Final Report for Period: 05/2007 - 04/2008 **Submitted on:** 06/25/2008

Principal Investigator: Michaels, Jennifer E. **Award ID:** 0401213

Organization: GA Tech Res Corp - GIT

Submitted By:

Michaels, Jennifer - Principal Investigator

Title:

Analysis and Modeling of Diffuse Ultrasonic Signals for Structural Health Modeling

Project Participants

Senior Personnel

Name: Michaels, Jennifer

Worked for more than 160 Hours: Yes

Contribution to Project:

Professor Michaels, as the PI of the project, has served as the principal advisor to the GRAs who have worked on this project (Mr. Yinghui Lu, Mr. James Hall and Mr. Ramaldo Martin). She has also been directly involved in both performing experiments and analyzing data.

Post-doc

Graduate Student

Name: Lu, Yinghui

Worked for more than 160 Hours: Yes

Contribution to Project:

Mr. Lu has participated in this project as a 1/2 time graduate research assistant for a period of about 3 years. As the primary GRA on this project, he was involved in all aspects including experiments, signal processing and algorithm development.

Name: Hall, James

Worked for more than 160 Hours: Yes

Contribution to Project:

Mr. Hall participated in this project as a graduate student and was supported for a period of 2.67 months as a 1/2 time GRA. His primary involvement was developing signal and image processing algorithms.

Name: Martin, Ramaldo

Worked for more than 160 Hours: No

Contribution to Project:

Mr. Martin participated in this project as a graduate student and was supported for a period of 2.6 months as a 1/3 time GRA. His primary involvement was assistance with experimental measurements and software development.

Name: Master, Zubin

Worked for more than 160 Hours: No

Contribution to Project:

Mr. Master was supported as a 1/3 time graduate research assistant for a period of one month. He worked primarily on data analysis.

Name: Loiselay, Florent

Worked for more than 160 Hours: No

Contribution to Project:

Mr. Loiselay was supported as a 1/3 time graduate research assistant for a period of two months. He worked primarily on data acquisition software.

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

Other Collaborators or Contacts

Professor Thomas E. Michaels (Electrical and Computer Engineering, Georgia Tech) has collaborated on some of the experimental work performed as a part of this project.

Some work on this project was performed in collaboration with Prof. Bruce Drinkwater, Dr. Paul Wilcox and Dr. Anthony Croxford of the University of Bristol, Bristol, UK.

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)

The research objective of this NSF project is to develop methods for monitoring the integrity of critical structures over large areas using diffuse ultrasonic waves. These reverberating waves 'fill' the structure with energy and are easy to generate, making them attractive for monitoring large areas with a small number of spatially distributed sensors. The problem with this method is that of sensitivity versus selectivity. Diffuse waves are sensitive to both damage and environmental changes such as temperature and surface wetting, so while it is quite straightforward to detect a change, it can be difficult to determine whether or not the change is due to damage.

Research activities consisted of (1) performing experiments on aluminum specimens instrumented with permanently attached ultrasonic sensors acting in transmit-receive pairs and subjected to both artificial damage and environmental changes, and (2) developing data analysis methods for detecting damage in the presence of the environmental changes. Research results have been disseminated via five referred journal articles and ten published conference proceedings; an additional journal article is in progress.

A number of different experiments were performed where both damage and environmental changes were systematically introduced with the goal of distinguishing structural damage from benign changes that also affect the diffuse signal. Temperature changes were detected based upon the behavior of local time shifts as determined from the local temporal coherence. Changes in diffuse signals due to temperature variations were modeled to first order by signal stretching and compressing, enabling a robust baseline comparison in the presence of modest temperature changes. This temperature compensation methodology is the foundation for not only discriminating damage from temperature changes but for minimizing temperature effects when considering other environmental changes such as surface wetting; it is also applied as a first step when localizing damage. Page 1 of the attached file illustrates detection of damage in the presence of temperature changes.

A major effort has been modeling of complex diffuse signals using the matching pursuit method. A numerical implementation of matching pursuit was developed and implemented, which uses an adaptive dictionary derived from the spectrum of the ultrasonic signal. An unconstrained decomposition is first performed on a baseline signal prior to introduction of damage or environmental changes. A constrained decomposition, which was developed as a part of this project, is then performed on the signal of interest where the basis functions from the unconstrained decomposition are retained but with adjusted amplitudes and time delays. This constrained decomposition facilitates quantitative analysis of the changes in the signals. Differential features can then be derived from the parameters of the basis functions.

A comprehensive set of experiments were carried out to investigate how varying surface conditions affect detection of damage. The surface conditions of wetting and metallic contact were considered, and both were varied incrementally in combination with incremental introduction of damage. Methods for analyzing these data were developed, and were based upon physically meaningful differential features from the local temporal coherence, temperature-compensated time domain signals, and matching pursuit decomposition parameters. Receiver Operating Characteristic (ROC) curves were employed to visualize the efficacy of the various features in discriminating damage from surface wetting. Detection thresholds were determined for each feature and sensor pair based upon a desired false alarm rate. A novel fusion strategy was developed to combine all features from all sensor pairs using a semi-automated search algorithm for determining the best thresholds and voting strategies to simultaneously achieve a high probability of damage detection with an acceptably low false alarm rate. Mr. Yinghui Lu presented this work at the 2007 International Workshop on Structural Health Monitoring, and his poster is included as page 2 of the attached file.

