3D Ultrasound Characterization of Woven Composites

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Recent studies on the Non-Destructive Testing (NDT) of composites for the aerospace industry have led to an understanding of ultrasonic propagation in these materials [1]. Techniques for enhanced ultrasonic imaging of the internal structure of composite laminates containing unidirectional fibers have been proposed and tested in a laboratory environment. For the automotive industry, textile composites are rather preferred and widely used. The reason for this is that these types of composites offer good mechanical performance, with resistance to delamination and reduced manufacturing costs. In this study, a 3D time-domain Finite Element (FE) model is developed [2] to study the ultrasonic response from woven composite specimens. Three parameters are defined and used to analyze the structure behavior. They are the instantaneous amplitude, instantaneous phase and instantaneous frequency. These parameters are employed to track the in-plane fiber orientation, the ply interface location and for the sentencing of features. Two woven specimens, 3D orthogonal and 2D plain weave are considered and scanned (using a focused ultrasonic transducer) to validate the proposed FE model. The results obtained from experimental and FE modeling, B-scan and C-scan are discussed and presented in terms of the above defined parameters.

Figure 1. FE Model geometry showing the ultrasound probe and the woven specimen embedded in water.

Acknowledgement:

This work was performed with support from the UK Engineering and Physical Sciences Research Council (EPSRC) aimed at underpinning the design of more efficient composite structures and reducing the environmental impact of travel.

References:

Overcoming Complexities: Damage Detection Using Dictionary Learning Framework

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Structural health monitoring systems are designed to periodically evaluate structures for anomalies and damages. Guided waves are used to accomplish this task as they can inspect large areas and are sensitive to variations resulting from structural damages. Yet, guided wave propagation is complicated, even in plate-like structures. Their analysis is challenging due to their dispersive, multi-modal, and multi-path behavior arising from waves reflecting from boundaries and structural elements. These effects can easily mask the reflections from damage in the received signal. Hence, accurately detecting damage is a difficult problem.

In prior work, the authors developed sparse wavenumber analysis (SWA) to overcome the complexities of guided waves. Yet, SWA works only for structures that have relatively few multi-path reflections. Hence, it is not acceptable for many real-world structures. In this paper, we present a damage detection method based on a dictionary learning framework to overcome this problem. Our method accurately detects damage by exploiting the complexities of guided waves, including multi-path reflections. Furthermore, it does not require training data from a damaged structure. Hence, it can be applied with no prior damage information.

We demonstrate the effectiveness of our method to detect damage (simulated by a metal washer) on a 10 cm by 10 cm aluminum plate. This structure, due to its small size, exhibits complex multi-path reflections. In Figure 1, we show an increase in the damage detection accuracy from 48\% using SWA to 98\% using our method. The correlation coefficient between measurements from the aluminum plate and data predicted by our dictionary learning or SWA framework is used as the classification feature. Each of the red and blue circles represent a set of 20 randomly chosen measurements from a damaged plate and undamaged plate respectively. We employ an unsupervised, classification technique called K-means to classify the two clusters.

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\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{(a) Damage Detection result using SWA. (b) Damage detection result using our dictionary learning framework. The y-axis represents correlation coefficient between the measurements from a plate and data predicted by SWA or our dictionary learning framework. The x-axis is a random number given to each set of measurements for visualization.}
\end{figure}
Ultrasonic Testing of Micro-flaws in Additive Manufacturing Stainless Steel with Extreme Value Statistics

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Additive manufacturing (AM) processes are based on localized melting and solidification of successive layers of metallic powder, and Selective Laser Melting (SLM) is one of the most prominent techniques. SLM additively manufactured parts can be produced with mechanical properties which are comparable to those of conventional cast parts. However, micro-flaws (e.g. micro-pores, micro-crack, and lack of fusion) can degrade the mechanical properties of SLM additively manufactured metallic material. To comply with the high safety standards, quality assurance is pursued using ultrasonic testing.

In this work, a novel method is developed to distinguish the micro-flaw echoes from the grain noise for the C-scan image of the SLM samples. A finite ensemble of waveforms containing grain noise from specific microstructure is investigated. The single-scattering response model is used to give the theoretical spatial standard deviation of the waveforms. Then, the theory of extreme value statistics is introduced to estimate the maximum scattering amplitudes with theoretical spatial standard deviation. Further, the extreme value theory is employed to calculate the confidence bounds of the maximum amplitude of grain noise, which can be used to obtain a flaw from the background of grain noise. Finally, the upper bound is treated as a time-dependent threshold to recognize the micro-flaws under high gain. 316L stainless steel samples are designed and manufactured with different laser-power of the SLM and the optical microscopy measurement results reveal the effectiveness of the proposed method.

References:
Simulation and experiment for depth sizing of flaws in anchor bolts by ultrasonic phased array technology

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There has been reported the occurrence of cracks in bolts in nuclear and thermal power plants. For conventional ultrasonic testing techniques, thread echoes are the obstacle to determine the flaw size accurately. Ultrasonic phased array technology has the potential to overcome the shortcomings. This paper proposes a new method for depth sizing of crack in bolts using ultrasonic phased array technology. The simulation of wave propagation in a bolt with the diameter of 30 mm is carried out by the means of the finite element method for linear array transducers, and sectorial views corresponding to different crack depths are predicted. As shown in Figure 1, a peak associated with the vicinity of crack tip appears in the curve of echo intensity versus refraction angle for deep cracks. The refraction angle with respect to this peak decreases with crack depth increasing, and it is larger than the refraction angle corresponding to central beam impinging the crack tip. Based on the refraction angle associated to the peak, a new method for depth sizing of crack in bolts is proposed. To verify numerical results, we prepared M24 and M30 bolt specimens with various slits and fatigue cracks introduced. Experimental results show that for cracks at axial positions less than 100 mm in M30 bolts, determining crack depths via the proposed method within an error of less than 2 mm is possible.

![Figure 1. Dependence of echo intensity on refraction angle](image-url)
Pipe wall thinning measurement and simulation with electromagnetic acoustic resonance method

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In nuclear power plants and fossil fuel power plants, the pipe wall thinning due to the flow accelerated corrosion (FAC) is a crucial form of age-related degradation. Continuous wave electromagnetic acoustic resonance (CW-EMAR) and pulse wave electromagnetic acoustic resonance (PW-EMAR) have been developed for measuring the thickness of pipe walls as scheduled or online with high accuracy and stability [1]. In order to resolve the problem of low signal to noise ratio by the electromagnetic acoustic transducer (EMAT), we proposed to process the received signal using a method known as the superposition of $n^{th}$ compression (SNC) [2, 3]. The purpose of this paper is to discuss the effect of back surface shape on the EMAR measurement using experiment and simulation.

According to the shape characteristics of FAC, the specimens with inclined bottom surface and circular arc bottom surface are made. Peak values of PW-EMAR and CW-EMAR decrease with the increase of angle of inclined bottom surface. The PW-EMAR method can accurately measure the wall thickness of a specimen with inclined bottom surface of angle less than 3°. Moreover, the PW-EMAR method can accurately measure the wall thickness of a specimen with circular arc bottom surface whose tangential angle less than 6°.

In addition, we applied a 3D finite element (FE) model for the thickness measurement with EMAT. The FE model consists of two simulation parts: the electromagnetic field and the ultrasonic propagation. These are simulated using the commercial software GiD and ComWAVE (Itochu Techno-Solutions Corp.), respectively, with the two parts coupled via the electromagnetic force. The calculation result of resonant frequency which corresponds to thickness for the PW-EMAR is in agreement with the experimental result as shown in Fig. 1. The simulation shows the effect of back surface shape on the accuracy of measurement.

![Figure 1](image)

**Figure 1.** Results of a specimen with thickness of 10 mm and inclined bottom of angle 1°.

Acknowledgement:

This work was partly supported by the JSPS Core-to-Core Program, A. Advanced Research Networks, “International research core on smart layered materials and structures for energy saving”.

References:

Fatigue Damage Evaluation of Ferromagnetic Material using Barkhausen Noise with Multi-frequency exciting

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Material fatigue is a gradual accumulation process, experienced crack initiation, crack propagation, and finally abruptly break. Getting the fatigue growth of the material during the service period will help to better assess the remaining life of the material. As the magnetic barkhausen noise (MBN) is sensitive to changes in the micro-structure of the material, many scholars have carried out their research on material fatigue assessment. Most of the current research using a single frequency AC signal excitation MBN signal\textsuperscript{[1,2]}, obtaining the variation law of MBN signal in fatigue process. Due to the yield effect, fixed frequency AC electromagnetic signal can only penetrate the surface of the measured material a certain thickness. The crack is always formed from the material with the highest stress, the weakest strength on the substrate. The weakest intensity may be anywhere on the surface of the material or inside the material. If using a fixed frequency, the skin depth is less than the material, it can not be able to get the complete growth information of material cracks. In this paper, the multi-frequency excitation method is employed to obtain the different MBN signal, compared with a single fixed excitation method, it can get more depth information of fatigue under the measured surface. Through the same excitation frequency of the MBN signal changes in the law, obtain the material fatigue information at the specified depth of the test sample. By comparing the changes of the MBN signal at different excitation frequencies, obtain the crack growth information on the entire depth of the surface under test sample. Through the low cycle test found, as Figure 1(a) shows, Q235 sample’s fatigue curve is parabolic. The first 20% stage signal is slightly increased. But within the other 80% range, with the increase in fatigue level, signal strength drops rapidly. As Figure 1(a) shows, Q345 sample’s fatigue curve is linear, with the increase in fatigue level, signal strength monotonically decreased. Differences between two kinds of material fatigue curves, is the difference in material composition and mechanical properties. But the process of fatigue changes in the signal monotonous, and changes significantly, it can be used to assess the residual fatigue life of the material.

Figure 1. Two materials with low cycle fatigue curves.

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References:
The signal receiver is an important part of the Barkhausen sensor. The coil wound on the ferrite is widely used to receive the MBN signal, which is generally placed on the surface of the sample in the middle of the yoke\(^1\)[\(^2\)]. Thus two problems affecting MBN signal reception need to be solved, one is the distribution of the MBN signal emission intensity at different locations in the magnetization region; the other is the relationship between the signal receiver placement position on the surface of the sample and the transmitted MBN signal of the detected point. In this paper, first, we simulate the magnetic field distribution on the surface of the sample, and then use the coil wrapped around the ferrite core as a receiver, scanned the distribution of the MBN signal on the surface of the test sample.

The test results are as follows:

1). As Figure 1(a) shows, before saturation magnetization, with the increase of magnetization, the MBN signal at each point of the magnetization region are gradually increased; in the magnetized area of the test sample, the MBN signal are gradually reduced from the center of the magnetization to the surrounding area.

2). As Figure 1(b) shows, when the MBN signal of sample center area reached saturation, the signal strength of this area is same and highest of the sample, and in the remaining regions is gradually reduced from the center of the magnetization to the surrounding area.

Through the experimental results, when the component is magnetized, the strength of the MBN signal is very weak. The receiver must be as close as possible to the specified point. The winding coil receiver can only receive the signal of its own attachment area. When the receiver size is smaller, the detection space resolution is higher.

![Figure 1. MBN signal distribution.](image)

**Acknowledgement:**

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**References:**


Guided waves are attractive for long range inspections from a single generation position. When the waveguide is embedded/immersed in another medium, the energy of the guided wave may leak into the surrounding material, causing significant reduction of the inspection distance. Analytical and numerical models have been developed to understand the properties of the guided wave in leaky waveguides, among which the SAFE-PML method, combining the Semi-Analytical Finite Element (SAFE) method and Perfectly Matched Layer (PML) is popular for waveguides with arbitrary cross-sections. This work implements the SAFE-PML method into a commercially available Finite Element package (COMSOL Multiphysics) for both embedded and immersed waveguides. As no source code is required, the presented method will be attractive to a wide range of researchers in Non-Destructive Evaluation (NDE). The method is first demonstrated and validated with analytical solutions on waveguides with regular cross-sections, including embedded/immersed plates and cylindrical bars which can be solved by analytical methods. Discussions have been carried out regarding the procedure to select the length of the PML. The method is then applied to a few practical applications, including half embedded pipes and immersed rectangular bars, showing the potential of guided waves for NDT applications.
Real Time Flaw Detection and Characterization in Tube through Partial Least Squares and SVR: Application to Eddy Current Testing

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The necessity of robust and real time inverse solutions becomes the main priority of different Nondestructive Testing (NDT) applications. Eddy Current Testing (ECT) is widely used for the assessment of the integrity of the structure under test (SUT) by means of crack detection, localization and characterization. Standard iterative inversion solutions are computationally expensive and time demanding [1]. Among different non-iterative approaches, Learning by Examples (LBE) methodology has recently been successfully applied for real time inversion in ECT [2]. In principle, LBE strategy aims to build a fast and accurate model from a training set of input/output (IO) pairs during a so called offline phase. The developed model is then used to predict the output associated to an unknown test sample during a so called online phase. Within the framework of LBE, this work presents a quasi-real time inversion strategy by combing Partial Least Squares (PLS) and Support Vector Regression (SVR) for crack detection and characterization in a conductive tube structure (Fig. 1a). Full-factorial (i.e., GRID) sampling technique and PLS feature extraction (i.e., GRID-PLS) are applied for generating a suitable training set. SVR is utilized for model generation and inversion during offline and online phases respectively. The performance and robustness of the proposed GRID-PLS/SVR strategy on noisy test set is evaluated by computing prediction accuracy in terms of normalized mean error (NME) for different signal to noise ratio (SNR) and compared with standard GRID/SVR [2] approach (Fig. 1b).

Figure 1. Example of (a) studied tube geometry and (b) prediction accuracy vs. the SNR on synthetic test measurements for estimating the crack length, \( l_c \)

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References:


Simulation of the Spatial Frequency-Dependent Sensitivities of Acoustic Emission Sensors

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Typical configurations of nondestructive testing by Acoustic Emission (NDT/AE) make use of multiple sensors positioned (possibly permanently attached) onto the structure under examination. AE testing is known to be very sensitive to early damaging processes. If elastic wave velocity in the structure is known, an AE event can further be localized by means of triangulation algorithms. However, in thin structures, waves propagate as guided waves which are multimodal and dispersive leading to significant uncertainties about the velocity of waves generated by an AE event. Typical waveforms measured in AE testing are complex as they result from the chaining of various physical phenomena arising at different time and space scales. A simulator of AE testing could provide means for interpreting these complex waveforms, then for helping the design of AE configurations by managing complexity. The study of such a tool has been carried out at CEA with partners to demonstrate its interest and feasibility. A global model \cite{1} operating several sub-models at different space- and time-scales was developed to predict sensors outputs (simplified model of AE sensor response \cite{2}) resulting from an evolving crack (model of AE source \cite{3} and radiation \cite{4}) in a structure in which the waves generated by the AE event would propagate as Rayleigh or guided waves (models of elastic wave propagation \cite{4}).

The present study aims at understanding the complex behavior of AE sensors to take it into account accurately within the framework of the above-described modeling approach. These sensors generally consist of a thick cylindrical piezoelectric element of radius comparable to its thickness, without damping and bonded to the sensor case. Sensors themselves are bonded the structure being tested. The electromechanical reciprocity principle \cite{5} allows us to determine the sensitivity of sensors to different incident wave components by simulating their behavior as transmitters. A study (using a FE package \cite{6}) is carried out to quantify the variation of sensor response with that of several parameters relative to its constituents, to its mechanical coupling to the structure and to the structure material. Predictions are compared to measured waveforms to validate the way parameters are accounted for in the FE model. Results demonstrate that the complex behavior cannot be predicted by a simple model and that the sensitivity is highly dependent on the piece material which mechanically loads the sensor. The sensitivity must be described by two functions (radial and axial sensitivities) of frequency and of position at the contact surface with the part. The knowledge gained from these results allows us to describe a strategy of simulation of AE testing avoiding the costly FE simulation of sensor behavior while ensuring that it is accurately taken into account in the overall AE testing simulation.

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Defect Recognition in Carbon Fiber Reinforced Polymer (CFRP) Components using Various Nondestructive Testing (NDT) Methods Within a Smart Manufacturing Process

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The manufacturing process of carbon fiber reinforced polymer (CFRP) components is playing a more and more significant role when looking at the increasing amount of CFRPs used in industries today. The monitoring of the manufacturing process and hence the reliability of the manufactured products, is one of the major challenges we need to face in the near future. Common defects which arise during manufacturing are e.g. porosity and voids which may lead to delaminations during operation and under load. To find those defects in an early stage of the manufacturing process is of huge importance for the safety and reliability of the finished products, as well as of significant impact from an economical point of view. In this study we present various NDT methods which are applied to similar CFRP laminate samples in order to detect and characterize defective volume. Besides ultrasound, thermography and eddy current, different x-ray methods like radiography, laminography and computed tomography are used to investigate the samples. These methods are compared with the intention to evaluate their capability to reliably detect and characterize defective volume. Beyond the detection of flaws, we also investigate possibilities to combine various NDT methods within a smart manufacturing process in which the decision which method to apply is made by the process itself. Is it possible to design an in-line or at-line testing process which can recognize defects reliably and reduce testing time and costs? This study aims to show up opportunities of designing a smart NDT process synchronized to the production based on the ideas of smart production (Industry 4.0). A set of defective CFRP laminate samples and different NDT methods were used to demonstrate how effective defects are recognized and how communication between interconnected NDT sensors and the manufacturing process could be organized.

