind turbines, turbines for use as mechanical drives and compressors for industrial applications. It also offers operations and maintenance and management services for its own technology as well as that of other manufacturers. Instrumentation and control systems, as well as air pollution control technologies, are also part of the portfolio. The company is also a leading supplier of high and medium voltage power delivery equipment, energy management systems, network planning and power system engineering software for regulated and deregulated generation, transmission and distribution markets. Siemens Energy employs approximately 73,000 people worldwide, with approximately 12,000 in the U.S.

Efforts at ***FBS Inc.*** are focused on being the preeminent ultrasonic guided wave technology transfer and product development company for all aspects of Nondestructive Evaluation (NDE) and Structural Health Monitoring (SHM) applications in pipeline, rail, aviation, power generation, manufacturing, civil infrastructure, and military products.

KCF Technologies is a privately-held research and product development company, founded in 2000. KCF delivers solutions to customers in industrial, research and defense markets with products and technology development solutions in our three business areas of Navigation, Energy Systems, and Devices. Our mission is to develop technologies and products that safeguard lives, save energy and conserve resources.

Structural Health Monitoring is published semi-annually by the Center of Excellence in Structural Health Monitoring at Penn State

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