Algorithms have also been developed for localization of damage for plate-like specimens. Even though these specimens support guided waves, the propagating waves can still be reverberating and diffuse-like because of structural complexities such as fastener holes, thickness changes and boundary reflections. Beamforming algorithms used for radar, sonar and ultrasonic imaging have been adapted for implementation on the differential, or residual, signals resulting from temperature compensated baseline subtraction. A new algorithm has been developed that is based upon relative times of energy arrivals of the differential signals. Methods were developed to quantify the localization capability of an algorithm, enabling quantitative comparison of imaging methods. Time history data of images and image features were investigated for more robust detection of damage in the presence of environmental changes. It is necessary to apply the temperature compensation method developed for damage detection prior to damage localization in the presence of even very small temperature changes. The combination of the feature-based detection algorithms and the imaging methods for damage localization was shown to be very effective for monitoring a plate for damage over a period of several days during which temperatures were varied and different types of damage were introduced.

Research activity has also included investigation of a feature extraction technique for diffuse waves using a state space approach. The transient diffuse signal is convolved with a steady state chaotic signal to simulate a chaotic excitation. The convolved signal is then reconstructed into state space by embedding. Features are extracted in the state space with the goal of showing correlation to the progression of damage. Diffuse ultrasonic waves were experimentally generated by an impulsive excitation and formed after multiple reflections from the boundaries. The recorded diffuse signals were then convolved with one of the computed state variables of the Lorenz system to simulate a chaotic excitation. The Lorenz system is tuned to have a similar frequency range as the diffuse signal, and the transient part of the convolution result is truncated. The state space is reconstructed from the convolved signal using time delayed embedding. Features are extracted from the phase portraits, and the specific features investigated are the number of non-zeros in the Cross Recurrence Plot (CRP) and the Nonlinear Cross Prediction Error (NCPE). The feature values were analyzed to determine if they were correlated to damage. Preliminary results show that the NCPE increases as the size of damage increases, and the number of zeros in CRP decreases as the size of damage increases. Mr. Yinghui Lu presented work on the chaotic excitation method at the 2005 Review of Progress in Quantitative Nondestructive Evaluation at the student poster competition, and his poster is included as page 3 of the attached file.

Findings:

Significant research findings include:

1. Temperature changes can be discriminated from damage in aluminum specimens using three different techniques: (1) changes in local temporal coherence, (2) method of temperature compensated differencing, and (3) parameters from constrained matching pursuit. The second method, that of temperature-compensated differencing, can also be utilized to pre-process signals prior to damage localization. See Michaels & Michaels 2005 (IEEE UFFC), Michaels et al. 2005 (SPIE), Lu & Michaels 2005 (Ultrasonics) and Wilcox et al. 2008 (QNDE).

2. Complex ultrasonic signals can be effectively decomposed using an optimized matching pursuit algorithm. For such signals the decomposition can be interpreted as characterization of time-localized energy rather than identification of discrete echoes. See Lu & Michaels 2006 (QNDE) and Lu & Michaels 2008 (IEEE UFFC).

3. A constrained matching pursuit algorithm, which constrains the frequency, scale and phase of the basis functions but allows the amplitude and time shift to vary, permits changes in complex signals to be quantitatively characterized. Furthermore, differential features can be derived from these decompositions, and these features are useful for detection of damage and environmental conditions. See Lu & Michaels 2008 (IEEE UFFC).

4. Surface wetting can be discriminated from damage in aluminum specimens by a differential feature based approach whereby physically meaningful features, including those calculated from the constrained matching pursuit method, are calculated for each sensor pair. Detection thresholds are determined for each feature, and detection decisions are fused at first the feature level and then at the sensor level. The result is a very high probability of detection combined with a low false alarm rate. See Lu & Michaels 2007 (IWSHM) and Lu & Michaels 2008 (QNDE)

5. Once damage is detected, it can be localized in plate-like structures using several different algorithms that were developed as a part of this project, but only if temperature compensation methods are utilized. Without temperature compensation, and for the sensors and structures considered as a part of this project, temperature differences must be smaller than about 2 degrees Celsius for damage detection, and 0.5 degrees Celsius for damage localization. See Michaels & Michaels 2007 (Wave Motion), Michaels & Michaels 2007 (SPIE), Michaels 2008 (Smart Materials & Structures), and Michaels et al. 2008 (IEEE Sensors Appl. Symp.).

6. The efficacy of damage localization was quantified from localization images generated from changes in received signals from a spatially distributed array. Time histories of images and imaging metrics were shown to be effective for detection and promising for additional

reduction in the false alarm rate. See Michaels 2008 (SPIE, two papers).

7. The method of state space analysis can be practically applied to the domain of diffuse ultrasonic waves, and performance of the features in detecting damage is consistent with vibration-based experiments. Chaotic excitations can be simulated by convolving the diffuse signal with a computer-generated Lorenz signal. Exciting high frequency diffuse waves with real chaotic signals is supported by the results and need to be verified experimentally. See Lu & Michaels 2006 (QNDE).