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Assessing Performance of Flaw Characterization Methods through Uncertainty Propagation

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In the field of NDE, parametric forward solvers [1] are employed to solve a wide variety of problems such as probe design, inspection method design, prediction of inspection results or analysis of field measurements. Their main advantage consists in ease of use, their computational performance (semi-analytical solutions or accurate approximate models are often available) in conjunction with a user-friendly description of the inspection scenario by its representative parameters: geometry, flaws, probe characteristics. Recently, the generation of databases and their successive exploitation through the associate surrogate model (or metamodel) have been successfully addressed for eddy current testing inspection problems [2, 3, 4]. The database technology has shown considerable potential by allowing fast sensitivity analyses and inversion studies [4]. However, in spite of the achievements obtained in the aforementioned works, many practical problems remain to be addressed. For instance, in order to get closer to real inspection scenarios and perform inversion on more challenging scenarios, one can take sources of uncertainty into account within the inversion process. These kind of sources can be associated to some discrepancies between nominal and real-inspection set-up parameters e.g., probe (lift-off, skew, tilt, etc.) or specimen parameters (parametric medium description such as conductivity, wave velocity, etc.). In this paper, we show how a database and the associated metamodel can be employed to propagate the uncertainties within the inversion process. Furthermore, comparisons between some classical deterministic (i.e., quadratic programming) and stochastic (differential evolution) algorithms among others will be carried out on two different kinds of applicative scenarios associated to eddy current testing and ultrasonic testing inspection problems. CIVA – Non destructive testing at CEA List, http://www-civa.cea.fr/en/, date last accessed, May 24, 2017

References:
Quantitative Evaluation of Thickness Reduction in Corroded Steel Plates using Surface SH Waves

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There are difficulties of the visual inspection for the steel components emended in concrete structures. For the secureness of structural safety, it is important to grasp the internal condition of invisible structural parts. The purpose of this study is to evaluate plate reduction depth of steel plate existing in concrete with surface SH(s-SH) waves of UT. The s-SH waves travel along the surface configuration of the plate as guided waves [1]. Accordingly, the time of flight(TOF) gets longer if the plate has thickness reduction. The parameter of this study is a delay time obtained from TOF comparison between a healthy plate and a damaged plate. The time difference is evaluated by the cross-correlation function after the reached waves are processed to envelope curves using the Hilbert transform.

Four processes are taken in this research. Firstly, sound pressure distribution of the s-SH wave, the center frequency of which is 5MHz, is obtained. Secondly, wave propagation paths are visualized by numerical simulations of FEM dynamic analysis. Thirdly, a theoretical equation is proposed to evaluate the thickness reduction level from the TOF. Finally, the validity of the proposed equation is examined by experiments. The plane steel plate specimen and artificially hollowed specimens [2] (Figure1) are used.

Figure 1 shows the results of delay time. The assumed delay time from the proposed equation mostly agrees with the experiment results(5MHz). The table in the below indicates the errors. The proposed equation can evaluate the hollow depth with the error about 10%.

![Figure 1. Configure of the specimen and results of the experiments.](image)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Depth (mm)</th>
<th>Evaluated depth (mm)</th>
<th>difference (mm)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.1</td>
<td>4</td>
<td>3.49</td>
<td>0.51</td>
<td>12.8%</td>
</tr>
<tr>
<td>No.2</td>
<td>6</td>
<td>5.38</td>
<td>0.62</td>
<td>10.3%</td>
</tr>
</tbody>
</table>

References:
Inspection of surface defect using LASWs (Laser-generated Surface Acoustic Waves) is available on various materials, such as nonmetal, nonmagnetic, or nonconductive. They are also applicable to complex shapes, high temperature, or moving object [1]. In this study, SAFT (Synthetic Aperture Focusing Technique) is applied to LSAW for the imaging of surface defects. A point laser beam without any spatial modulation was used to generate the surface acoustic wave, which acts like a point source of the surface wave. Therefore, the propagation of the generated surface wave is omnidirectional which may cause error in the location of the defect in the conventional B-mode imaging. The proposed SAFT overcomes this limitation [2]. Experiments were performed to demonstrate the proposed method. An aluminum 6061 plate specimen with an artificial notch defect on the surface was prepared. The length, width, and depth of the defect are 10 mm, 1 mm, and 3 mm, respectively. The LSAWs were transmitted and received on a defect specimen as a non-contact manner using a pulsed laser (1064 nm Nd:YAG laser) and a laser detector (photorefractive interferometer). The specimen was moved along a line to obtain a set of scan data. In order to test the influence of scanning interval on imaging quality, this scanning was performed for various scan intervals from 0.2 mm to 5 mm in 0.4 mm increment. The experimental results showed that the error in defect length obtained from SAFT imaging was within 3% when the scan interval was less than 2.2 mm. On the other hand, the defect length in the B-mode imaging was 30% smaller than that of actual and that in B-mode was fluctuated when the scan interval was longer than 1 mm.

Acknowledgements:

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References:

Relative Acoustic Nonlinearity Measurement Using Phase Inversion Method

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Conventional methods for the acoustic nonlinearity measurement have used a narrow-band long-cycle burst wave to measure harmonic components accurately [1]. This study aims to show that the phase-inversion method via the single-cycle broad-band burst wave can be applied to the acoustic nonlinearity measurement. In order to demonstrate the proposed method, the changes of nonlinearity in Al6061-T6 according to the thermal aging were measured. Specimens were heat-treated at 220\degree C with different aging time up to 1000 hours. The default (phase: 0\degree) and the phase-inversed (phase: 180\degree) acoustic waves were transmitted and the relative acoustic nonlinearity parameter was measured by summing those wave signals. Figure 1 shows the experimental result and Figure 2 shows the reference obtained via the conventional method using the long-cycle burst wave. The trend is in good agreement each other, which supports that the proposed method is suitable for measuring the relative acoustic nonlinearity.

![Figure 1. Relative acoustic nonlinear parameter using single-cycle burst waves](image1)

![Figure 2. Relative acoustic nonlinear parameter using long-cycle burst waves](image2)

Acknowledgements:

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References:

Employing Unmanned Aerial Vehicle to Monitor the Health Condition of Wind Turbines

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Unmanned aerial vehicle (UAV) can gather the spatial information of huge structures, such as wind turbines, that cannot be collected with traditional approaches. In this paper, the UAV used in the experiments is equipped with high resolution camera and thermal infrared camera. The high resolution camera can provide a series of images with resolution up to 10 Megapixels. Those images can be used to form the 3D model using the digital photogrammetry technique. The recorded thermal images are analyzed with the image segmentation technique. Each segmented image is segmented into a series of sub-regions according to the surface temperature distribution. Those sub-regions are separated by the differences of the surface temperature. Possible defects shown in the wind turbine can be located according to the temperature difference. The high resolution and segmented images are fused so as to form the 3D model of wind turbines. Furthermore, the 3D models generated by the photogrammetry technique based on both high-resolution images and laser scanning will be presented. Feasibility will be discussed on the potential application of health monitoring of wind turbines using the 3D models.

Figure 1. Temperature distribution illustrated on the 3-D meshed object

Acknowledgements:

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Blending of Phased Array Data

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The use of phased arrays is growing and the trend is toward 2D arrays. Due to wiring, hardware limitations and time constraints, it is currently not possible to record the signals from all elements of a large 2D array, resulting in aliased data.

In the past we proposed to overcome this aliasing by a data interpolation scheme ‘beyond spatial aliasing’. In this paper we demonstrate a different approach: blending and deblending of data.

First, we blend (group) selections of piezo elements in only a few transmit/recording channels. This allows us to transmit and record with all elements, i.e., alias-free, in a shorter acquisition time and with less channels. Of course, the blended data now consists of simultaneous transmissions and simultaneous recordings.

In the next step this blended data is deblended (separated) by transforming it to a different domain and applying an adaptive thresholding in a way similar to the interpolation beyond-spatial-aliasing approach.

An example is shown for a 48x48 element phased array. The medium is homogeneous with three diffractors. The figures on the left show the ideal 48x48 channel recording for one transmit element in the center. The figures in the middle show the data reconstructed by deblending and the figures on the right show the blended data where six receive elements were grouped (48x48/6 receive channels). Note that in Figure 1c each recorded trace appears six times.

![Blended Data](image)

**Figure 1.** Simulated recordings of a 2D array of 48 by 48 elements. The middle element of the array acted as source. Top row: time slices (t=15μs), (a) unblended, (b) deblended, (c) blended. Bottom row: time-space slices (y-position=24), (d) unblended, (e) deblended, (f) blended.
Material State Awareness (MSA) has been defined as “Digitally Enabled Reliable Nondestructive Quantitative Materials / Damage Characterization Regardless of Scale” [1]. This definition aligns with the description published for the 2014 Workshop on MSA organized under the auspices of the National Academies of Science which reads as follows: “Materials State Awareness seeks to quantify the current state of a material and/or damage [to a material or structure] with statistical metrics of accuracy located in individual systems, structures, or components and is the heart of condition-based management strategies. In principle, such quantitative evaluation should be based on knowledge of the initial state, damage or failure process, operational environment, and nondestructive evaluation (NDE) assessment of state. However, most frequently the initial state is not known and the assessment must be done from an unknown reference state.” Thus, there is a need to develop nondestructive methods for characterizing material properties and/or damage features as this has significant potential to enable and/or refine methods to certify new materials, sustain existing systems, and enhance methods to forecast future maintenance of engineered systems. This is relevant for certification of new material systems, such as those being made via additive manufacturing or tailored composite lay-ups, and for the augmented sustainment practices, such as the aforementioned Condition-based Maintenance, plus improved representation of a system via digital surrogates to improve current prognostic methods to manage the integrity, or safety, of the system.

This presentation expands on the objective and motivation for NDE-based characterization and includes a discussion of the current approach using model-assisted inversion being pursued within the Air Force Research Laboratory (AFRL). This includes a discussion of the multiple model-based methods that can be used, including physics-based models, deep machine learning, and heuristic approaches. The benefits and drawbacks of each method are reviewed and the potential to integrate multiple methods is discussed. Initial successes are included to highlight the ability to obtain quantitative values of damage. Additional steps remaining to realize this capability with statistical metrics of accuracy are discussed and how these results can be used to enable probabilistic life management are addressed. The outcome of this initiative will realize the long-term desired capability of NDE methods to provide quantitative characterization to accelerate certification of new materials and enhance life management of engineered systems.

Acknowledgement:
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References:
Benefits of GMR sensors adapted for NDT applications

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Main concept of magnetism and, therefore, of magnetic imaging can be subdivided into different levels, macroscopic, magnetic domain, and atomic [1]. While conventional sensor solutions cover only the macroscopic level, the spatial resolution of GMR (Giant Magneto Resistance) sensors go down to the domain scale. In addition, those low cost sensors are well suited for automotive and industrial applications, particularly high-speed solutions. Main reason is their outstanding performance in terms of high spatial resolution, high accuracy, high bandwidth combined with field sensitivity, energy efficiency and durability.

In contrast to industrial use, down to the present day GMR sensors do not get beyond scientific scope in case of non-destructive testing (NDT) applications. Nevertheless, there are scientific and industrial NDT applications in which adapted GMR sensor [2,3] can be promising compared to the conventional NDT methods.

This contribution summarizes findings at the BAM over the last decade which demonstrates the preeminent properties of GMR-based testing solutions. This comprises the active and passive testing of different materials with hidden defects and flaws near geometric boundaries like edges where conventional methods meet their limits. Another promising application for adapted GMR sensors is the characterization of magnetic materials, where the sensors provide additional information on microstructure, mechanical stress state, phase transformations and their interaction with magnetic fields [4]. The examples show the need and benefit of NDT adapted GMR sensors.

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Influence of Surface Roughness on Measurement of Ultrasonic Nonlinear Parameter using Contact-type Transducer

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Ultrasonic nonlinear parameter can be obtained from the fundamental frequency and higher harmonic amplitudes of ultrasonic wave which propagated in material [1]. However, the measurement system affects the result of ultrasonic nonlinear parameter. The contact condition between transducer and material is especially important when using contact-type transducer [2]. Therefore, in this study, the influence of surface roughness was experimentally investigated. For this purpose, the both sides of Al6061-T6 specimens were polished in different surface roughness values of 0.5, 1.5, 2.2, 2.7 and 3.2 µm. The measurement of relative and absolute ultrasonic nonlinear parameters was conducted under same experimental condition, and the piezo-electric detection method was used for measuring absolute nonlinear ultrasonic parameter. The relative ultrasonic nonlinear parameter increased depending on increment of the surface roughness. On the other hand, the absolute ultrasonic nonlinear parameter was constant until the roughness of 2.7 µm. From these results, we can confirm that the surface roughness critically affects the measurement of relative ultrasonic nonlinear parameter using contact-type transducer but the influence of surface roughness can be compensated by calibration process in the measurement of absolute ultrasonic nonlinear parameter using piezo-electric detection within a limited range.

Acknowledgements:

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(172)
Evaluation of cold work and sensitization in 304 Stainless Steel using nonlinear Rayleigh Waves

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Austenitic stainless steels have a wide range of applications in the energy industry due to their high temperature performance and high corrosion resistance. Type 304 SS, is a widely used stainless steel, but this material is susceptible to sensitization, the formation of chromium carbide precipitates along the grain boundaries, causing chromium depletion when exposed to a certain temperature, ultimately leading to intergranular stress corrosion cracking (IGSCC). Sensitization tends to occur in the heat affected zone (HAZ) of welds where heat is induced for a certain amount of time during welding. This is of great concern in nuclear power plants since the sensitization and associated IGSCC is a main cause of the cracking in boiling water reactor piping systems.

The objective of this research is two-fold. First, the research evaluates the changes of microstructure caused by cold work (cold rolling) using nonlinear ultrasound (Rayleigh waves). Second, the effect of prior cold work on the sensitization behavior of 304 SS is investigated using nonlinear ultrasound and then compared with previous work [1] that investigated just the effect of sensitization. The results show that (1) cold work causes significant variations in the nonlinearity parameter which can be attributed to the formation of a large number of dislocations and twins as a consequence of the plastic deformation and phase transformation and (2) cold work has large influences on the sensitization behavior of 304 SS.

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References:

The spectral characterization of x-rays transmitted via microstructured optical fiber is presented for the first time. An x-ray tube provides the source of x-rays with an x-ray spectrometer as the detector. The fiber is comprised of a micron scale quartz structure which allows transmission of x-rays within continuous voids of the fiber microstructure. The evacuation and subsequent metal coating of the fiber ends prevents liquid from entering the fiber and can reduce x-ray attenuation within the fiber microstructure. Several fiber geometries are compared for their x-ray spectrum transmission characteristics. The experimental configuration and results of the x-ray transmission measurements are discussed.

Reference:
Finite Element Analysis for Ultrasonic Inspections of Tapered CFRP Components

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The use of carbon fibre reinforced polymer (CFRP) materials has become more prominent in industry due to their high strength and light weight. These materials pose challenges to ultrasonic NDE techniques as their anisotropic materials and laminate construction cause scattering and refraction of the beam, both of which can detrimentally affect inspection coverage. Tapered components further complicate inspections since the number of plies in the laminate must change across component length. The point where this change occurs is known as a ply drop, which typically creates a resin rich area surrounded by variations in ply orientation.

This work uses time domain finite element analysis (FEA) to simulate ultrasonic B-Scan inspection of tapered CFRP components, allowing both inspection coverage and the detectability of defects to be assessed. A pre-processing tool was developed to create detailed geometric information of tapered CFRP components, including ply drops, ply orientation and resin layer thickness. The geometry was then used as an input to an explicit time domain FEA model, implemented in the PZFlex software package. Pulse-Echo inspections were simulated at multiple locations on the component surface and combined to create an ultrasonic B-Scan image. In addition, the maximum velocity magnitude in each simulation was computed and combined to create a coverage map containing the maximum velocity at each point in the component during the B-Scan. This coverage map can be utilised to evaluate the scan performance by identifying any areas of the component which are less exposed to the ultrasonic wave. Inspections were simulated for various tapered structures ranging up to a taper angle of 45°. An example of a 5° tapered CFRP geometry and the simulated B-Scan coverage map, inspected using a 7.5MHz single element probe, is presented in Figure 1. Finally, inspection performance is assessed across a range of inspection setups. Transducer frequency and focal depth are altered to maximise scan coverage and the ability to detect and locate defects such as porosity.

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Figure 1. Image of tapered CFRP geometry (top) and simulated B-Scan coverage map illustrating maximum acoustic velocity (bottom)
Detecting, localizing and identifying defects in homogeneous media using ultrasound has been an active research topic for decades. The present work focuses on the experimental detection and localization of defects in strongly heterogeneous media. The medium under investigation in this work is made of a regular 2D pattern of steel bars immersed in water. It is investigated with a transducer array in pulse echo mode. Such a medium exhibits long lasting time responses due to the multiple acoustic interactions between the numerous bars. For this reason, the signature of a potential defect is hidden in the experimental response. Furthermore, even when this signature is isolated, classical Time Of Flight methods tend to fail because they rely on the assumption the medium is homogeneous. The present work uses the topological imaging method [1] to overcome the heterogeneous nature of the medium. The experimental results obtained are compared to the application of more classical imaging processes. As the method relies on a numerical model of the unperturbed medium, extra effort has been made for simulating the experiments. It is also investigated if the method takes advantage of the complexity of the medium in terms of localization and resolution, as it has been demonstrated in homogeneous reverberating media [2].