Training and Development:

Dr. Yinghui Lu, who was the primary graduate research assistant on this project, was able to develop both experimental and analytical skills related to acquisition and processing of data from health monitoring experiments. In particular, he learned how to analyze signals by embedding them in state space and extracting features, he researched and developed signal decomposition methods, and he gained significant laboratory experience with transducer fabrication, specimen preparation and data acquisition. As a senior graduate student in the research group, he also had the opportunity to mentor both graduate and undergraduate students, both by group presentations and one-on-one training sessions in the laboratory. He graduated in the Summer of 2007, and the title of his Ph.D. thesis is, 'Analysis and Modeling of Diffuse Ultrasonic Signals for Structural Health Monitoring.' He is now employed as a Research Scientist at the Henry M. Jackson Foundation for the Advancement of Military Medicine, Inc. in Frederick, MD.

Mr. James Hall has been a graduate research assistant on this project for part of 2008, and it has been instrumental in his initial training in ultrasonic signal processing for structural health monitoring. In particular, he has been able to adapt radar signal processing methods to damage localization in plates. He has also worked on methods for characterizing dispersion from overlapping multi-modal ultrasonic signals; this work is still in progress and was the basis for his successful application to the NASA Graduate Student Researchers Program, beginning in August 2008.

During the four years of this NSF project, four undergraduates have worked in the QUEST Lab as part of the Georgia Tech SURE (Summer Undergraduate Research Experience) program, an NSF program targeting underrepresented minorities. These four students were able to interact with the graduate students sponsored by this project and make relevant research contributions in the areas of instrumentation, damage localization, sensor mounting and dispersion compensation. Having this NSF-supported program was essential for providing us the opportunity to properly train and mentor these undergraduates.

Outreach Activities:

This project is compelling to non-technical people because they can easily relate to the idea of detecting damage before catastrophic failures occur. The PI, Professor Jennifer Michaels, has used this project as a basis for preparing material for presentations to both junior high and high school girls to motivate them to consider engineering as a career. Due to the interdisciplinary nature of the work (aspects from electrical, mechanical and civil engineering), it is particularly suitable for use in this type of presentation. Professor Michaels received the 2005 Women in Engineering Excellence Faculty Mentoring Award in recognition for her efforts.

Journal Publications

Jennifer E. Michaels and Thomas E. Michaels, "Detection of Structural Damage from the Local Temporal Coherence of Diffuse Ultrasonic Signals", IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, p. 1769, vol. 52, (2005). Published,

Yinghui Lu and Jennifer E. Michaels, "A Methodology for Structural Health Monitoring with Diffuse Ultrasonic Waves in the Presence of Temperature Variations", Ultrasonics, p. 717, vol. 43, (2005). Published, 10.1016/j.ultras.2005.05.001

Jennifer E. Michaels, Yinghui Lu and Thomas E. Michaels, "Methods for Quantifying Changes in Diffuse Ultrasonic Signals with Applications to Structural Health Monitoring", Proceedings of SPIE, Health Monitoring and Smart Nondestructive Evaluation of Structural and Biological Systems III, p. 97, vol. 5768, (2005). Published, 10.1117/12.598959

Yinghui Lu and Jennifer E. Michaels, "State Space Feature Extraction Applied to Diffuse Ultrasonic Signals Using Simulated Chaotic Excitations", Review of Progress in Quantitative Nondestructive Evaluation, p. 625, vol. 25A, (2006). Published,

Yinghui Lu and Jennifer E. Michaels, "Ultrasonic Signal Decomposition via Matching Pursuit with an Adaptive and Interpolated Dictionary", Review of Progress in Quantitative Nondestructive Evaluation, p. 579, vol. 26A, (2006). Published, Jennifer E. Michaels and Thomas E. Michaels, "Guided Wave Signal Processing and Image Fusion for in situ Damage Localization in Plates", Wave Motion, p. 482, vol. 44, (2007). Published, 10.1016/j.wavemoti.2007.02.008

Yinghui Lu and Jennifer E. Michaels, "Numerical Implementation of Matching Pursuit for the Analysis of Complex Ultrasonic Signals", IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, p. 173, vol. 55, (2008). Published, 10.1109/TUFFC.2008.626

Jennifer E. Michaels and Thomas E. Michaels, "An Integrated Strategy for Detection and Imaging of Damage Using a Spatially Distributed Array of Piezoelectric Sensors", Proceedings of SPIE, Health Monitoring of Structural and Biological Systems, p. 653203-1, vol. 6531, (2007). Published, 10.1117/12.715438

Jennifer E. Michaels, "Detection, Localization and Characterization of Damage in Plates with an in situ Array of Spatially Distributed Ultrasonic Sensors", Smart Materials and Structures, p. 035035-1, vol. 17, (2008). Published, 10.1088/0964-1726/17/3/035035

Yinghui Lu and Jennifer E. Michaels, "Consideration of Surface Variations on Ultrasonic Structural Health Monitoring", Proceedings of the 6th International Workshop on Structural Health Monitoring, p. 1275, vol. , (2007). Published,

Jennifer E. Michaels, Anthony J. Croxford and Paul D. Wilcox, "Imaging Algorithms for Locating Damage via In Situ Ultrasonic Sensors", Proceedings of the 2008 IEEE Sensors Applications Symposium, p. 63, vol. , (2008). Published,

Yinghui Lu and Jennifer E. Michaels, "Discriminating Damage from Surface Variations via Feature Analysis for Ultrasonic Structural Health Monitoring Systems", Review of Progress in Quantitative Nondestructive Evaluation, p. 1420, vol. 27B, (2008). Published,

Paul D. Wilcox, Anthony J. Croxford, Jennifer E. Michaels, Yinghui Lu and Bruce W. Drinkwater, "A Comparison of Temperature Compensation Methods for Guided Wave Structural Health Monitoring", Review of Progress in Quantitative Nondestructive Evaluation, p. 1453, vol. 27B, (2008). Published,

Jennifer E. Michaels, "Effectiveness of In Situ Damage Localization Methods Using Sparse Ultrasonic Sensor Arrays", Proceedings of SPIE, Health Monitoring of Structural and Biological Systems II, p. 693510-1, vol. 6935, (2008). Published, 10.1117/12.775788

Jennifer E. Michaels, "Ultrasonic Structural Health Monitoring: Strategies, Issues and Progress", Proceedings of SPIE, Smart Sensor Phenomena, Technology, Networks and Systems, p. 6933Z01-1, vol. 6933, (2008). Published, 10.1117/12.778700

Books or Other One-time Publications

Web/Internet Site

URL(s):

http://www.quest.gatech.edu/

Description:

This URL is for the QUEST (Quantitative Ultrasonic Evaluation, Sensing and Testing) Laboratory, of which Prof. Jennifer Michaels, the PI of this NSF project, is co-director. Research results from this project, in the form of journal articles, conference proceedings and theses, are disseminated on this website.

Other Specific Products

Contributions

Contributions within Discipline:

This project does not fit neatly into a specific discipline since it consists of inherently multi-disciplinary work. The main contribution of this project within the discipline of Electrical Engineering is providing a methodology for quantitative, time domain analysis of changes in complex signals. These techniques have not been developed in the related areas of sonar and radar signal processing because for these applications, the motion of the source leads to truly stochastic signals. In contrast, in situ ultrasonic applications have fixed sensors and a relatively slowly varying medium of wave propagation, which means that the signals are, in a sense, deterministic within a short time interval. However, due to the nature of diffuse waves, they can also be considered stochastic since a small variation in, for example, transducer mounting or specimen geometry can result in a completely different signal. Thus, each received signal can be thought of as one member of an ensemble of signals from nominally identical specimens and transducers. The primary contributions of this project are (1) identification of the local temporal coherence as an effective method of analyzing these signals, (2) development of the temperature compensated differencing method to specifically address simultaneous damage and temperature changes, (3) the development and application of state space embedding methods for analyzing diffuse ultrasonic signals, (4) novel implementation of unconstrained and constrained matching pursuit algorithms for decomposition of complex ultrasonic signals and classification of changes, and (5) damage localization algorithms considered as single images and time series of images.

Contributions to Other Disciplines:

The methodologies developed as a part of this project have application to a number of disciplines in which fixed sensors are actively monitoring complex environments. Four examples are (1) active acoustics using fixed sensors such as sonar monitoring of marine traffic in a harbor, (2) geophysical monitoring whereby active devices emit elastic waves to interrogate the earth and look for changes over a long time period, (3) elastography in which soft tissues are characterized by acquiring ultrasonic data before and after pressure is applied, and (4) unattended active acoustic and seismic sensors for surveillance and monitoring applications. What characterizes these examples are a combination of fixed sensors and a long time scale of data acquisition compared to the period of the center frequency.

Contributions to Human Resource Development:

This project has directly contributed to the development of Dr. Yinghui Lu, Mr. James Hall, Mr. Ramaldo Martin, Mr. Florent Loislay and Mr. Zubin Master, the graduate students supported on this project, as well as the four undergraduates supported as part of the NSF SURE program. It has indirectly contributed to the development of many students in the QUEST (Quantitative Ultrasonic Evaluation, Sensing and Testing) Laboratory here at Georgia Tech as they have been exposed to the work performed. This work has also served as the foundation of several outreach presentations by Professor Michaels at the junior and senior high school level, which will have longer term payoffs in human resource development.

Contributions to Resources for Research and Education:

The main contribution of this project thus far to resources for research and education are the software and methods which have been developed. The software is a part of the overall software infrastructure that is being developed on multiple projects for analyzing ultrasonic data, and is used both for research and education (e.g., class projects and demonstrations). For example, the local temporal coherence method was incorporated into a senior capstone design project in which the students had to design an ultrasonic system for monitoring glass display cases; they were provided the software and designed the system to utilize it. Methods developed for this project also directly contributed to a completed Homeland Security project for detecting breaches in shipping containers, and a current project from the Air Force Office of Scientific Research for structural health monitoring over a wide range of length scales.

Contributions Beyond Science and Engineering:

The primary contribution beyond science and engineering is providing a foundation for practical utilization of diffuse ultrasound for structural health monitoring, which will directly affect the public welfare. It is anticipated that the eventual result will be commercialized technology, and that methods developed as a part of this project will provide the basis for establishing appropriate sensors, instrumentation, codes and standards.