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References:

Nonlinear Resonance Ultrasonic Spectroscopy (NRUS) for characterizing radiation damage in small stainless steel specimens

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Since many nuclear reactors in the US and abroad will soon reach their original design operation time, a means to quantify radiation damage in nuclear reactor pressure vessels becomes increasingly important. The aim of this research is to evaluate the radiation damage in stainless steels by measuring their material nonlinearity. The specimens have small dimensions and thus it is difficult to employ the nonlinear ultrasonic techniques based on the use of propagating waves. This study applies the nonlinear resonance ultrasound spectroscopy (NRUS) technique.

A thin circular disk (20mm x 0.5mm) stainless-steel specimen is fixed between a piezoelectric transducer and a steel base at two opposite edges of its perimeter. The transducer excites the various resonance modes of the specimen and a laser vibrometer detects the out-of-plane velocity of the vibrating specimen surface. The amount of the shift of the resonance frequency for increasing excitation levels represents the nonlinearity of the material. The measurement setup together with the measuring and data processing protocol is optimized by analyzing and comparing various metallic specimens with results from previous research. The optimized setup is then used to detect microscopic material damage in irradiated steel specimens in a hot cell.

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Improvement of the TFM Imaging in Nuclear Coarse Grained Steel with Different Signal Acquisition Strategies Associated with Noise Filtering Algorithms

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In this communication, defects are imaged in nuclear coarse grained steels with the Total Focusing Method (TFM). This method, sometimes described as the “gold standard” in ultrasonic imaging, provides optimal focusing in every point of a region of interest. It also improves the characterization of crack-type defects with half-skip focusing modes. However, in coarse grained steels, the TFM images may be altered by a strong scattering noise introduced by the heterogeneous microstructure [1]. Thus, in order to enhance the image quality, we compare different signal acquisition processes associated with noise filtering algorithms.

In the conventional TFM, the signals are recorded by firing elements one by one, thus giving the full array response matrix \( K(t) \). In this paper, two alternative acquisition methods are studied and evaluated on components provided by EDF, in the framework of a collaborative program with CEA-LIST. The first one consists in obtaining an equivalent \( K(t) \) matrix with spatially coded transmissions [2], while the second one relies on the acquisition of the \( S(t) \) matrix when planes waves are transmitted at different angles [3]. The TFM images obtained with the three acquisition methods are compared with each other for two types of nuclear steel. It is shown that images formed from incident plane waves are less sensitive to the structural noise, especially for crack-type defects imaged with half-skip modes.

In the second part, the scattering noise is filtered with singular value decompositions of the acquisition matrices \( K(f) \) and \( S(f) \), and algorithms to separate the signal and noise subspaces. After the noise filtering operation and inverse Fourier transforms, the TFM images provide better signal-to-noise ratios when the coherent noise is mainly due to a single scattering process.

References:
Resonant ultrasound spectroscopy (RUS) is a nondestructive evaluation (NDE) method that uses measured resonance frequencies of solids to estimate its complete set of elastic moduli[1]. The goal of this project is to measure elastic properties of micrometer size pillars of single crystals. RUS is well known for its applicability to small single crystals[2], however to meet this goal for micrometer sized specimens a non-contact detecting technique needs to be developed. A new LASER-based non-contact measurement technique was developed and demonstrated using millimeter sized samples. The measured resonances and the estimated elastic moduli obtained with the LASER-based system are comparable to the results obtained in the traditional contact RUS measurements. In order to determine the uncertainty in the calculated elastic moduli, a framework for error propagation through the RUS measurement technique was developed.

References:
High-Temperature Through-Wall Data Communication Based on Reflection Wave Modulation Technique

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In nuclear industry, many important components, such as nuclear reactor pressure vessels (RPV) and spent fuel storage canisters, are completely enclosed by metal and surrounded by thick concrete walls. Monitoring temperature, pressure, radiation, humidity, etc inside these enclosed vessels is crucial to ensure the reactor safe operation and fuel security. Such physical boundaries present huge challenges to sensing and instrumentation, because metal enclosures and thick concrete shield electromagnetic waves, preventing the transmission of data. Wiring through holes in the vessel walls is undesirable and largely unfeasible in nuclear environments.

This paper presents an experimental study of ultrasonic through wall data communication system designed based on reflected carrier wave modulation technique. The proposed metal wall has two ultrasonic transducers bonded on its outside surface, one transducer is connected to a carrier wave generator for sending an ultrasonic carrier signal into the wall and the other is for receiving modulated output information signal from the wall. One inside ultrasonic transducer is used to introduce the sensed data signal into the Wall. High temperature piezo based ultrasonic transducers are used to send data across solid walls. The entire ultrasonic system with transducers are placed inside the high temperature oven and temperature is varied from 0 to 1000C. The frequency and amplitude of carrier wave are fixed as 109.94KHz and 5Vpp, these values are decided based on the dimensions of the metal wall and piezo. For an initial analysis, a 10Hz pulsed signal is used as an input sensed data signal which is given to the inside transducer. The modulated signal is received at receiver transducer which is used to decode the sensed input data signal experimentally.
Towards an efficient characterization of the viscoelastic properties of anisotropic media based on the ultrasonic polar scan: experiments and numerical modelling

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Composite materials (e.g. CFRP) are more and more used for critical components in several industrial sectors (e.g. aerospace, automotive,…). Their complex and often anisotropic nature makes it difficult to accurately determine their material properties or to detect internal damages that may have occurred during manufacturing or material loading. To resolve these challenges, the Ultrasonic Polar Scan (UPS) technique has been introduced. In a UPS experiment, a fixed material spot is insonified at a multitude of incidence angles ($\theta, \varphi$) and the transmission amplitude as well as the arrival time are subsequently measured \cite{1-2}. Mapping these quantities on a polar diagram gives rise to a local fingerprint of the visco-elasticity of the investigated material. In the present study, we propose a novel two stage inversion scheme which is able to infer both the elastic and the viscous properties of the complex (anisotropic) media. In the first step, we solve the inverse problem of determining the elastic constants of the medium from cross-sections of time-of-flight UPS recordings (Figure 1a). The second stage handles a similar inverse problem, but now operates on the amplitude recordings of a UPS experiment and uses the elasticity values obtained in step one to inversely determine the viscous part of the viscoelastic tensor (Figure 1b). The developed characterization scheme has been employed on both virtual (numerical) experiments, to test the effectiveness of the method, and on actual experimental UPS recordings on CFRP plates.

![Figure 1: Cross-section of a UPS experiment (blue) and simulation (red) at an in-plane $\varphi$-angle of 0° for a 1 mm thick CFRP plate using a 5 MHz pulse. The simulation parameters were obtained through the proposed inverse characterization technique.](image)

Acknowledgment:
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Fundamentals of Angled-beam Ultrasonic NDE for Potential Characterization of Hidden Regions of Impact Damage in Composites

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There is the need to improve NDE characterization of impact damage, to support improved life predication models for composites. Gaps currently exist for NDE capability to evaluate the state of the shadow region of impact damage. Ideally, the goal is to characterize the extent and layers of delaminations through thickness, the back-wall surface deformation and far surface matrix cracking. In this study, the use of angled-beam ultrasonic NDE will be explored for the potential characterization of the hidden regions of impact damage in composites. Simulated studies using CIVA FIDEL 2D with experimental verification was used to explore this problem. Quasi-shear (qS) modes can be generated over a wide range of angles and used to reflect off the backwall and interrogate under the top delaminations of impact damage. However, interpretation can be quite difficult because of the lack of ‘normal’ reference indications from the test panel. Secondary probe signals that do propagate normal to the surface were found to be significant under certain probe conditions, and can potentially mask weakly scattered signals from within the composite panel. Simulations were used to evaluate the source of the multiple paths of reflections from the edges of a delamination, whose time-of-flight and amplitude will depend on the depth of the delamination and location of neighboring delaminations. For these oblique angle inspections, noise from both the top surface roughness and internal features (such as fine porosity) was found to potentially mask the detection of signals from edges of delaminations. Through optimization of the transducer frequency, incidence beam angle and focal depth, improvements in the signal-to-noise for a side-drilled hole reference standard were achieved. Lastly, the potential of generating ‘guided’ waves along the backwall using an angled-beam source and subsequently measuring scattered signals from a far surface crack hidden under a delamination was explored.

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Flaw Characterization through Nonlinear Ultrasonics and Wavelet Cross-Correlation Algorithm

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Ultrasonic measurements have become increasingly important non-destructive techniques characterizing flaws found in various in-service industrial components. The prediction of remaining useful life based on fracture analysis depends on the accurate estimation of flaw size and orientation. However, amplitude ultrasonic measurements are not able to provide an estimate of the plastic zones that exists ahead of the crack tips. Estimating the size of the plastic zone is an advantage since some flaw may propagate faster than others. This paper presents a wavelet cross-correlation (WCC) algorithm that was applied to nonlinear analysis of ultrasonic guided waves \cite{1}. By using this algorithm, harmonics present in the waveforms were extracted and nonlinearity parameters were used to identify both the tip of the cracks and the size of the plastic zone \cite{2}. B-scans performed with the quadratic and cubic nonlinearities were sensitive to micro-damage specific to plastic zones in a cracked plate of 2024-T3 aluminum (Figure 1). In the context of nonlinear ultrasonics, the WCC algorithm improves the quantification of the plastic zone and thus provide additional information to fracture mechanics analysis.

Figure 1. Nonlinear ultrasonic measurements with guided waves on a cracked 2024-T3 aluminum plate – left. Right: B-scan of quadratic nonlinearity parameter, \(\beta\), along the width of the plate. The crack tip starts position 76 mm and it is indicated by the high values of \(\beta\) - zone 1. Zone 2 indicates the plastic zone at the crack tip.

References:
Acoustics enjoys a wide array of applicability in the Oil and Gas industry. Signals with very low-frequencies (tens of Hertz) are routinely used on surface to image the earth subsurface delineating hydrocarbon reservoirs while signals with mid-frequencies (thousands of Hertz) to high-frequencies (hundreds of kiloHertz) are used in deep boreholes to probe rock mechanical properties and evaluate completion hardware. This article review a few recent advances in these applications spanning both measurement concepts and processing and inversion approaches. Three applications will be covered. The first relates to the deployment of novel accelerometers added to hydrophone on marine seismic cables to capture the subsurface-reflected pressure signals and their spatial gradients. The combination of the two sensors provides the means to improve signal-to-noise ratio (SNR), deghost the signal from the sea surface reflection, and more importantly, reconstruct the subsurface seismic wavefield that is poorly sampled across cables that are spaced 75m to 100 m apart. Novel compressive-sensing schemes coupled with wave physics are employed for the wavefield reconstruction at virtual sampling rates way beyond Nyquist’s criterion. The second relates to an ultrasonic imager deployed in open boreholes to probe the laminated structure of unconventional shale rock formations at depth of 10,000 feet. The imager yields rock compressional and shear wavespeed images as a function of depth and azimuth revealing a host of geomechanical manifestations of the borehole shape and near-wellbore region at an unprecedented centimetric spatial resolution. The quantitative images have bearing on rock strength and local stresses as they relate to the hydraulic fracturing of these shale formations. The third relates to the interpretation of the complex sonic response in a well cased with double steel strings cemented to the rock formation for the purpose of evaluating the cement integrity placed between the outer string and formation. Here, machine learning-based approaches are employed with training on modeling and experimental datasets to develop effective and autonomous diagnosis for the condition of the cement sheath.
Automatic Force Loss Detection of Post-Tensioning Tendon using Low Power Pulsed Eddy Current Measurement

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In the field of bridge engineering, pre-fabrication of a bridge member and its construction in situ have been issued and studied, which achieves improved quality and rapid construction [1, 2]. For integration of those pre-fabricated segments into a structural member (i.e. a concrete slab, girder and pier), post-tensioning (PT) technique is adopted utilizing a high-strength steel tendon and an effective investigation of the remained PT tendon force is essential to assure an overall structural integrity [3]. This study proposes a pulsed eddy current based tendon force loss detection system [4, 5]. A compact eddy current sensor is designed to be installed on the surface of an anchor holding a steel PT tendon. The intensity of the induced eddy current varies with PT tendon force alteration due to magnetostriction effect of a ferromagnetic material [3]. The advantages of the proposed system are as follows: (1) low power consumption, (2) rapid inspection, and (3) simple installation. Its performance was validated experimentally in a full-scale lab test of a 3.3-m long, 15.2-mm diameter mono-tendon that was tensioned using a universal testing machine. Tendon force was controlled from 20 to 180 kN with 20 kN interval, and eddy current responses were measured and analyzed at each force condition. The proposed damage index and the amount of force loss of PT tendon were monotonically related, and an excessive loss as much as 30% of an initially-introduced tendon force was successfully warned.

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References:
Oil and gas wells are cemented before they are put in production. The cement is placed in the annulus between steel casing and rock formation to provide mechanical integrity and zonal isolation. Evaluating that the cement has indeed displaced drilling mud and has set well enough to provide well integrity is a regulatory requirement. The well-honored ultrasonic pulse-echo technique, implemented with a trans-receiver housed on a fluid-immersed rotating tool, was originally introduced to meet this need. It was, however, shown to have limitations in (i) resolving light-weight cements with mud-like acoustic impedance as well as in (2) radially probing the entire annular space. Both limitations stem from the significant impedance contrast encountered by the acoustic beam at the steel layer: less than 10% of the signal amplitude is coupled to the steel and a fraction of that, at best, returns from within the cement sheath.

Investigations to go beyond these limitations led to the identification of the high-frequency casing quasi-Lamb $A_0$ (aka flexural) mode as having attractive imaging characteristics. The implemented pitch-catch measurement, named flexural wave imaging or FWI, features signals with temporally-compact (i.e., imaging-friendly) echoes: propagating axially in the casing with an amplitude attenuation informing on the material in contact with the steel as well as reflecting from interfaces deep within the cement sheath such as at the rock face, with relatively large amplitudes seemingly defying the impedance contrast premise. This presentation will focus on FWI and will describe the rich and intricate wavephysics arising from the dispersive nature of the flexural mode and that is manifested in particular with the signal propagation in the cement sheath: elastic-wave propagation and evanescence often co-exist, steel-cement bond conditions markedly affect the signal characteristics, and shear only or both compressional and shear wave reflections from the cement-rock interface whose time of flights are explainable in terms of simple ray acoustics whereas their relatively large amplitudes require elaborate scattering (non-specular) considerations.

Extensive theoretical results and raw and processed field data from an operating measurement tool in real wells will be presented to explain and illustrate the intricate wavephysics of FWI as well as comment on the general challenges faced in this industrial application.
Enhanced Model-based Inverse Methods for Sizing Cracks in Multilayer Bolt-hole Eddy Current (BHEC) Inspections

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To support the long-term goal for greater use of condition-based maintenance, there is a need for innovative methods to not simply detect damage but to completely characterize the state of the structure. This paper presents progress on the characterization of discontinuities and the surface condition of multilayer fastener sites using bolt hole eddy current (BHEC) techniques. A comprehensive approach is presented to perform model-based inversion of cracks and notches using eddy current techniques with an automated BHEC system. The inversion process leverages fast surrogate models built using VIC-3D® simulations. Improved sizing results with respect to prior work [1] were achieved through increasing the resolution of the surrogate model, using the flaw calibration process to compensate for ‘scale differences’ between the measurements and simulations, improved signal registration in both hole depth and angular orientation, and reparameterization of the unknown discontinuity properties for improving model sensitivity to the measurement data during inversion. Sizing performance was found to be greatly improved over prior work for a set of well characterized corner EDM notches and cracks, with varying size and aspect ratio. Additional work has investigated the role of the adjacent material on eddy current response from corner cracks. Studies were performed investigating changes in the crack response adjacent to aluminum, steel, titanium and free surface conditions. With new BHEC hardware, it is feasible to characterize the material state through absolute coil measurements, and compensate for varying conductivity in the inversion of any discontinuities present.

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Guided Wave Tomography: Application to Corrosion Detection

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Guided wave tomography offers a quantitative and very robust way of monitoring corrosion in planar structures. We explore here different tomography algorithms and compare their performances to reconstruct an extended area of corrosion (represented by a continuous thickness reduction) in an aluminum plate. These studies are performed on both experimental and simulated data.

The first tomography algorithm, SART, is based on a straight ray propagation assumption and requires the determination of the time of flight between all the couples of the sensor’s distribution around the monitored area. Then, the potential refraction caused by the defect is introduced by allowing a curvature of the rays (bent-ray algorithm [2]).

The last algorithm, HARBUT [3], is able to take into account the diffraction phenomena, but requires not only the time of flight but the whole signal between the different couples of transducers.

The range of validity of these imaging algorithms (e.g. with respect to Born approximation) are explored using simulations performed with a spectral finite element formulation offered within CIVA simulation platform developed at CEA. Finally, tomographic reconstructions based on experimental results are presented.

(a) Experimental setup, (b) example of experimental reconstruction and (c) comparison between ray-tomography and HARBUT algorithm.