Categories for which nothing is reported:

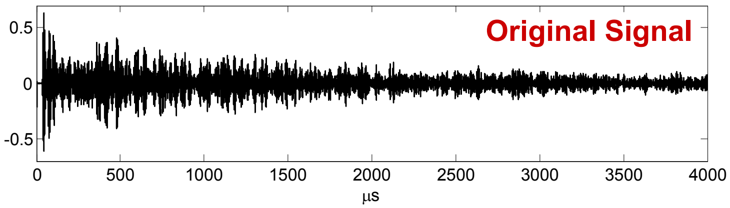
Organizational Partners

Any Book

Any Product

Damage Detection with Temperature Changes

1st Order Effect: Signal Stretching (or Contracting)



Theory

slope $= \beta \cdot \Delta T =$ slope of time shift vs. transit time curve

$$\beta = \alpha - \left(\frac{f_s \kappa_s}{c_s} + \frac{(1-f_s)\kappa_l}{c_l} \right)$$

$\alpha =$ linear coefficient of thermal expansion

$c_l, c_s =$ longitudinal (L) and shear (S) wave speeds

$\kappa_l, \kappa_s =$ temperature change coefficients for L & S waves

$f_s =$ shear fraction of total wavefield

$$R = 2\left(\frac{2-2\upsilon}{1-2\upsilon}\right)^{\frac{3}{2}} = \text{ratio of shear to longitudinal energy}$$

$\upsilon =$ Poisson's Ratio

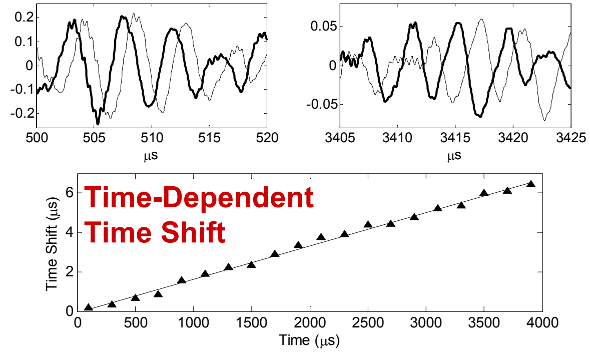
$$f_s = \frac{R}{1+R}$$

Weaver and Lobkis, *Ultrasonics*, **38**, pp. 491-494, 2000
Lu and Michaels, *Ultrasonics*, **43**, pp. 717-731, 2005

Temperature Compensation Strategy

Pre-stretch baseline signals to best match signal of interest prior to further processing

Original and Temperature-Stretched Signals



Signal Processing

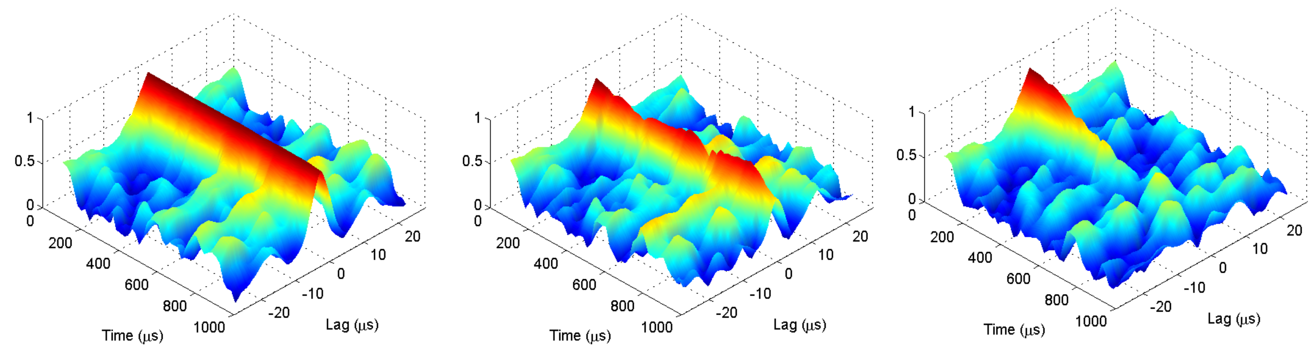
$$R_{xy}^T(\tau,t) = \frac{1}{T}\int_{t-\frac{T}{2}}^{t+\frac{T}{2}} x(s)w(s-t)y(s+\tau)w(s+\tau-t)ds$$
$$= \text{Short Time Cross Correlation}$$

$$\gamma_{xy}^T(\tau,t) = \frac{R_{xy}^T(\tau,t)}{\sqrt{R_{xx}^T(0,t)R_{yy}^T(0,t)}}$$
$$= \text{Local Temporal Coherence}$$

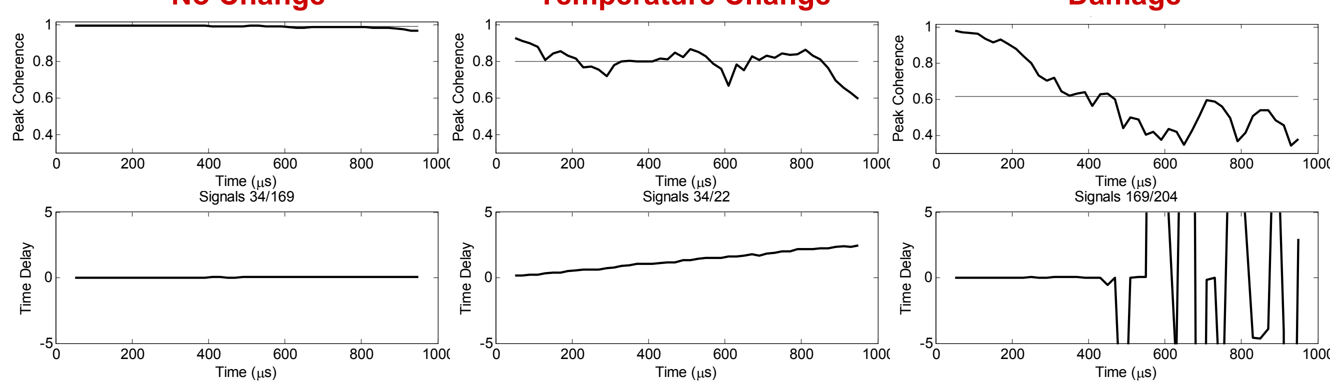
$$C_{xy}(t) = \max_{\tau}\left|\gamma_{xy}^T(\tau,t)\right| = \text{Peak Coherence}$$

$$T_{xy}(t) = \arg\max_{\tau}\left|\gamma_{xy}^T(\tau,t)\right| = \text{Local Time Shift}$$

Local Temporal Coherence – Three Cases



No Change | **Temperature Change** | **Damage**



Georgia Institute of Technology

QUEST Laboratory at Georgia Tech
www.quest.gatech.edu

Consideration of Surface Variations on Ultrasonic Structural Health Monitoring

Georgia Institute of Technology

National Science Foundation
WHERE DISCOVERIES BEGIN
Grant No. ECS-0401213

Yinghui Lu and Jennifer E. Michaels
School of Electrical & Computer Engineering

QUEST Laboratory at Georgia Tech
(Quantitative Ultrasonic Evaluation, Sensing and Testing Laboratory)

1. Research Objective

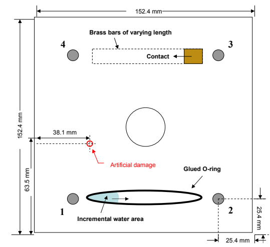
Diffuse ultrasonic waves "fill" the structure with energy, are easy to generate, and have the potential to monitor large areas with a small number of spatially distributed sensors.

The objective of this paper is to investigate the effects of surface condition changes, including surface wetting and surface contact, on structural health monitoring using diffuse ultrasonic waves.

The approach of this research is to extract features which are mainly sensitive to damage but insensitive to the applied surface variations.

A detection strategy consisting of feature and sensor fusion is proposed and implemented using experimental data.

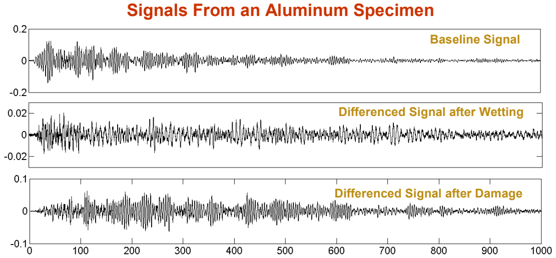
Experiments



- Aluminum plate, 6" x 6" x 0.25"
- 1" diameter central hole
- Four transducers (six pairs)
- Hole enlarged in 12 steps to simulate damage
- For each hole size, the surface is incrementally wetted (16 steps) or, contacted by brass bars of varying length (12 steps)

The challenge is to reliably discriminate damage from environmental changes, even when both occur simultaneously

Signals From an Aluminum Specimen



2. Features and Their Selectivity

Seven Features

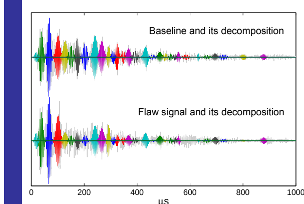
Time domain

F1. Mean square error (absolute signal change)
F2. Loss of local coherence (local shape change)
F3. Loss of correlation (global shape change)
F4. Differential curve length (change in signal complexity)

Matching pursuit decomposition

F5. Peak-to-peak amplitude change
F6. Standard deviation of amplitude change
F7. Frequency ordered amplitude change ratio

Equations and Illustrations for Matching Pursuit



$$f(t)=\sum_{n=1}^{N}\mathrm{Re}\left[A_n e^{i\phi_n} g_n(t)\right]+r(t)$$

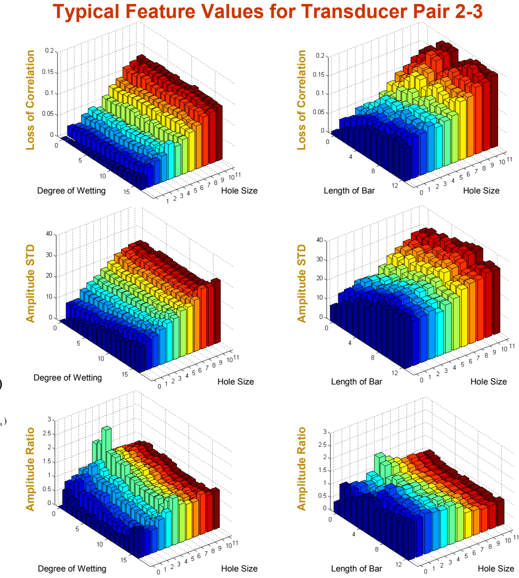
$$g_n(t)=\frac{1}{\sqrt{2\pi s_n}}e^{-(t-u_n)^2/(2s_n^2)}e^{i\xi_n(t-u_n)}$$