References:
Comparative study of 2D ultrasound imaging methods in the frequency domain (f-k) and evaluation of their performances in realistic inspection configurations

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In this communication, a new approach that combines incident plane waves and imaging algorithms in the f-k domain is proposed to achieve very fast computation times. Two Fourier domain algorithms are introduced to calculate images from a plane wave acquisition: one is derived from Stolt’s theory in seismic imaging [1], and the other one from Lu’s theory in medical imaging [2]. We provide a detailed break-down of their algorithmic complexities and show that f-k methods can theoretically reduce the complexity by a factor up to the number of transducer elements of the array. In order to perform conventional inspections with immersion probes or contact probes equipped with Plexiglas wedges, we extend both imaging methods to multilayered media including water/steel or Plexiglas/steel interfaces. In addition, the ability of each method to image flaws outside of the array aperture is discussed. Stolt’s and Lu’s methods are then implemented in Matlab, and compared to the PWI (Plane Wave Imaging) method in the time domain by post-processing the same experimental data acquired with a linear array probe. The comparison of these methods dwells on computation time, lateral resolution and signal/noise ratio. Compared to the PWI method, we show that the f-k methods provide images of similar or even better quality according to these criteria, while significantly reducing the computation time.

References:
Quantification of damage using reflectance Fourier Transform Infrared (FTIR) spectroscopy

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Fourier Transform Infrared spectroscopy is a powerful surface chemical characterization technique. Development of portable FTIR devices has enabled the use of this tool to quantify damage, through the related chemical changes, in polymer matrix composites. The quantification of damage from FTIR signals of PMCs depends on the fact that PMCs are absorbing in the relevant wavenumber region (650-4000 cm⁻¹). The physics for reflecting materials, including ceramic matrix composites (CMCs), do not avail themselves to the analysis routines that are used for absorbing materials. Nonlinear regression analysis, including an experimental model calibration technique to account for the varying quality of the data across the spectrum, applied to the analysis of the FTIR spectra of CMCs is discussed. The assumptions made in the implicitly made in the data analysis routines and the evaluation of their validity are presented. FTIR data from CMCs that have been thermally and mechanically treated are analyzed and compared to FTIR data from as received CMCs. The quantification of the damage through the chemical changes observed in the spectra is summarized.
Monitoring the carbonation-induced microstructural changes in cementitious materials by nonlinear resonant acoustic spectroscopy (NRAS)

Sara Ghahremani, Alexandra Radlińska, Parisa Shokouhi; Department of Civil and Environmental Engineering, The Pennsylvania State University, University Park, PA, USA

We use nonlinear resonant ultrasound spectroscopy (NRAS) to monitor the changes in linear resonance frequency ($f_0$) and the hysteretic nonlinearity parameter ($\alpha$) of several mortar samples exposed to accelerated carbonation. Linear resonance frequency $f_0$ of the sample is measured at very low excitation amplitudes ($\varepsilon < 10^{-7}$). In contrast, NRAS involves measuring the resonance frequencies at a number of excitation amplitudes ranging from very low ($\varepsilon < 10^{-7}$) to moderately high strains ($\varepsilon \sim 10^{-6}-10^{-5}$). The nonlinearity parameter $\alpha$ quantifies the strain-dependency (i.e., nonlinearity) of the obtained resonance frequencies. This study demonstrates that the hysteretic nonlinearity parameter $\alpha$ is highly sensitive to the carbonation-induced porosity changes in alkali-activated mortars. The change in porosity is independently investigated using SEM and Mercury Intrusion Porosimetry (MIP). Our findings suggest that not only the total porosity but also the void size distribution influences the materials nonlinearity. Large wide cracks decrease the overall stiffness and reduce $f_0$, but do not contribute to nonlinearity. As such, simultaneous monitoring of $\alpha$ and $f_0$ provides complementary information on the microstructural development of cementitious materials in terms of size and density of microcracks.

![Figure 1](image.png)

**Figure 1.** (a) Evolution of the nonlinearity parameter $\alpha$ with the progress of the carbonation front for two different alkali-activated mortar samples: SS-AS and SH-AS. The green curve (circular markers) corresponds to the changes in $\alpha$ in a control sample kept in a Nitrogen chamber. (b) Carbonation results in microcracking in the binder matrix and increases the nonlinearity of the samples. Once the microcrack sizes in SS-AS sample surpass a certain threshold, the nonlinearity decreases.

References:
1. S. Ghahremani, Y. Guan, A. Radlińska, and P. Shokouhi “Carbonation-induced microstructural evolution of alkali-activated slag (AAS) revealed by nonlinear resonant acoustic spectroscopy (NRAS),” to be submitted to *Cement and Concrete Research*. 
Generalization of frequency domain (f-k) migration methods to 3D imaging with matrix array probes

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The advent of transducer arrays in NDE has paved the way for the development of new imaging techniques, based on various emission modes, allowing for better resolution and contrast, but also an increased field of view. While most controls are still done using linear arrays for 2D imaging, one might want to detect defects exhibiting a 3D geometry or to image a large volume of the material in a fixed position. For that matter, matrix arrays make it possible to form 3D images but computation times are often prohibitive because of the large number of voxels and array elements to deal with. To reduce image reconstruction times, we introduce two frequency-domain methods inspired by Lu’s method for medical imaging \cite{1} and Stolt’s f-k migration for seismic imaging \cite{2} and apply them to plane wave emissions \cite{3}. The former is based on a forward model of wave propagation in the physical medium \((x, y, z, c)\) and relies on Weyl’s identity which states that the Green’s function of the Helmholtz equation can be written as a sum of plane waves. The latter is based on the Exploding Reflector Model (ERM), which states that the back and forth propagation time in the physical medium is equivalent to the travel time from sources simultaneously exploding at \(t = 0\) in a virtual medium \((\hat{x}, \hat{y}, \hat{z}, \hat{c})\) to the array. We then compare these methods in realistic NDT configurations (probes immersed in water or equipped with Plexiglas wedges) with the standard time domain Plane Wave Imaging (PWI) and show they not only slightly improve spatial resolution and SNR, but also significantly speed up the image calculation.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Spherical inclusions of diameter 0.3mm inside steel imaged with a 16 × 16 array (pitch 0.6mm, center frequency 5MHz) in immersion (water height : 10mm) using Lu’s method.}
\end{figure}

References:
Handheld FTIR devices are being investigated for detection and quantification of surface degradation such as oxidation and coating removal of ceramic matrix composite (CMC) materials [1,2]. This will prevent some failures by enabling early detection of non-visible damage. Experiments will examine changes in chemical composition for different distances from the heat source, and exposed different mechanical and thermal conditions. Using mathematical, physical, and statistical models for FTIR reflectance data, this research seeks to quantify any detected spectral changes as an indicator of heat damage. Progress towards classification of regions in an unknown sample as heat damaged, heat affected, and unaffected will be reported.


Uncertainty Quantification of Resonant Ultrasound Spectroscopy for Material Property and Single Crystal Orientation Estimation on a Complex Part

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Resonance Ultrasound Spectroscopy (RUS) is a nondestructive evaluation method which can be used to quantify the elastic properties of materials by measuring their resonance spectra, and has shown sensitivity to variation in the grain structure and certain damage states. Recent work has addressed enhancements of forward and inverse modeling capabilities for RUS, and demonstrated a process for quantifying the propagation of uncertainty in RUS frequency results for models and measurements [1]. For complex parts, numerical models like the finite element method (FEM) are necessary to represent the resonance frequencies; however, these models will have some error that will impact the inversion process and results. In this paper, a case study is presented evaluating error in RUS inversion for a single crystal (SX) Ni-based superalloy Mar-M247 cylindrical bone specimens. A number of surrogate models were developed with FEM model solutions, using different sampling schemes (regular grid, Monte Carlo sampling, Latin Hyper-cube sampling) and representational models, N-dimensional cubic spline interpolation and Kriging. Repeated studies were used to quantify the well-posedness of the inversion problem, as well as the overall uncertainty in material property and crystallographic orientation estimates for select geometric dimension variability with tolerance bounds. The benefit of proper mode sorting in the model space as well as mode selection was studied for different surrogate model designs. Results were evaluated over a range of simulated and experimental results with different levels of model error. Both the surrogate model and mode sorting were found to be less critical when inverting properties of experimental data versus ideal simulated results. The model calibration process was also studied, that evaluates inversion fitting to differences from a designated reference sample rather than absolute property values, yielding a reduction in fit error.

Acknowledgements:

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References:
Measurements of Acoustic Nonlinearity Parameters in a Reflection Mode

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Measurements of the acoustic nonlinearity parameter $\beta$ are frequently made for early detection of damage in various materials. The practical implementation of the measurement technique has been limited to the through-transmission setup for determining the nonlinearity parameter of the second harmonic wave. For the purpose of practical applications, a pulse-echo measurement technique is more desirable which enables the single-side access of test components. The issue with using the second harmonic wave reflected from the stress-free interface is that such a boundary destructively alters the nonlinear generation process and consequently makes it difficult to obtain the reliable results of $\beta$. Our previous simulation study \cite{1} shows that the average displacement of the second harmonic wave reflected from the stress-free boundary is as large as one third or one half of the through-transmission mode of the same total propagation distance depending on the thickness. When the sample was rather thin, the average pulse-echo displacement of the second harmonic is very small and consequently the total correction to be made becomes very large. Therefore, the $\beta$ determination in this case largely depends on the sensitivity of the second harmonic displacement measurement and on the accuracy of making total corrections. In this work, the acoustic nonlinearity parameter is measured for water using two different reflecting boundaries: water-metal and water-air. Fig. 1 shows that the correct $\beta$ values can be obtained in both setups if total corrections are made for material attenuation, beam diffraction and boundary reflection.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{$\beta$ measurement results for water using the reflected waves from (a) water-metal boundary, and (b) water-air boundary.}
\end{figure}

Acknowledgement:

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References:

Mid-IR Laser Ultrasonic Testing for Fiber Reinforced Plastics

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Fiber reinforced plastics (FRPs) has been used as structural materials for airplanes and automobiles because of their high specific strength and corrosion resistance. Since the reliability guarantees demand higher level, non-destructive testing (NDT) for FRP products is indispensable. Laser ultrasonic testing (LUT), which is one of ultrasonic testing methods, realizes instantaneous inspection without contacting with materials so that it has many advantages in high efficiency and extensive application. In order to generate ultrasonic waves in FRPs, a laser light with a wavelength in the vicinity of 3.2 μm is optimal [1]. However, such a wavelength laser is not available in the market. Thus, we developed the most efficient wavelength conversion device for generating 3.2 μm wavelength mid-IR pulsed light by pumping an optical parametric oscillator using a Nd:YAG solid-state laser [2].

In the present study, we demonstrate the performance of the mid-IR LUT system (Fig.1) by inspecting FRPs, thermoplastics, and polymer coated samples. The mid-IR laser generated several times higher amplitude of ultrasonic waves than other laser sources. In addition, the experimental data coincided with simulated results by finite element method. As a result, the system can inspect thicker sample compared with conventional laser sources.

Fig. 1. A schematic diagram of mid-infrared laser ultrasonic testing system

Acknowledgement:
This research was supported by the Structural Materials for Innovation of the Cross Ministerial Strategic Innovation Promotion Program (SIP) of Japan Science and Technology.

References:
Ultrasound Phase Velocities for Synthetic Three-Dimensional Polycrystalline Materials

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The generation of three-dimensional (3D) realizations of polycrystalline microstructures is becoming an increasingly important topic. These simulations provide the means to study certain aspects of materials that are complicated to quantify experimentally. Dream.3D is a software platform with which 3D microstructure volumes of polycrystalline materials can be simulated. In this presentation, ultrasonic phase velocity behavior is examined using Dream.3D to quantify the mean and standard deviation with respect to the propagation direction and number of grains within the model. For each simulated microstructure, the average elastic modulus tensor is derived using Voigt, Reuss, and self-consistent approaches. From the average modulus tensor, longitudinal and shear wave speeds are determined. Comparisons are then made with theoretical values for materials with cubic single-crystal symmetry including aluminum, copper and nickel. The simulation results show good convergence with the theories as long as the theories include appropriate probability distribution functions for the Euler angles of the grains. The analysis also shows that Dream.3D creates microstructures with a slight anisotropy that is dependent on material type (e.g., copper shows an anisotropy factor of about 3 percent). Simulated ultrasonic velocities for copper are also compared with measured values from Ledbetter [1]. The overall results show that the self-consistent average with Dream.3D microstructures agrees best with the longitudinal and shear velocities of Ledbetter. In fact, the slight shear wave anisotropy from [1] can be matched if a specific propagation direction in Dream.3D is assumed. Such analysis tools are expected to provide new insights into the relations between the interaction of ultrasound with polycrystalline materials. [Research supported by AFRL under prime contract FA8650-15-D-5231].

Reference:
Cement-based composites have been used as reliable materials in building and civil engineering infrastructure for many years. Although there are many advantages, some drawbacks such as premature cracking, which may occur during and after construction, may be problematic for sensitive applications such as those found in nuclear power plants. Moreover, several characteristics of cement-based materials including micro-crack formation, which may lead to durability concerns, originate early in the hydration process. Therefore, the evaluation of early hydration and associated damage processes of cement paste have gained interest. In this study, acoustic emission was employed to monitor the hydration process of cement paste and damage progression during uniaxial compression testing. Unsupervised pattern recognition was employed to categorize the data into appropriate classes. This method was used to organize and interpret the acoustic emission data during the early hydration and compression testing of cement paste specimens.
Two-Point Statistics of Synthetic Three-Dimensional Polycrystalline Microstructures

Musa Norouzian and Joseph A. Turner, Mechanical and Materials Engineering, University of Nebraska-Lincoln, Lincoln, Nebraska, 68588, USA

The two-point spatial statistics of a heterogeneous material play a crucial role in ultrasonic attenuation and backscatter calculations. Information about the degree to which two grains in a polycrystal are spatially correlated and how much the orientation of one grain influences the other is contained in the covariance of the elastic modulus tensor. In this presentation, several common assumptions used for modeling polycrystals are examined. In most studies, the spatial and tensorial elements of the covariance function are assumed to be decoupled from each other. Also, two-point correlation models often assume a single effective grain size for polycrystalline materials and a spatial correlation function that is considered to have an exponential decay at a rate directly proportional to the average grain diameter. This investigation uses the Dream.3D software platform to generate three-dimensional (3D) realizations of polycrystalline materials in order to study their two-point statistics. Using lognormal distributions with fixed means but different widths, a variety of different polycrystalline microstructures are simulated. The results show that the spatial correlation function is directly influenced by the grain size distribution. For a fixed mean grain size, wider distributions exhibit longer range correlations than narrower ones. The results also show that decoupling of the tensorial and spatial elements of the covariance function may not be valid for all lognormal grain size distributions. This effect is quantified with respect to the grain size statistics by calculating the correlation coefficient between different tensorial components of the covariance function. These results are anticipated to have an important impact on ultrasonic attenuation and backscatter models.

Acknowledgement:

Research supported by AFRL under prime contract FA8650-15-D-5231.
Measurement of the fiber orientation in a carbon fiber composite material is crucial in understanding the load carrying capability of the structure. As manufacturing conditions including resin flow and molding pressures can alter fiber orientation, verification of the as-designed fiber layup is necessary to ensure optimal performance of the structure. In this work the development of an eddy current probe and data processing technique for analysis of fiber orientation in carbon fiber composites is presented. A proposed directional eddy current probe is modeled and its response to an anisotropic multi-layer conductor simulated. The modeling results are then used to finalize specifications of the eddy current probe. Experimental testing of the fabricated probe is presented for several samples including a truncated pyramid part with complex fiber orientation draped to the geometry for resin transfer molding. The single sided measurement technique has been tested on composites up to 12 plies in thickness. The fast and cost effective technique can be applied as a spot check or as a surface map of the fiber orientations across the structure. This paper will detail the results of the probe design, computer simulations, and experimental results.
Detection And Quantification Of Creep Strain Using Process Compensated Resonance Testing Sorting Modules Trained with Modeled Resonance Spectra

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Process Compensated Resonant Testing (PCRT) is a full-body nondestructive evaluation (NDE) method that measures the resonance frequencies of a part and correlates them to the part’s material state and/or damage state. Automated PASS/FAIL inspection applications, or “sorting modules” based on Vibrational Pattern Recognition (VIPR) algorithms and Mahalanobis-Taguchi System (MTS) statistical scoring are created to distinguish parts with nominal process variation from those with the defect(s) of interest [1]. Prior work in the aerospace industry has demonstrated PCRT’s sensitivity to overtemperature exposure, casting flaws, and other defects that can lead to unacceptable structural performance [2]. PCRT requires a sample training set consisting of enough acceptable and unacceptable parts to enable an analysis of the resonance frequency differences between part populations. However, gathering a training set can be time-consuming, and the availability of defective parts may be limited. Prior work has demonstrated that virtual database training sets, created through finite element method (FEM) modeling, can be used to train PCRT sorting modules to detect and quantify creep strain in simple coupon geometries [3]. The work presented here describes the creation of PCRT sorting modules for complex shapes, in this case single crystal (SX) nickel-based superalloy turbine blades, using virtual database training sets. Turbine blade FEM models were used to create populations of turbine blade resonance spectra. These populations included modeled blades with nominal levels of variation in crystallographic orientation, geometric dimensions, and material properties. Model results were verified by comparing the frequency variation in the modeled populations with the measured frequency variation of several physical blade populations. The modeled populations also included blades with creep strain deformation simulated using the methods described and verified in [3]. The resonance spectra for the modeled populations were mode matched and used to create a virtual training database. The virtual database spectra were analyzed with VIPR to identify modes that were the most sensitive to creep strain while allowing acceptable variation. Finally, PCRT sorting modules using the selected modes were created to first detect creep strain in the modeled population then quantify the level of creep strain using correlations to MTS scoring. This work demonstrates that virtual training databases can be used to develop PCRT sorting modules to detect and quantify specific damage types. It also indicates the potential for the application of this approach to many other geometries and damage mechanisms.