A_n,ϕ_n = amplitude, phase

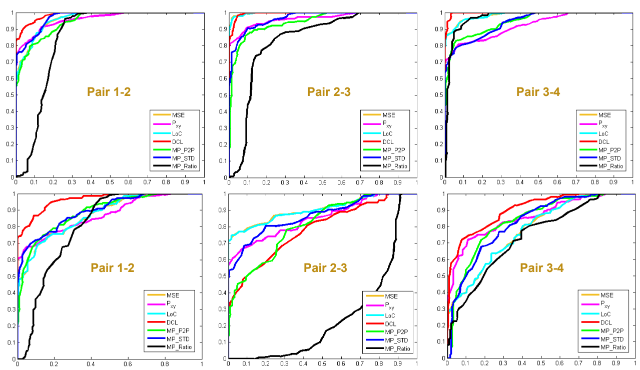
s_n,u_n = width, time shift

ξ_n = frequency

Typical Feature Values for Transducer Pair 2-3



3. ROC Curves and Data Fusion Procedure



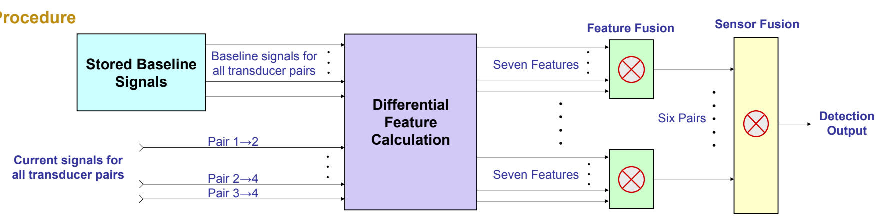
Feature Fusion

- Set a detection threshold for each feature using a preset false alarm rate
- Apply a voting method for feature fusion for each transducer pair
- Result: six transducer pair declarations

Sensor Fusion

- Apply a voting method for transducer pair decision fusion
- Preset false alarm rate, voting method for feature fusion, and voting method for transducer pair fusion work together to reach the overall decision

Fusion Procedure

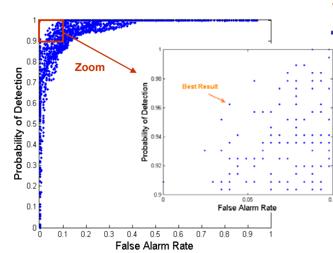


4. Best Data Fusion Strategy

Search for the Best Fusion Strategy

0-50% preset false alarm rate with 1% increment (51)
All N of 7 voting methods for feature fusion (7)
All N of 6 voting methods for sensor fusion (6)
Search 51x7x6=2124 combinations

Based on Surface Wetting Data



2% Preset FA Rate, 1 of 7 Voting for Feature Fusion, 3 of 6 Voting for Sensor Fusion

Wetting

Performance Metric	Feature Fusion						Sensor Fusion
	1-2	1-3	1-4	2-3	2-4	3-4	
Probability of Detection	85.6%	87.7%	94.7%	97.9%	96.3%	8.4%	96.3%
False Alarm Rate	5.9%	4.9%	6.4%	6.9%	6.4%	5.9%	3.9%
Minimum Hole Size Detected	2.0 mm	2.0. mm	1.5 mm	2.0 mm	1.5 mm	1.5 mm	1.5 mm

Contact

Performance Metric	Feature Fusion						Sensor Fusion
	1-2	1-3	1-4	2-3	2-4	3-4	
Probability of Detection	79.0%	67.8%	84.6%	76.2%	58.7%	70.6%	76.2%
False Alarm Rate	10.4%	8.2%	7.7%	9.9%	6.6%	7.7%	3.9%
Minimum Hole Size Detected	3.5 mm	5.5 mm	4.0 mm	4.5 mm	4.5 mm	5.0 mm	4.5 mm

Research Contributions

- Investigation of the effects of surface condition changes on structural health monitoring
- Determination of differential features with good selectivity and sensitivity to damage
- Implementation of the exhaustive searching method for the best data fusion strategy
- Demonstration of the efficacy of feature and sensor fusion for detecting damage in the presence of surface condition variations

Georgia Institute of Technology

State Space Analysis of Diffuse Ultrasonic Signals Using Simulated Chaotic Excitation

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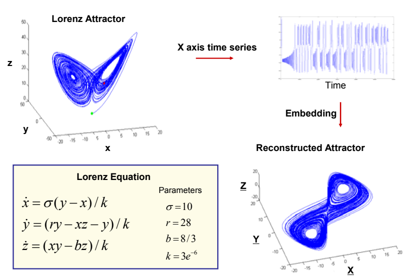
Introduction

For structural health monitoring, diffuse ultrasonic waves are an appealing alternative to guided waves. 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 for diffuse waves using a state space approach. The transient diffuse signal is convolved with a steady state chaotic signal to simulate a chaotic excitation. The convolved signal is then reconstructed into state space by embedding. Features are extracted in the state space, showing correlation to the progression of damage.

State Space Reconstruction

Time delayed embedding is the most common reconstruction method. The embedding dimension and the time delay are two critical parameters. They are determined by calculating the false neighbors and mutual information of the signal [1].