References:
Part-to-Itself Model Inversion in Process Compensated Resonance Testing

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Process Compensated Resonance Testing (PCRT) is a non-destructive evaluation (NDE) method involving the collection and analysis of a part’s resonance spectrum to characterize its material or damage state. Prior work used the finite element method (FEM) to develop forward modeling and model inversion techniques. Forward modeling generates a virtual part’s resonance frequencies from a given set of material and geometric parameters, whereas inverse modeling estimates those parameters from a given set of frequencies [1]. In many cases, the inversion problem can become confounded by multiple parameters having similar effects on a part’s resonance frequencies. To reduce the uncertainty caused by confounding parameters and isolate the change in a part (e.g. creep), a part-to-itself (PTI) approach can be taken. Unlike prior PCRT inversion work, which uses absolute frequency values, a PTI approach involves inverting only the change in resonance frequencies from the before and after states of a part. This approach reduces the possible inversion parameters to only those which change in response to in-service loads and damage mechanisms. To evaluate the effectiveness of using a PTI inversion approach, creep strain and material properties were estimated in virtual and real samples using FEM inversion. Creep strain was chosen as a damage state because variation in initial part dimensions can mimic its effects on the part’s resonance. Virtual and real samples used a dog bone geometry composed of nickel based superalloy Mar-M-247. Virtual samples were modeled with typically observed variations in material properties and dimensions. Resonance spectra were calculated both before and after various amounts of modeled creep deformation. An experimental verification sample was crept in stages and the resonance spectrum was collected after each incremental elongation. All samples were inverted against a model space that allowed for change in the creep damage state and the material properties but was blind to initial part dimensions. Results quantified the capabilities of PTI inversion in evaluating creep strain and material properties, as well as its sensitivity to confounding initial dimensions.

References:
Dielectric Properties Measurement for NDE of Nuclear Power Plant Cable Insulation

Mario V. Imperatore¹,², Leonard S. Fifield³, Davide Fabiani¹, and Nicola Bowler²,⁴, ¹University of Bologna, Bologna, 40136, Italy, ²Department of Materials Science and Engineering, Iowa State University, Ames, IA 50011, USA, ³Pacific Northwest National Laboratory, Washington, 99354, USA, ⁴Center for Nondestructive Evaluation, Iowa State University, Ames, IA 50011, USA

A method for characterizing the dielectric properties of nuclear power plant (NPP) cable insulation material is developed. The integrity of low-voltage control cables is important for the safe, long-term operation of NPPs. Against the backdrop of reflectometry measurements, that are particularly good for detecting ‘hard’ faults such as a defective conductor in a cable structure, and indenter measurements that measure the elastic modulus of the jacket material and infer insulation health from it, there is a need for a nondestructive measurement approach that assesses the condition of the insulation material directly. In this work, a connector was developed by which one of the three conductors was held at positive potential while the other two, and an outer metal sheath applied to the cable jacket, were grounded. In this way, electrical energy was concentrated in the insulation material surrounding the conductor held at positive potential, and the complex capacitance measured between this conductor and those grounded conductors was found to be sensitive to the dielectric properties of the insulation material. With this setup, capacitance and dissipation factor (tan δ) were measured over the frequency range from 0.01 Hz to 1 MHz on a set of PVC-jacketed, EPR-insulated NPP cables, Figure 1 (left), that had been aged thermally at 140 °C for up to 1,270 h. Results showed that, at some frequencies, capacitance and tan δ are leading indicators of insulation material property degradation, as compared with changes in elongation-at-break on the same materials, Figure 1 (right).

![Figure 1](image)

**Figure 1.** PVC-jacketed, EPR-insulated tri-core NPP cable (left); EaB and tan δ versus aging time for samples aged thermally at 140 °C for up to 1,270 h (right). The color coding for tan δ measurement indicates the insulation color of the wire held at positive potential during the measurement.

**Acknowledgement:**

This work was performed in the Department of Materials Science and Engineering at Iowa State University with support from the University of Bologna and the United States Department of Energy under contract number DE-NE0008269.
Use of Apparent Thickness for Pre-processing of Low Frequency Electromagnetic Data in Inversion-based Multi-Barrier Evaluation Workflow

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Steel casing corrosion inspection using low frequency electromagnetic measurements is widely adopted in well integrity evaluation for ensuring environment-friendly and efficient hydrocarbon production and for well abandonment at the end of the productive life of the well [1]. To determine effective permeability, conductivity, and thicknesses of individual pipes, we developed an inversion-based workflow [2] for quantitative evaluation of multiple nested casings using multi-spacing and multi-frequency electromagnetic measurements. The workflow raises a QC flag, indicating eccentered casings, when inversion gives poor reconstruction of short spacing measurements. Excellent results are reported for synthetic and lab data. Some artifacts are evident in field data processing. Conventional RFEC tool measurements [1] with non-collocated transmitter and receiver antennas have double indication of metal change due to the corrosion and/or casing collars, when antennas cross the heterogeneity. Quantitative evaluation of individual casing thickness is further complicated by casing eccentering and uncertainty in casing magnetic permeability and electric conductivity.

In this work processing enhancements are presented. The concept of apparent thicknesses is introduced, assigning each measurement a thickness value in order to simplify interpretation and evaluation of multi-spacing multi-frequency data from the new casing inspection tool. The two new pre-processing algorithms are developed to remove artifacts from RFEC measurement responses due to non-collocated antennas. Firstly, long-spacing (RFEC data) apparent thicknesses are used to remove artifacts (‘ghosts’) from the pipe sections due to transmitter crossing a casing collar or corrosion. Secondly, a collar identification, localization and assignment algorithm is used. It uses peak value of squared long-distance collar responses and distance between them to group together individual casing collars. Each collar group is assigned to a casing based on the location of collar signatures on transmitter current and long-distance response width of the group. Lastly, 3D modeling examples will be presented demonstrating that the casing eccentering can also be indicated based on opposite response deviation from nominal thickness in short spacing phase and magnitude apparent thicknesses. The developed data pre-processing enables robust inversion in collar sections. The proposed algorithms have been successfully validated on synthetic data and applied to several field data sets.

References:
Models for the simulation of ultrasonic inspections of flat and curved plate-like composite structures, as well as stiffeners, are available in the CIVA-COMPOSITE module released in 2016. A first modelling approach using a ray-based model, is able to predict the ultrasonic propagation in an anisotropic effective medium obtained after having homogenized the composite laminate. Fast 3D computations can be performed on configurations featuring delaminations, flat bottom holes or inclusions for example. In addition, computations on ply waviness using this model will be available in CIVA 2017. Another approach is proposed in the CIVA-COMPOSITE module. It is based on the coupling of CIVA ray-based model and a finite difference scheme in time domain (FDTD) developed by AIRBUS. The ray model handles the ultrasonic propagation between the transducer and the FDTD computation zone that surrounds the composite part. In this way, the computational efficiency is preserved and the ultrasound scattering by the composite structure can be predicted. The main advantages of this numerical model is the ability to visualize the wavefield at each time step and the consideration in the computation of intermediate epoxy layers whose periodicity pattern may engender structural noise. Until now, this approach is limited to 2D configurations but its extension to 3D is planned. Alternatively, a high order finite element approach is currently developed at CEA but not yet integrated in CIVA. The advantages of this approach will be discussed and first simulation results on Carbon Fiber Reinforced Polymers will be shown.
Monitoring and Localization of buried plastic natural gas pipes using passive RF tags

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Buried pipelines are one of the major transportation medium for diverse type of liquids and gases which are being used by industry and households. The need for pipe identification plays an important role in maintenance operations to ensure safety for different distribution systems. Traditionally Ground Penetrating Radar (GPR) is used to locate buried objects. However, there is a tradeoff in frequency vs resolution for GPR based imaging. For higher penetration depth in soil, the GPR must operate at lower frequency, which would degrade the resolution of the image. Hence, it would be difficult to image small diameter non-metal pipes at a considerable depth (>5 feet). Moreover, GPR would fail to distinguish between two identical buried objects at same depth. Those problems can be solved by tagging the pipes using RFIDs during underground deployment. A passive RF tag on the pipe can also allow us adding some sensing capabilities as integral structure of the pipe. RFID based tagging has already emerged as a potential solution for chemical sensing, location detection, animal tagging, etc. Harmonic transponders are already quite popular compared to conventional RFIDs due to their improved SNR [1]. However, the operating frequency, transmitted power and tag efficiency become critical issues for underground RFIDs. In this paper, a comprehensive on-tag sensing, power budget and frequency analyses is performed for buried harmonic tag design. The main factors for reducing damage to underground pipelines that have been studied and implemented are: 1) Track of Burial depth and 2) Changing Stress over pipe. Burial depth is estimated using phase information of received signal at different frequencies as well as using genetic algorithm for post processing. A polypropylene based nano-generator is used as a stress sensor that can be used at higher frequencies with good resolution. The sources of power loss involved in tag communication are: 1) Path loss in soil; 2) Conversion loss in tag; 3) Air-Soil interface loss in between reader antenna and soil. Suitable frequency range is determined for a variety of soil with different moisture content for small tag-antenna size. The maximum transmitted power level was also determined for a frequency of operation as it is limited by FCC regulations. Different types of harmonic tags such as 1) Schottky diode, 2) Non-linear Transmission Line (NLTL) [2] were compared with conventional simple modulation RFIDs for underground applications. In this study, the power, frequency and tag have been optimized for small antenna size, minimum signal loss and simple reader circuit for underground detection at 5 feet depth in different soil medium and moisture contents.

Acknowledgement:
This work was performed with support from the Department of Transportation (DOT).

References:
Scattering of harmonics from an anisotropic nonlinear inclusion having up to cubic elastic nonlinearity

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Nonlinear ultrasound has developed into a valuable nondestructive evaluation tool of material microstructures over the past couple decades. One such method uses ultrasound of finite strain amplitude to incite a nonlinear elastic response, which causes the generation of integer-order multiple harmonics. Thus, the measurement of harmonic amplitudes forms a direct link to the nonlinear elastic properties of the material, i.e., the third- and fourth-order elastic constants. For NDE applications involving metals, the nonlinear elastic property to be measured might be associated with dislocation dynamics during fatigue, residual stress and plastic deformation from thermomechanical processes, fatigue microcracks, micro-porosity from sintering processes, among others. These effects are often local, spatially dependent, and anisotropic. Hence, for these cases, it is appropriate that the nonlinear region be treated as an inclusion, which generates (scatters) harmonics. This presentation will give a theoretical model of the scattering amplitudes of second- and third-harmonics from an inclusion of arbitrary shape that has anisotropic, spatially-dependent nonlinear elastic properties. Specific cases such as the scattering of second- and third-harmonics from a spherically shaped inclusion having transversely isotropic elastic properties will be highlighted. Physical findings will be discussed including: the absence of a radiation-induced static strain for cubic nonlinearity, mode conversion (e.g., scattered shear wave from an incident longitudinal wave), and the generation of a scattered fundamental wave caused by cubic nonlinearity.

\textbf{Figure 1.} Normalized longitudinal scattering amplitudes for the (a) fundamental, (b) second-harmonic, and (c) third-harmonic of an incident longitudinal wave from a spherical inclusion. The inclusion was considered to be a monocrystal of nickel where the incident wave was in the [100] direction with scattering in the (001) plane. The scattering amplitudes are plotted against the angle between the incident and scattered directions (180° for backscatter, 0° for forward scattering). Different cases of $ka$ (wave number times inclusion radius) are considered ($ka$ is proportional to incident wave frequency).
Bounds on the ratio of longitudinal to shear wave attenuation constants of polycrystalline materials

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Recently, a lower bound on the ratio of the longitudinal and shear wave attenuation coefficients $\alpha_L/\alpha_S=4c_S^3/3c_L^3$ was discovered for viscoelastic materials [1]. For this case, the lower bound corresponds to energy dissipation associated with shear deformation. The question of whether a similar bound exists for polycrystalline materials was posed quickly thereafter. In this presentation, a derivation of the attenuation ratio is provided for the case of scattering induced attenuation of ultrasound. In the low-frequency, Rayleigh scattering regime, a lower bound was discovered that is exactly the lower bound derived in Ref. [1]. Additionally, a new upper bound was derived. The lower bound is realized when the single-crystal elastic anisotropy is fully characterized by its shear modulus. Conversely, the upper bound is achieved when the single-crystal elastic anisotropy is characterized by its bulk modulus only. Polycrystals containing crystallites of cubic symmetry always reside on the lower bound because the anisotropy of cubic single crystals is completely characterized by its extreme shear moduli. To affirm these findings, the theoretical attenuation ratio was analyzed using a dataset consisting of 2,176 crystalline materials, with their single-crystal elastic constants and mass densities obtained from density functional theory [2]. The dataset provided material examples spanning all 32 crystallographic point groups. All data points were observed to reside within the bounds, while all polycrystals with crystallites of cubic symmetry were found to reside on the lower bound. Application of the bounds will be discussed with an emphasis on computational wave propagation models and experimental methods.

References:
The interior visual inspection of pipelines in the nuclear industry is a safety critical activity conducted during outages to ensure the continued safe and reliable operation of plant. Typically, the video output by a manually deployed probe is viewed by an operator looking to identify and localise surface defects such as corrosion, erosion and pitting. However, it is very challenging to estimate the nature and extent of defects by viewing a large structure through a relatively small field of view. This work describes a new visual inspection system employing photogrammetry using a fisheye camera and a structured light system to map the internal geometry of pipelines by generating a photorealistic, geometrically accurate surface model. The error of the system output was evaluated through comparison to a ground truth laser scan (ATOS GOM Triple Scan) of a nuclear grade split pipe sample (stainless steel 304L, 80mm internal diameter) containing defects representative of the application – the error was found to be submillimetre across the sample.
Welding Induced Residual Stress Evaluation Using Laser-Generated Rayleigh Waves

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Welding induced residual stress could affect the dimensional stability, fatigue life, and chemical resistance of the weld joints. Ultrasonic method serves as an important non-destructive tool for the residual stress evaluation due to its easy implementation, low cost and wide application to different materials. Residual stress would result in the ultrasonic wave velocity change, which is the so called acoustoelastic effect. Bulk waves such as longitudinal wave [1], shear wave and longitudinal critical refracted (LCR) wave [2] have been used to evaluate the average residual stress over the thickness of the sample. In this paper, we propose a Laser/EMAT ultrasonic technique to evaluate surface/subsurface longitudinal residual stress developed during Gas Metal Arc Welding (GMAW) process. The relative velocity difference $\delta V / V$ of Rayleigh wave, which is a surface wave, is studied. The broad band ultrasonic waves are excited by pulsed Q-Switched Nd: YAG laser. Electromagnetic acoustic transducer (EMAT) attached to the welded plates is used to capture the Rayleigh wave signals propagating along the weld seam direction. The experiment setup is shown in Fig. 1. Different ToF measurements are conducted by varying the distance between the weld seam and Rayleigh wave propagating path in the range of 0 to 150 mm. The maximum relative velocity difference is found to be on the weld seam. With the increasing distance away from the weld seam, the relative velocity difference sharply decreases to negative value. With further increase in distance, the relative velocity difference slowly increases and approaches zero. As has been extensively reported, the relative velocity deference of ultrasonic waves is closely related to the material residual stress states, as shown in Fig. 2. Therefore, our research will show that the maximum tensile stress appears on the weld seam while compressive stress appears in the heat affected zone (HAC). Preliminary examination shows that the proposed method offers a potential means of evaluating welding induced surface/subsurface residual stress profile.

![Fig. 1 Experiment setup](image1)

![Fig. 2 Schematic plot of $\delta V / V$ and $\sigma$ relationship](image2)

References:
Flexible, Multi-Signal Guided Wave Environmental Compensation

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Guided wave damage detection systems require comparable measurements to identify damage signatures in data. Yet, temperature and other environmental effects distort data, often with a much greater effect than damage. Using stretching methods, such as the scale transform and dynamic time warping, we can compensate for the effects of temperature. Even with temperature compensation, variations related to temperature remain and can still hide damage.

Damage detection methods often apply stretch-based temperature compensation to match and compare data to a single baseline. Yet, temperature compensation errors are often distributed differently across the data set. Therefore, to achieve more accurate damage detection, we should account for variations between all pairs of measurements. In this paper, we present a multi-signal temperature compensation method that achieves this goal. Our approach utilizes the temperature compensated correlation matrix between measurements. This shows that undamaged and damaged measurements achieve high correlations with data from their respective states. We then apply singular value decomposition to the matrix to extract and identify the damage indicator.

We validate our multi-signal temperature compensation method using experimental data from an aluminum plate and compare our results with traditional damage detection methods. We apply a step detector to our damage indicator (obtained from singular value decomposition) to detect sudden damage. In Figure 1(a), the damage indicators from the singular value decomposition, using both multi- and single baseline methods, are shown. The multi-signal method achieves a lower variance in the damage indicator where the single baseline has large peaks that may hide damage. Furthermore, in Figure 1(b), the multi-signal method achieves a detection value above 0.95. Comparatively, the single baseline method achieves a maximum detection value of 0.72.

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![Figure 1](image-url)

**Figure 1.** The inclusion of damage is identified using damage indicators. (a) The multi-signal method (solid-blue) achieves lower variance than the single baseline method (dashed-red). (b) The detection value achieves above 0.95 for the multi-signal case, but only 0.72 for the single baseline case.
Additive manufacturing is a rapidly maturing process for the production of complex metallic, ceramic, polymeric, and composite components. The processes used are numerous, making quality control and standardization difficult. The authors have identified acoustic emissions monitoring as a potential means of monitoring metal additive manufacturing processes for process noise characteristics and events characteristic of defects, including cracks and delamination. Acoustic emissions monitoring has been used previously to monitor a number of processes including machining and welding [1,2]. We present results of acoustic emissions monitoring of a metal additive manufacturing process (directed energy deposition). The work seeks to correlate acoustic emissions and process noise with variations in machine state and deposition parameters as a proof of concept.

Acknowledgement:

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References:


Nondestructive Strain Depth Profiling with High Energy X-Ray Diffraction: System Capabilities and Limitations

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CNDE developed a laboratory, bench-top high-energy X-ray diffraction (HEXRD) system to non-destructively measure internal residual strain via measuring changes in the lattice parameters [1]. Traditional X-ray diffraction strain measurements are only capable of achieving a few microns depth due to the use of Cu Kα1 or Mo Kα1 characteristic radiation. For further strain depth profiling, destructive methods are necessary to access deeper points of interest by removing layers. HEXRD method uses an industrial 320 kVp X-Ray tube and the Kα1 characteristic peak of tungsten, produces a brighter X-ray beam and allows for a depth profiling measurement of lattice strain. An aluminum bar in bending rig demonstrates that the HEXRD method is sensitive up to 3mm strain depth profiling. Another aluminum sample is measured by both HEXRD method at CNDE and traditional X-ray diffraction method with destructive etching layer removal by commercial provider PROTO. The results demonstrate comparable accuracy up to 1mm depth. Nevertheless, higher attenuation capabilities in heavier metals limit the applications in other materials. Simulations predict that HEXRD works for Fe and Ni up to 200µm, but experiment results indicate that the HEXRD method signals for Fe are insignificant.

Acknowledgement:

This work is supported by the NSF Industry/University Cooperative Research Program of the Center for Nondestructive Evaluation at Iowa State University.

References:
Model Based Defect Characterization in Composites

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This paper reports on work to explore model based defect characterization methods for NDE of CFRP composites. The work is examining defect responses obtained with ultrasound and thermography, for the purpose of classifying and characterizing the defect through combined analysis of the multiple-mode data. Analysis is premised on the availability of forward scattering models to predict NDE response to specified defects. The approach to defect characterization identifies a set of parameters describing the defect, then optimizes agreement between NDE measurements and measurement predictions through manipulation of defect descriptors, subject to ancillary measures of defect properties imposed to regularize an otherwise ill-posed inversion. Motivation for the project is the detection and characterization of defects in out-of-autoclave large composite structures. Defects of interest in these structures are delamination, excessive porosity, and fiber misalignment. This presentation will summarize the forward measurement models being adapted for this purpose, and will outline the approach being taken to implement well-conditioned data inversion. Examples of application to actual CFRP laminate damage will be presented.

Acknowledgement:

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This paper reports on a computational study of ultrasound propagation in heterogeneous metal microstructures. Random spatial fluctuations in elastic properties over a range of length scales relative to ultrasound wavelength can give rise to scatter-induced attenuation, backscatter noise, and phase front aberration. It is of interest to quantify the dependence of these phenomena on the microstructure parameters, for the purpose of quantifying deleterious consequences on flaw detectability, and for the purpose of material characterization. Valuable tools for estimation of microstructure parameters (e.g. grain size) through analysis of ultrasound backscatter have been developed based on approximate weak-scattering models. While useful, it is understood that these tools display inherent inaccuracy when multiple scattering phenomena significantly contribute to the measurement. It is the goal of this work to supplement weak scattering model predictions with corrections derived through application of an exact computational scattering model to explicitly prescribed microstructures. The scattering problem is formulated as a volume integral equation (VIE) displaying a convolutional Green-function-derived kernel. The VIE is solved iteratively employing FFT-based convolution. Realizations of random microstructures are specified on the micron scale using statistical property descriptions (e.g. grain size and orientation distributions), which are then spatially filtered to provide rigorously equivalent scattering media on a length scale relevant to ultrasound propagation. Scattering responses from ensembles of media representations are averaged to obtain mean and variance of quantities such as attenuation and backscatter noise levels, as a function of microstructure descriptors. The computational approach will be summarized, and examples of application will be presented.

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This material is based on work supported by the Iowa State University Center for Nondestructive Evaluation NSF Industry-University Cooperative Research Center.
Model development for UT Inspection of Anisotropic Materials

This paper reports on CNDE activity in the modeling UT inspection of anisotropic materials. A computational model for predicting UT response to flaws/features in anisotropic solids is being developed and interfaced to the CNDE UTSIM inspection simulator. The development is targeting inspection of homogeneous generally anisotropic linearly elastic solids, as would represent single crystal materials, uni-directionally reinforced composites, and quasi-isotropic composites in the long wavelength regime. The model extends an established Asymptotic Green Function (AFG) UT beam transmission formulation, to accommodate more complicated transmission phenomena introduced by material anisotropy. The AFG formulation represents radiation/reception by complex geometry transducer elements and entry surface geometries by projecting surface fields onto Gaussian-derived basis functions for which phase integrals are evaluated analytically. Extension of the model entails identification of contributing phase fronts associated with relevant energy directions on non-spherical slowness surfaces, including particularly challenging phenomena associated with concave/convex slowness surface transitions. The issues and approach to implementation will be summarized, and examples presented of application to more challenging inspections.

Acknowledgement:

This material is based on work supported by the Iowa State University Center for Nondestructive Evaluation NSF Industry-University Cooperative Research Center.
The present study reports the influence of surface roughness on the measurement of acoustic nonlinearity parameter. Measurements were carried out using contact piezoelectric transducers on samples polished to five different surface roughness conditions. Nonlinearity parameter was measured by calibrating the transducer using the reciprocity technique. Experiments were performed on aluminum and steel samples to study the influence of hardness of the material. Results suggest a large variation (~35%) in nonlinearity parameter for aluminum compared to steel between two consecutive experiments. Experiments were also performed with 3 different setup configurations; 1) receiver and transmitter on rough sides, 2) receiver on smooth and transmitter on rough side and 3) receiver on rough and transmitter on smooth side. Results suggest that least variation in nonlinearity parameter can be observed when the receiver is placed on the smooth side. Finally, a comparison between relative nonlinearity parameter calculated using voltage ratio, and absolute nonlinearity parameter determined using displacement amplitude was carried out.

Acknowledgment:

Funding Source: This work was supported by the Industry/University Cooperative Research Program of the Center for Nondestructive Evaluation at Iowa State University.
Interactive X-ray simulations of complex computer-aided design (CAD) models can provide valuable insights for better interpretation of the defect signatures such as porosity from X-ray CT images. Generating the depth map along a particular direction for the given CAD geometry is the most compute-intensive step in X-ray simulations. We have developed a GPU-accelerated method for real-time generation of depth maps of complex CAD geometries. We preprocess complex components designed using commercial CAD systems using a custom CAD module and convert them into a fine user-defined surface tessellation. Our CAD module can be used by different simulators as well as handle complex geometries, including those that arise from complex castings and composite structures. We then make use of a parallel algorithm that runs on a graphics processing unit (GPU) to convert the finely-tessellated CAD model to a voxelized representation. The voxelized representation enables modeling the volume enclosed inside the CAD model and can be used to assign heterogeneous material properties in specific regions. The depth maps are generated from this voxelized representation with the help of a GPU-accelerated ray-casting algorithm. The GPU-accelerated ray-casting method enables interactive (>60 frames-per-second) generation of the depth maps of complex CAD geometries. This enables arbitrarily rotation and slicing of the CAD model, leading to better interpretation of the X-ray images by the user.
Composite materials used for aerospace applications are highly susceptible to impacts, which can result in barely visible delaminations. Reliable and fast detection of such damage is needed before structural failures occur. One approach is to use ultrasonic guided waves generated from a sparse array consisting of mounted or embedded transducers for performing structural health monitoring. This array can detect introduction of damage after baseline subtraction, and also provide localization and characterization information via the minimum variance imaging algorithm [1]. Imaging performance can vary considerably depending upon where damage is located with respect to the array; however, prior work has shown that knowledge of expected scattering can improve imaging consistency for simulated damage at various locations [2]. In this study, wavefield data are recorded before and after impact damage is introduced, and wavefield baseline subtraction is applied to isolate scattered waves. In addition, anisotropic material attenuation and wave speed are estimated as a function of propagation angle using wavefield data recorded along radial lines at multiple angles with respect to an omnidirectional guided wave source. The full 2-D scattering matrix is formulated by analyzing and interpolating data from multiple incident directions, and incorporates the attenuation and wave speed estimates. Estimated scattering patterns are shown and the scattering matrix is incorporated into the minimum variance algorithm. The resulting images are compared to those generated using simpler propagation and scattering assumptions.

Acknowledgement:

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References:


Where does the nonlinearity come from?

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One of the impediments to the wide adoption of nonlinear ultrasonic testing for early damage detection is the qualitative nature of the diagnostics. Numerous studies on a broad spectrum of materials report a significant increase in the measured nonlinearity parameters with the early to moderate accumulation of damage. However, only few studies to date have investigated the quantitative relationships between damage features (crack density, length and aperture size, etc.) and the nonlinearity parameters. In this study, we combine nonlinear acoustic testing with finite element modeling and high-resolution imaging to understand the origins of the measured nonlinearities. We employ dynamic acousto-elastic testing (DAET) [1] to evaluate the nonlinearity of a series of aluminum samples with fatigue cracks at various locations near or far from the cracks. DAET provides a complete picture of the nonlinear elastodynamic response including the presence of hysteresis and tension/compression asymmetry, which is used to evaluate the classical and non-classical nonlinearity parameters. The imaging gives quantitative information about the length, opening, and the roughness of the cracks, which help interpret the DAET results. Finite element modeling is used to test the validity of a number of hypotheses concerning the origins of the observed nonlinearities including crack face clapping, adhesion, and friction.

Figure 1. SEM images at 4 positions along the fatigue crack. The length, opening and the roughness of the crack are obtained from SEM images and used to interpret the measured nonlinearity along the crack.

References:
Photoacoustic Microscopic Imaging of Surface and Subsurface Damages in CFRP

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Photoacoustic (PA) imaging [1] consists of optical excitations within a target zone and detections of the created ultrasonic wave. A pulsed laser illuminates the target zone, then a rapid thermo-elastic expansion generates broadband high-frequency ultrasonic waves. In this study, basic experiments on nondestructive testing using PA microscope (PAM) are demonstrated. The specimen used in the experiments is a carbon fiber reinforced plastic (CFRP). Figure 1 (a) shows artificial delaminations in an 8-ply unidirectional CFRP specimen (the total thickness of the specimen is approx. 1.0 mm). One of the delaminations is located at 0.39 mm depth, and the other is 0.52 mm depth. The laser with 532 nm wavelength is irradiated from the top surface of the specimen, and the ultrasonic wave is received by a point-focusing immersion transducer on the same side. The scan pitch in the lateral direction is 50 µm. The maximum intensity projection images with the PAM are shown in Figs.1 (b) and (c). It is found that the depth and width of the delamination can be estimated with high accuracy. Figures 2 (a) and (b) show freehand lines drawn by a black permanent marker on the CFRP specimen and the C-scan image on the surface, respectively. Since the intensity of the generated ultrasonic wave depends on the absorption of the laser, the freehand lines can be clearly discriminated from bare CFRP surface.

Figure 1. Two delaminations in CFRP and maximum intensity projection (MIP) images.

Figure 2. Freehand lines drawn with permanent marker on CFRP surface and its C-scan image.

References:
A lot of materials exhibit anisotropic behavior such as composites, fibers, crystal, wood and so on. Composite material is usually made from two or more constituent materials with significantly different physical or chemical properties. Different kinds of composite materials perform some common features such as: stronger, lighter, less expensive when compared to traditional materials. They have a lot of applications such as housings and casings for bridges, buildings, spaceships, autos, sport equipments and so on. Composite materials are especially useful in aerospace industry because they are good substitutions for metals due to the fact that they are not as electrically conductive as traditional materials [1]. Therefore, it becomes very important to investigate electromagnetic interactions of composites. We propose to analyze multilayered biaxial anisotropic material with different orientations based on transmission line theory to derive the reflection and transmission coefficients in matrix form. Using effective medium theory [2], we can combine multilayered medium with an equivalent layer to extract the effective permittivity, permeability and orientation angle. Analytical expressions for effective parameters and orientation angle are derived for low frequency limit. Good agreement is achieved by comparing the effective parameters extracted with and without low frequency approximation. We show that the frequency-independent equivalent model is valid for frequency up to 10 GHz for the total thickness up to several millimeters.

Acknowledgement:

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References:

**A Huygens-Wavelet Analysis Approach to the Polycrystalline Grain Scattering Problem**

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The ultrasonic grain scattering problem is studied using a Huygens-wavelet superposition analysis approach. Previous research [1-3] has shown evidence of coherent spatial energy patterns occurring as local peak amplitude increases in ultrasonic image fields for polycrystalline materials. These patterns have been attributed to wave scattering and interference effects in the near-field by the polycrystalline grain boundaries. In the present effort a Huygens-wavelet superposition approach is used to study idealized grain scattering processes in the Rayleigh and Stochastic regimes, where grain anisotropy levels and grain size distributions were varied systematically. The preliminary results (Figure 1) show evidence of the time-evolving and peak-integrating elastic wave patterns in the near-field, which is consistent with wavefield imaging experimental results and FEM forward model results. The characteristics of ultrasonic backscatter signal were also studied using the method as elastic waves transitioned from the near-field to the far-field. The research is being used to understand the complex nature of ultrasonic grain scattering with the ultimate goal of determining root-cause scattering for localized grain features and improving backscatter signal inversion methods.

![Wavefield Experimental](image1)
![FEM Forward Model](image2)
![Huygens-Wavelet Approach](image3)

**Figure 1.** Coherent backscatter observed with wavefield imaging experimental (left), FEM model (center), and Huygens-Wavelet superposition (right) methods.

**References:**

Adaptive Sparse Grid approach for the efficient simulation of pulsed eddy current testing inspections

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Pulsed Eddy Current Testing (PECT) is a popular nondestructive testing (NDT) technique for some applications like corrosion monitoring in the oil and gas industry, or rivet inspection in the aeronautic area. Its particularity is to use a transient excitation, which allows to retrieve more information from the piece than conventional harmonic ECT, in a simpler and cheaper way than multi-frequency ECT setups. Efficient modeling tools prove, as usual, very useful to optimize experimental sensors and devices or evaluate their performance, for instance.

Simulation of PECT inspections means solving an electromagnetic problem in quasi-static regime, either directly in time domain [1, 2] or through a Fourier synthesis of time domain excitation waveform [1, 3]. In the latter case, the transient excitation signal is first decomposed in Fourier harmonics and frequency-domain solvers [4] are used to evaluate the probe response for each of these harmonics. Then the time domain probe signal is obtained using an inverse Fourier transform. Such an approach is clearly advantageous when dealing with narrowband excitations, however it can quickly become inefficient for broadband ones. In order to overcome this difficulty, many interpolation strategies have already been proposed in order to limit the number of harmonic resolutions, but ensuring robustness and accuracy of the procedure is not a trivial problem. This paper proposes an adaptive strategy relying on database generation of ECT signals and incremental interpolation to compute the spectrum of the probe signal [5]. The tool used to this end is an adaptive sparse grid interpolator, which has been recently applied in the ECT problems with very promising results [6]. Simulation results corresponding to existing industrial configurations will be presented and the performance of the strategy will be discussed by comparison to reference results.

References:
Diffuse ultrasonic backscatter, the result of the interaction of elastic waves with material heterogeneity, can be used to characterize microstructural information. The scattering that occurs within the material can be complex and requires accurate modeling in order to interpret measurements quantitatively. This effect is particularly important for higher-scattering materials with large single crystal anisotropy. Recently, a double scattering model was derived for which the wave was assumed to scatter twice prior to detection. This model was an improvement upon earlier models that assumed only single scattering. In this presentation, the significance of this addition to the model is examined using a combination of theory and experiments. The first portion of the presentation is devoted to theoretical results for both the single-scattering and double-scattering models. The contribution of the second scattering within the predicted response is quantified with respect to various measurement parameters including the transducer size, frequency and focal length as well as the material properties and focal depth of the experiment. The results show that single-scattering models are appropriate for weakly scattered materials, such as aluminum, for a wide range of experiments and correlation lengths. However, stronger scattering materials are predicted to have significant components beyond single-scattering for certain measurement parameters even in the Rayleigh scattering regime. Next, experimental results for two higher-scattering materials, one steel and one nickel alloy, are presented for a range of frequencies from 5-15 MHz, and several inspection depths. The experimental work shows the domain for which the doubly-scattered response becomes significant as well as the limitations at which the double scattering model is no longer applicable. The results can be used to predict the frequency range that applies for each model given a material, its grain size and experimental details.
Inspection of Cup-shaped Steel Parts from the ID Side using Eddy Current

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An Eddy Current method was developed to inspect cup-shaped steel parts from the ID side. During the manufacturing process of these parts, a thin Al tape foil is applied to ID of the part as shown in Figure 1. It is critical that no more than one layer of foil be applied. Therefore, an Eddy Current inspection system was developed to reject parts with more than one foil layer. The Al tape foil is cut to length to fit the inner diameter. However, after application of the foil there is a gap created between the beginning and end of the foil. It was determined that this gap interfered with the Eddy Current inspection causing a false positive indication. Therefore, a sensor design and data analysis process was developed to overcome the effects of these gaps. The developed system incorporates simultaneous measurements of multiple Eddy Current sensors and signal processing to achieve the desired result.