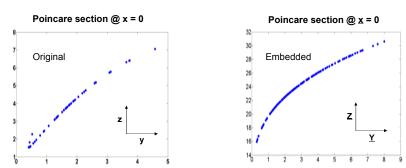


Lorenz Equation

$$\dot{x} = \sigma(y-x)/k$$
$$\dot{y} = (ry - xz - y)/k$$
$$\dot{z} = (xy - bz)/k$$

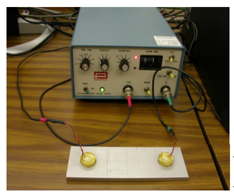
Parameters: $\sigma = 10$, $r = 28$, $b = 8/3$, $k = 3e^{-6}$

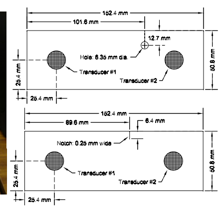
Poincare sections illustrate that the topological structure of the phase portrait is preserved in reconstruction.



Experiments

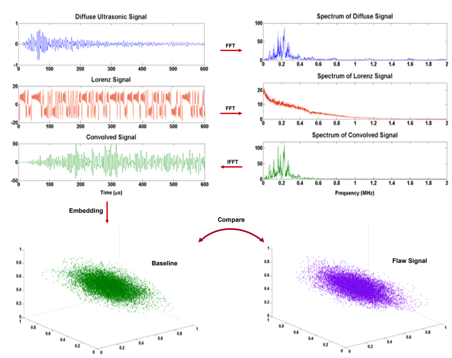
Two 6061 aluminum plates (50.8mm x 152.4mm x 6.35mm) are used as specimens. A through thickness hole and a through thickness notch are made to simulate damage. Diffuse ultrasonic waves are generated by an impulsive excitation and formed after multiple reflections from the boundaries. The sampling frequency is 12.5MHz and the signal is digitized with 8 bits resolution.





Convolution & Embedding

The diffuse signal is convolved with state variable X of the Lorenz system to simulate the chaotic excitation. The Lorenz system is tuned to have a similar frequency range as the diffuse signal, and the transient part of the convolution result is truncated. The convolution is computed in the frequency domain.

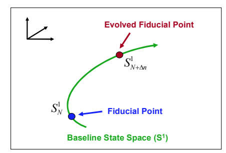


Feature Extraction

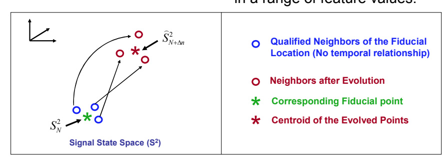
Features are extracted from the phase portraits. Features investigated are the number of non-zeros in the Cross Recurrence Plot (CRP) [2] and the Nonlinear Cross Prediction Error (NCPE) [3].

Nonlinear cross prediction error

$$Measure: \left|S^1_{N+\Delta n} - \hat{S}^2_{N+\Delta n}\right| \quad \text{where} \quad \hat{S}^2_{N+\Delta n} = \frac{1}{\left|U_\varepsilon(S^2_N)\right|}\sum_{S_n \in U_\varepsilon(S_N)} S_{n+\Delta n}$$

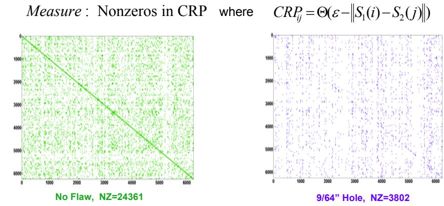


Multiple fudicial points are chosen at different positions in the baseline state space. The NCPE is calculated for each point, and the feature is the average value. This method is a local comparison. The choice of points is arbitrary, resulting in a range of feature values.



Nonzeros in cross recurrence plot

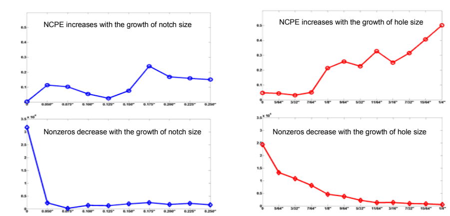
$$Measure: \text{Nonzeros in CRP} \quad \text{where} \quad CRP_{ij} = \Theta(\varepsilon - \|S_1(i) - S_2(j)\|)$$



The recurrence map is plotted by calculating the Euclidian distance or 1-Norm between every pair of phase points in the state space. If the distance is less than a threshold, the corresponding matrix value is assigned to be 1; otherwise, 0 is assigned. For the above two plots, 6000 phase points are used.

Results

In the first experiment, a through thickness notch is cut to simulate damage. The length of the notch is increased in steps, simulating progression of damage. In the second experiment, a through thickness hole in a different location is drilled and the diameter of the hole is enlarged in steps to simulate the progression of damage.



For both cases, the results show that the NCPE increases as the size of damage increases, and the number of zeros in CRP decreases as the size of damage increases.

The results of the second experiment are better than the first one, most likely because the damage size is bigger in the second experiment.

Summary & Conclusions

- The method of state space analysis is applied to the domain of diffuse ultrasonic waves.
- Chaotic excitation is simulated by convolving the diffuse signal with a computer-generated Lorenz signal.
- The performance of the features is consistent with vibration-based experiments [2,3].
- Exciting high frequency diffuse waves with real chaotic signals is supported by the results and should be the next step in research.

References:

[1]. Holger Kantz, Thomas Schreiber, University Press, Cambridge, 2004.

[2]. Jonathan M. Nichols, Proc. of SPIE, 5394(329-339), 2004.

[3]. M. Todd, L. Chang, K. Erickson, K. Lee, and J. Nichols, Proc. of SPIE, 5394(317-328), 2004