Figure 1. Cup-shaped steel part with Al foil applied to the ID
This paper describes a technology review of non-destructive examination (NDE) methods that can be applied to cold spray coatings. Cold spray is a process for depositing metal powder at high velocity so that it bonds to the substrate metal without significant heating that would be likely to cause additional residual tensile stresses. Coatings in the range from millimeters to centimeters are possible at relatively high deposition rates. Cold spray coatings that may be used for hydroelectric components that are subject to erosion, corrosion, wear, and cavitation damage are of interest. The topic of cold spray NDE is treated generally however and may be considered applicable to virtually any cold spray application except where there are constraints of the hydroelectric component application that bear special consideration.

Hydroelectric turbine components are primarily made from low carbon and austenitic stainless steels. They are typically very large components that are partially assembled on-site. Transport of these components within the hydroelectric facility and away from the hydroelectric facility is challenging due to the component’s size and weight, high cost of disassembly, and the confined space of the dam. One method for prolonging component life is application of cold spray and thermal powder metal coatings to the components most susceptible to erosion, corrosion, cracking, and mechanical wear. Process controls and visual inspections have historically been applied to cold spray application; however, quantitative NDE could detect anomalies not readily apparent from such a visual examination.

Eddy current, ultrasound, and hardness tests are shown for a range of cold spray samples to demonstrate inspection possibilities. Information of interest to the inspection primarily includes:

- Presence/absence of the cold spray coating including possible over-sprayed voids
- Coating thickness
- Porosity primarily caused by improper process conditions (temperature, gas velocity, spray standoff, spray angle, powder size, condition, surface cleanliness, surface oxide, etc.).

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Sonic Infrared (IR) NDE, as a relatively new NDE technology, has been demonstrated as a reliable and sensitive method to detect defects. It uses ultrasonic excitation with IR imaging to detect defects and flaws in the structures being inspected. An IR camera captures infrared radiation from the target for a period of time covering the ultrasound pulse. This period of time may be much longer than the pulse depending on the defect depth and the thermal properties of the materials. This technology can be used to detect defects in metal structures, and delaminations and disbands in composite materials as well. With the increasing deployment of composites in modern aerospace and automobile structures, fast, wide-area and reliable NDE methods are necessary. Impact damage is one of the major concerns in modern composites since damage can occur at certain depth without any visual indication on the surface. Defect depth information can influence maintenance decision. In this paper, we’ll present our work on the defect depth profiling by using the temporal information of IR images. Meanwhile, we will also address different factors from the temporal information and their role in depth profiling.

Acknowledgement:

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Characterizing the vibration behavior in crack vicinity in Sonic Infrared Imaging NDE

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Sonic Infrared Imaging uses ultrasound excitation and infrared imaging to detect defects in different materials, including metals, metal alloys, and composites. In this NDE technology, the ultrasound excitation applied is typically a short pulse, usually a fraction of a second. The ultrasound causes the opposing surfaces of a crack or a defect to rub each other and result in temperature change with noticeable infrared radiation increase. This thermal signal can be captured by IR camera and used to locate the defect within the target. Probability of detection of defects can be significantly improved when chaotic sound is introduced to the materials. This nonlinearity between the ultrasound transducer and the target materials is an important phenomenon and the understanding is critical to improve the repeatability and reliability of this technology. In this paper, we will present our study on this topic with emphasis of characterizing vibration in the crack vicinity.

Figure 1

Acknowledgement:
This work is sponsored by Wayne State University

Reference
Nonlinear Ultrasonic Phased Array Imaging of Partially-Closed Fatigue Cracks

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Phased array ultrasonics is a highly advanced technique that is not only used in nondestructive evaluation (NDE) of defects in materials but also in the medical ultrasound, for instance, e.g. for a noninvasively examination of the heart. However, difficulties occur in NDE applications when it comes to monitoring some challenging (nonlinear) defects such as small fatigue cracks in the early stages or partially- or fully- closed cracks. Small cracks may be undetected or sizes of closed cracks may be underestimated. The aim of this research is to obtain images of the closed part of a fatigue crack using the nonlinear ultrasonic phased array method. The present technique is based on a subtraction of response signals at two (or more) different energy levels.

In this study, the essential experiments are performed on an aluminum CT specimen of 15mm thickness that has a fatigue crack of 25mm length. In order to investigate and evaluate the fatigue crack, a commercial phased array system (OmniScan, Model MX2, Olympus), along with 16 and 64 element probes, is used. The frequency of these probes are 1.5MHz. Even with a 16 element probe the image of the crack tip is successfully generated by postprocessing of the received signals at excitation levels. The results clearly demonstrate the efficiency of the presented method to detect and image nonlinear defects.

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Automated Acoustic Scanning System for Evaluation of Concrete Bridge Decks

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Chain drag testing is common practice for concrete bridge deck evaluation due to its low cost and ease of use. However, this method is subjective, and highly depends on the experience of the operators. Ambient noise caused by traffic affects the test speed and accuracy of results. In this presentation, we present a recent effort to develop an automated acoustic scanning system to detect delaminations in concrete structures, including bridge decks. The system consists of an array of chains or impactors, a noncontact MEMS microphone sensor array, multi-channel data acquisition device, RTK GPS positioning system, and signal processing schemes. The multi-channel design improves the spatial coverage and resolution of testing. An algorithm for interpreting acoustic signals from the automated acoustic test is developed. This system will allow fast and continuous scanning of structures, and enable real time visualization of tested areas. Compared to the conventional manual chain drag test, the automated system provides improved accuracy, spatial resolution, repeatability, and practicality.

Figure 1. Time series and phase difference of two overlapping echoes.

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Anisotropic Modeling and Joint-MAP Stitching for Improved Ultrasound Model-Based Iterative Reconstruction of Large and Thick Specimens

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We document the implementation of a Model-Based Iterative Reconstruction (MBIR) algorithm for one-sided, non-destructive evaluation (NDE) of thick heterogeneous specimens with ultrasound signals. Ultrasound signals have been used extensively for NDE. However, typical reconstruction techniques for NDE, such as the synthetic aperture focusing technique (SAFT), are limited to quasi-homogenous thin media. MBIR can overcome this limitation. We describe an on-going effort to use MBIR as the reconstruction backbone of a phased array ultrasound imaging system for NDE of reinforced concrete structures for commercial nuclear power plants. Identification and management of the aging and degradation of concrete structures is fundamental to the long-term operation of nuclear power plants as they provide critical functions including shielding, and containment. Previously, we have demonstrated the design of an ultrasonic MBIR for a homogeneous medium, improvements to the forward model to eliminate artifacts caused by surface waves cross-talk, and validated the technique with simulated and experimental results.

Several new challenges were encountered while transitioning from testing the algorithm with synthetic data to real field data. For example, the model assumes a homogenous specimen, which is not an accurate model for reinforced concrete. The mismatch between the actual and MBIR physical models generated incorrect estimation of reflections arrival times and consequently reconstruction artifacts. In addition, we observed that our isotropic assumption was a contributor to additional reconstruction nonidealities. This paper documents improvement to the MBIR forward model that includes techniques to estimate the time delay caused by the change in acoustic speed and compensate for it to match the direct arrival signal location, and an upgrade from an isotropic to an anisotropic propagation model.

In addition, past work used image-stitching techniques to generate panoramic reconstructions of specimens that are larger than the measurement system. Usually, these approaches produce discontinuities at the boundaries of each b-scan or loss of resolution due to over filtering. We propose a new technique called Joint-MAP estimate, which is embedded in the MBIR forward model—MBIR merges or stitches several b-scan images as part of the reconstruction. The Joint-MAP technique makes use of the data that is otherwise lost in the conventional stitching method and reduces reconstruction time by 25%.

The paper includes reconstruction results of empirical ultrasound data. We provide results of the improved MBIR forward model, the Joint-MAP MBIR, and the traditional SAFT technique.

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Phononic band gaps and phase singularities in the ultrasonic response from toughened composites

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Ultrasonic 3D characterisation of ply-level features in layered composites, such as out-of-plane wrinkles and ply drops, is now possible with carefully applied analytic-signal analysis [1]. Study of instantaneous amplitude, phase and frequency in the ultrasonic response has revealed some interesting effects, which become more problematic for 3D characterisation as the inter-ply resin-layer thicknesses increase. In modern particle-toughened laminates, the thicker resin layers cause phase singularities to be observed; these are locations where the instantaneous amplitude is zero (Figure 1a), so the instantaneous phase is undefined. The depth at which these occur has been observed experimentally to vary with resin-layer thickness, such that a phase-singularity surface is formed; beyond this surface, the ultrasonic response is reduced and significantly more difficult to interpret, so a method for removing the effect would be advantageous.

Figure 1. (a) Instantaneous amplitude (red) and RF waveform (black) for 50 plies with 0.02 mm resin layers, embedded in resin. (b) Instantaneous frequency at the time-of-flight of the zero amplitude in (a) as a function of centre frequency and bandwidth. (c) Instantaneous frequency at the time-of-flight of a single porous ply as a function of its void volume fraction and bandwidth.

Note: an abrupt change from large positive (red) to large negative (blue) instantaneous frequency is indicative of a phase singularity.

The underlying physics has been studied using an analytical one-dimensional multi-layer model [1]. This has been sufficient to determine that the cause is linked to a phononic band gap in the ultrasound transmitted through multiple equally-spaced partial reflectors. As a result, the phase singularity also depends on input-pulse centre frequency and bandwidth (Figure 1b). Similar phase singularities have been discovered in the modelled response of a single porous ply for particular input-pulse characteristics (Figure 1c). Various methods for overcoming the confusing effects in the data have been proposed and subsequently investigated using the analytical model. This paper will show experimental and modelled evidence of phase-singularities and phase-singularity surfaces, as well as the success of methods for reducing their effects.

Acknowledgement:
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Reference:
Evaluation of the fidelity of feature descriptor-based specimen tracking for automatic NDE data integration

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Our research addresses inspection location tracking and automatic data integration in the context of the digital thread/digital twin. An actual challenge in this context is the integration of NDE data into the digital manufacturing environment. NDE data can be associated to a digital twin of a product to keep track of the product's quality during its lifetime and to leverage data-driven management. This integration process, if in any capacity applicable, needs to be automated. However, today a manual or semi-automatic process is more in common, if data integration of this type is applied at all. Our goal is to provide means for fully automatic NDE data integration using vision-based object detection and tracking technology, denoted as inspection location tracking.

Inspection location tracking refers to a set of vision-based methods that are able to track objects such as specimens, parts, and products in real time. Here, tracking means to compute the spatial position and orientation of the specimen with respect to a reference point. We use a feature descriptor-based approach that represents the curvature of an object as an invariant signature. The tracking data can be used to automatically map NDE data onto a 3D model of a specimen, using projective texturing. Our focus is currently on flash-thermography and thermal images of composite specimens. We developed a prototype system and prepared an evaluation setup (Figure 1a) incorporating a thermography flash-hood, the specimen, and a range camera. The last provides data to track the specimen and the flash-hood in real time.

Knowing the spatial position and orientation of the thermal camera as well as of the specimen allows one to computationally project the thermal image onto the surface of the specimen at exact the location from which it was taken. (Figure 1b). We evaluated the fidelity of this projection process using feature-based tracking data as well as marker-based tracking data. This project is funded by the Iowa State University Center for Nondestructive Evaluation Industry/University Cooperative Research Program.

Figure 1a) the evaluation setup. b) the digital twin of the specimen augmented with thermal data.
Further investigation of surface velocity measurements for material characterization in laser shockwave experiments

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As part of the US High Performance Research Reactor program, a laser shockwave system is being developed by the Idaho National Laboratory (INL) to characterize interface strength in innovative plate fuel for research reactors around the world. The INL has been working with National Research Council Canada (NRC) on this project for the last five years. One of the concerns is the difficulty of calibrating and standardizing the laser shock technique. The generation of a stress wave by the laser impinging on the plate surface is dependent on the surface preparation, temporal and spatial power distribution of the laser spot, and material properties of the plate. Thus the resulting back surface velocity used to measure the time-varying stress field within the plate is difficult to reproduce across different measurement systems.

A recent analytical study and testing support the use of the Hugoniot Elastic Limit (HEL) in materials as a robust and simple benchmark to compare stresses generated by different laser shock systems [1]. Using a non-contact laser velocimeter based on a solid Fabry-Perot etalon, the systems at NRC and INL showed that the velocity reached at the HEL is consistent, independent of the laser power used. In this work, the laser velocimeter of the NRC system is tested against a fast rotating wheel to verify accuracy and determine best operating conditions. A round robin test between the two laser shock systems on plates of different Al alloys is presented that shows the correct classification of the Al alloys based on the HEL as well as determining the bias between the systems. Also the effects of some setup parameters on other characteristics of the surface velocity and corresponding stress wave are discussed.

Reference:
A quantitative and qualitative analysis of vibrothermographic crack heating mechanisms


Vibrothermography is an NDE inspection technique that uses vibration to stimulate surface cracks and measure the resultant heat generation. Over the years, a number of plausible heating mechanisms have been suggested in literature, including friction\(^1\) (implying tangential sliding friction between the crack flanks), plastic flow or thermo-plastic heat generation at the crack flanks or near the crack tip\(^2\), thermoelasticity\(^3\), viscoelasticity and anelasticity\(^4\), or a combination of mechanisms\(^5\).

Recent experiments\(^6\) have led to several observations regarding the behavior of heat generation at cracks: i) a linear dependence on excitation frequency, ii) a dependence on excitation amplitude somewhere between linear and quadratic, iii) crack heating occurs at or near the closure point where the crack transitions from closed (crack faces in contact) to open (crack faces not in contact). In this work, we analyze a number of these heating mechanisms through experimental observations and theory. Previously, we have concluded only adhesion hysteresis and friction are consistent with experiment. We will review these mechanisms and the underlying theory. An experiment was performed evaluate the relevance of adhesion hysteresis to crack heating. Calculations suggest a large percentage of the surface area of the crack would need to be involved in a process dominated by adhesion to produce the amount of heating typically observed in vibrothermography experiments. To test this hypothesis, we wedge a fatigue crack open by introducing Tungsten Carbide particles expecting to see a reduction in heating if the process is driven by adhesion hysteresis. However, heating did not decrease – rather it slightly increased.

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References:

Once an oil or gas wellbore has been drilled, steel casings and cement slurry are placed to ensure structural support, protection from fluid invasion, and most importantly providing zonal isolation. The actual wellbore and string structure is rarely concentric and but rather is often an eccentric one, especially in deviated boreholes. The term “eccentricity” is used to describe how off-center a casing string is within another pipe or the openhole. In a typical double-string configuration, the inner casing is eccentered with respect to the outer string which itself is also eccentered within the cylindrical hole. The annuli may or may not be filled with solid cement, and the cement may have liquid-filled channels or be disbonded over localized azimuthal ranges. The complexity of wave propagation along axial intervals is significant in that multiple modes can be excited and detected with characteristics that are affected by the various parameters, including eccentricity, in a non-linear fashion. A successful diagnosis of cement flaws largely relies on a thorough understanding of the complex acoustic modal information. The present study employs both modeling and experiments to fully understand the acoustic wave propagation in the complex fluid-solid nested cylindrically layered structures with geometric eccentricities. The experimental results show excellent agreement with the theoretical predictions from newly developed borehole acoustic modeling approaches. As such, it provides the basis for better understanding the operative wave physics and providing the means for effective inspection methodologies to assess well integrity and zonal isolation of oil wells.
Towards a Technical Justification for Eddy Current Inspection of Bolt Holes in Aircraft Wing Structures

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Fatigue cracks are prone to develop around fasteners found in multi-layer aluminum structures on aging aircraft. Bolt hole eddy current (BHEC) is used for detection of cracks from within bolt holes after fastener removal. A target $a_{90/95}$, i.e. detect 90% of cracks at this depth 95% of the time$^1$, of 0.76 mm (0.030”) has been set as the goal for inspection capability. In support of the qualification of the BHEC method, a preliminary technical justification$^2$ was prepared to identify those parameters whose variation may keep a bolt hole inspection from attaining this target. Parameters that were examined included variability in lift-off due to probe type, out-of-round holes, holes with diameters too large to permit surface-contact of the probe and mechanical damage to the holes, including burrs. The study also examined the probability of detection (POD) for BHEC of corner cracks in unfinished and cleaned fastener holes extracted from service material. 68 EDM notches were introduced into two specimens of a horizontal stabilizer from a CC-130 Hercules aircraft. The fastener holes were inspected twice, first in the unfinished state and second in the cleaned/prepared state, by 7 qualified inspectors using a manual BHEC setup with an impedance plane display and with one inspection conducted utilizing a BHEC automated C-Scan apparatus. The work highlighted a number of areas where there was insufficient information to complete the technical justification. Consequently, a number of recommendations were made. This included; development of a specification for minimum probe requirements; criteria for condition of the hole to be inspected, including out-of-roundness and presence of corrosion pits; statement of range of hole sizes; inspection frequency and data display for analysis.

Acknowledgements:

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References:

Model Based Optimization of Driver-Pickup Separation for Eddy Current Measurement of Gap

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The fuel channels in CANDU® (CANadian Deuterium Uranium) nuclear reactors consist of a pressure tube (PT) contained within a larger diameter calandria tube (CT). The separation between the tubes, known as the PT-CT gap, ensures PT hydride blisters, which could lead to potential cracking of the PT, do not develop. Therefore, accurate measurements are required to confirm that contact between PT and CT is not imminent. The gap is monitored using an eddy current based inspection probe, but this probe is sensitive to lift-off variations, which can adversely affect estimated gap. A validated analytical flat plate model of eddy current response to gap [1,2], shown in Figure 1, was used to examine the effect of driver-pickup spacing on lift-off and gap calculations at a frequency of 4 kHz, which is used for in-reactor measurements. This model was compared against, and shown to have good agreement with, a COMSOL® FEM model [3]. Both models investigated the effect of varying the separation between the receive coil and drive coil. The variation of the effect on coil response to gap under variable lift-off was also investigated for different driver coil-to-pickup coil separations. The ideal coil separation was found to be 11 mm, for the particular coils used, for a phase response to lift-off at or near 90°, with respect to a change in gap. However, these are only ideal distances obtained using a flat-plate approximation and the optimum separation may change when the curvature of the PT and CT is considered. This work demonstrates the advantages of using analytical models for optimizing coil designs for measurement of parameters that may negatively influence the outcome of an inspection measurement.

Figure 1. Cross-sectional view of flat-plate driver-pick model showing the pressure tube (PT), calandria tube (CT), PT-CT gap, drive and receive coil, as well as coil spacing.

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References:

Fabrication of Paint-On Ultrasonic Transducers for High-Temperature Applications using Bismuth Titanate

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Monitoring the structural health of large valve bodies in high-temperature environments such as power plants faces several limitations: commercial transducers are not rated for such high-temperatures, gel couplants will evaporate, and measurements cannot be made in-situ. To solve this, we have furthered the work of Barrow and Kobayashi in applying a transducer in liquid form by making it more field-deployable; the sintering step is removed and the fabrication time is reduced.

The transducer material is a piezoceramic film composed of Bismuth Titanate and a high-temperature binding agent, Aremco Ceramabind 830. The impact of several fabrication conditions on transducer performance were studied to optimize transducer performance and ensure repeatability. These fabrication conditions include humidity, water-to-binder ratio, substrate roughness, and film thickness. The final product is stable for both reactive and non-reactive substrates, has a stable operating temperature beyond the safe operating temperature of PZT (150°C), and quick fabrication time. Furthermore, signal processing techniques can be used to enhance the signal-to-noise ratio by over 15 dB of the obtained signal to approach that of a commercial transducer.

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Elastic wave propagation in hydrostatically stressed polycrystals

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It has long been known that the apparent elastic modulus of a material depends on the state of stress present in the material. For materials under hydrostatic pressure, the pressure derivative of the modulus depends, in part, on the materials third-order elastic constants. Because elastic waves propagate with squared wavespeeds proportional to the apparent modulus, measurement of the elastic wave speed versus the magnitude of hydrostatic pressure is a viable method to investigate the third-order elastic constants and the nonlinear material behavior of solid materials. Additionally, changes in the apparent elastic modulus should impact the energy dissipation of the elastic wave as it propagates. The dissipation (or attenuation) of a wave and its dependence on hydrostatic pressure in polycrystalline materials is the subject of this talk. Starting from a nonlinear constitutive relation, the apparent, stress-dependent, elastic moduli tensors are defined. These moduli are used to define an elastodynamic mean Green's function that governs the propagation of the wave and scattering of the wave from grain boundaries in a hydrostatically stressed polycrystal. The imaginary parts of the mean Green's function are the attenuation coefficients. It is shown that the attenuation coefficients depend on the anisotropy of the single-crystal third-order elastic constants. A comparison of sensitivity between wavespeeds and attenuations is given. The influence of these results on the equipartition of elastic wave energy or the so-called diffusivity of wave energy is discussed.
Eddy Current Proximity Measurement of Perpendicular Tubes from within Pressure Tubes in CANDU® Nuclear Reactors

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Fuel channels in CANDU® (CANadian Deuterium Uranium) nuclear reactors consist of two non-concentric tubes; an inner pressure tube (PT) and a larger diameter calandria tube (CT), within which the PT is contained. The gas annulus space between the tubes, known as the gap, is maintained by 4 coiled spring spacers placed along the channel. Physical separation between the PT and CT ensures that hydride blisters do not form on the outer diameter of the PT as these can lead to potential cracking. As a consequence, accurate measurements are required to ensure that contact between PT and CT is not imminent[1],[2]. The PT-to-CT gap is monitored from within the PT using an eddy current probe. The fuel channels may also pass over perpendicularly oriented tubes (nozzles) that are part of the liquid injection shutdown system (LISS)[3],[4], as shown in Figure 1. The proximity of (LISS) nozzles not only compromises the gap measurement, but in the case of contact between the LISS nozzle and CT, flow-induced vibrations from within the moderator could lead to fretting and deformation of the CT, which also requires inspection. LISS nozzle proximity to CTs is currently measured optically from within the moderator[5]. Measurement by an alternative means would provide confidence in the optical results and supplement cases where optical observations are not possible. Investigation of the eddy current based gap probe as a tool to measure the proximity of LISS nozzles was carried out experimentally. Eddy current response as a function of LISS-PT proximity was determined. When PT wall thickness, PT resistivity and probe lift-off variations were not present this dependence could be used to determine the LISS-PT proximity up to 25 mm with sub-millimetre accuracy. This method has the potential to provide LISS-CT proximity using existing gap measurement data. Obtaining LISS nozzle proximity at multiple inspection intervals could be used to provide an estimate of the time to LISS-CT contact, and thereby provide a means of optimizing maintenance schedules.

Acknowledgements:
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Figure 1: Quarter section view of fuel channel above a LISS nozzle and half sectioned gap probe coils.

References:
A Comparison of Angle-Beam Shear Wave Scattering from Hidden Defects in Single and Two-Layer Plates

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Quantification of shear wave scattering from hidden defects is challenging because it is difficult to separate defect-scattered waves from waves that are scattered from benign structural features such as interfaces and fastener holes. It is even more difficult for the case of a crack emanating from a through-hole because there is complicated scattering from both the hole and the crack. Prior work has shown that at least in some cases it is possible to separate notch-scattered waves from hole-scattered waves by simple spatial windowing \cite{1}, which enables direct quantification of the notch scattering. However, this approach is not always successful because the notch-scattered waves may not be sufficiently separated from the hole-scattered waves in all directions of interest.

This present work reports the results of a study that considers measurements from several far-surface notches emanating from through-holes in an aluminum plate both before and after a second plate is bonded to the back surface of the first plate. Measurements are also made of scattering from just a through-hole in both the simple and bonded plates as a basis for comparison. The presence of the second layer provides a path for energy to leak out of the first plate, which can reduce the scattered energy. The recorded data show that notch scattering is clearly visible in the wavefield data for all of the notched holes. This scattering is quantified by first applying frequency-wavenumber filtering to extract shear waves of interest, and then computing scattered energy as a function of direction. Results for the different specimens are reported and compared to show the differences in scattering caused by the presence of the second layer.

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References:

Remote NDE - Remote diagnostics is the act of diagnosing a given symptom, issue or problem from a distance.

Ralf Schallert, Fraunhofer IKTS, Berlin

Thinking of non-destructive evaluation someone holding a UT probe and staring at A-scans is most likely the picture in your mind. With today's broadband capacity expanding, smart sensor and miniaturized electronics ranging in affordable prices it is surprisingly simple to remotely connect to NDE data from a distance. Remote diagnostics is already common for formula 1 racing cars, medical guidance or even with the Apollo Space program. The benefit of use is manifold: limit local personnel to a minimum, limit workload, limit risks i.e. exposure to dangerous environments, remotely/centralized solve complex problems by experts, reduce travel time to get expert and system or subject together.

This approach calls for a shift in development of NDE systems. NDE devices are no longer encapsuled but a source of measuring data transferred globally to: a) a group of experts, servers for machine interpretation and learning as well as storing the data for later education, training and order parts or plan maintenance and after detected performance degradation, predict the failure moment by extrapolation. These NDE devices can either be operated by non-experts or being stationary attached to the component of interest (health monitoring). In the first case the NDE device has to be available for a large group of users, competitive in price and form factor.

The smartphone has become an integral part in our social life. Rumour has it that you can still use the smartphone for voice communication. As funny as it sounds, the smartphone is a highly integrated and powerful electronic device that comprises a computer, a camera and a wide range of sensors like GPS, a barometer, an acceleration sensor, an electromagnetic sensor, a gyroscope, a luminance sensor, an air humidity sensor, a magnetometer, a microphone, cellular antennas, bluetooth, a proximity sensor, a thermometer and wi-fi capability. With all these sensor technology at hand the smartphone has rarely been used for scientific applications.

In the future with sensors being further miniaturized the smartphone could also been used as a chemical spectrometer, a cardiogram measurement device (i.e. using the monitor for detecting small voltage differences), a Terahertz scanner (Schottky-Barrier-Diodes on a small scale detect terahertz radiation and the signals can be transformed into pictures) or simply utilizing the smartphone’s optical capabilities for a variation of optical detection algorithms i.e checking the level of maturity of an apple.

The calculating capacity itself and the sensors available makes the smartphone platform a candidate for further research and innovation in the NDE scope. It is also mandatory to stress out, that the combination of features like the camera and the voice communication capacity offers a big advantage for testing purpose and enables a totally different approach for collaboration on testing matters – in real-time and in sync with experts and customers connected with the testing inspector.
Incorporating smart technology in Nondestructive Evaluation (NDE) broadens the horizon of its applications. Experiments will be presented to display results from three smartphone adaptable nondestructive testing devices. The devices to be used are:

- EddyCation: An eddy current app for android smartphones, where a transducer is attached to the phone, which makes the measurement on the specimen
- FLIR ONE Thermal Imaging - an Infrared camera that is attached to a smartphone through USB jack and relays heat images to the phone
- Walabot DIY - a terahertz antenna array that creates images in the near field when connected to a smartphone

The paper will present results for the application of the android systems to several NDE tasks. Test samples have been developed to quantify to performance of these low cost systems. The results from these experiments will be compared to results from standard NDE equipment used in service today. Similar results from both the approaches will validate the usage and reliability of the new devices.

Potential applications and limitations of the android adaptable system will be discussed. Implementation of these techniques on communication devices (like smartphones) opens new options for data processing and analysis. One can include cloud computing to access database in real time.

Acknowledgement:

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Space-Time Windowing of Angle-Beam Wavefield Data to Characterize Scattering from Defects

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Detection and characterization of discrete flaws is typically the primary focus of ultrasonic nondestructive evaluation procedures. In the aerospace industry, fatigue cracks are commonly found emanating from fastener holes and present a potential hazard if undetected. Therefore, ultrasonic wave scattering from both actual cracks and simulated crack-like defects is of practical interest. One common ultrasonic method for inspecting plate-like structures for cracks is the shear wave angle-beam technique. In prior work, ultrasonic wavefield data were acquired and analyzed in the frequency-wavenumber domain to characterize cumulative scattering of angle-beam shear waves from corner-notches [1]. In addition, space-time filters were developed to effectively characterize through-hole scattering in the time-space domain caused by a specific incident shear wave skip [2]. This present work focuses on applying space-time filtering to the analysis of scattering from notches emanating from through-holes.

Two strategies are considered. The first is to directly track notch-scattered waves in the time-space domain as was done in [2] for hole-scattered waves. A spatial filter can then be constructed at each time snapshot of interest to capture the scattered wavefronts. These filtered, scattered waves can then be quantified as energy-versus-direction curves. The second strategy is to apply the same space-time filters developed previously [2] to track hole-scattered waves from through-holes both with and without a notch. Then, their respective filtered waves can be quantified as energy curves and then compared to indirectly characterize the effect of the notch. Both strategies are implemented and applied to several inspection scenarios of interest.

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Progress on the Development of a Linear Phased Array Transducer for Harsh Environments

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Ultrasonic inspections in conditions such as elevated temperature, pressure and radioactivity generate difficulties for current commercially available phased array ultrasonic transducers. Industry standard piezoelectric material for commercial transducers cannot be used in high temperature environments because of operational temperatures in excess of the Curie temperature. In nuclear environments the nuclear heating effects on the piezoelectric can induce short-duration, high amplitude spikes in received waveforms. Various other materials that are used in commercially available transducer construction can suffer degradation from heat, as well as embrittlement and transmutation because of cumulative radiation effects\textsuperscript{1,2}.

The research being performed will lead to a phased array ultrasonic transducer that will be used to detect component characteristics such as cracks/flaws, bowing and thickness variations in an Advanced Test Reactor (ATR) loop, where it will operate in deaerated primary water (DPW) at a temperature of 700 °F and fast (>1 MeV) neutron fluence of $1 \times 10^{20} \text{n/cm}^2$. Work completed includes multiple brazing and high temperature adhesion techniques being evaluated as well as various brazing/high temperature paste materials using ultrasonic measurements to assess bondline thickness and surface coverage. Crosstalk of multi-element high temperature cable was performed. An off-the-shelf phased array linear transducer was purchased and was able to detect a simulated flaw in a room-temperature mock scenario where it was coupled to a 3 mm thick steel plate at a distance of 20 mm from the sample target with a 1 mm diameter drill flaw. This setup simulates the space constraints set by the inspection position within the loop. There is still work that needs to be completed, but the milestones that have been completed to date show that the feasibility of constructing a phased array transducer for harsh environments is possible.

References.
Nonlinear Effects of Cumulative Guided Waves Caused by Internal Resonance under Nonlinear Boundary Conditions

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In recent years, nonlinear ultrasonic methods, utilizing contact acoustic nonlinearity (CAN) or material nonlinearity, are counted on as more sensitive non-destructive testing (NDT). Also, ultrasonic methods using guided waves propagating over long distances can be applied to NDT for long structures. Therefore, nonlinear guided wave methods attract attention and are researched. In particular, the cumulative nonlinear guided waves caused by internal resonance are said to have merits of both nonlinear ultrasonic methods and guided wave methods. In analysis of the cumulative nonlinear guided waves caused by internal resonance, previous researches estimated growth of a higher harmonic mode by the straightforward expansion method of the perturbation analysis. However, it may lack nonlinear contribution from the fundamental mode.

In this research, we theoretically investigated the nonlinear guided waves caused by internal resonance using the method of multiple scales (MMS). Further, we examined effects of nonlinear boundary parameters on internal resonance of modes.

In order to simplify this nonlinear phenomenon, our model includes a nonlinearity of its system only in its boundary conditions, which are given as elastic support by some quadratic nonlinear springs. Our theoretical results obtained by MMS show amplitude decay and growth of fundamental and 2nd-harmonic modes with their propagation, reflecting their nonlinear interaction through the boundary conditions. Obtained results further show effects of wavenumber detuning from the phase matching condition for different values of the quadratic nonlinear parameter.

Acknowledgement:

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References:
Thick film ultrasonic transducers (UT) have been developed for high temperature applications in nuclear power plants using a derivation of the sol-gel method described in [1], [2]. This new method substitutes acidic sol-gel solution with high pH (basic), high temperature inorganic binder, which can help avoid long-term corrosion problems on mild steels and iron pipes. Lithium niobate – barium titanate, \([x\text{LN}-(1-x)\text{BT}]\)\((x = 0.5\text{wt})\), piezoceramic film was then fabricated by the presented sol-gel derived technique. As a strong candidate for high temperature applications, LN was chosen due to its high Curie temperature, \(~1210\,^\circ\text{C}\). However, previous tests indicated that LN requires a large coercive field to pole. BT was added to the piezoelectric/binder slurry as a high dielectric constant additive, thus increasing the effective dielectric constant of the mixture. LN/BT thick film \((\sim100\,\mu\text{m})\) was painted onto aluminum substrate and successfully poled at room temperature (RT) via conventional silver paint electrode poling. Ultrasonic echoes reflected from the substrate were monitored from RT up to \(700\,^\circ\text{C}\) inside a furnace. Seven end wall echoes with a high signal-to-noise ratio were observed throughout the test, as indicated in Fig. 1. This sol-gel derived method proved to be useful and, for being relatively quick and easy to perform, is ready for field-deployment and high-temperature in-situ NDE applications.

Acknowledgement:

The authors are grateful for the financial support received from Pacific Northwest National Laboratory, USA.

Figure 1. Ultrasonic response of thick LN/BT film fabricated on 1”-thick 6061 aluminum substrate at RT.

References:

A Non-Collinear Mixing Technique to Measure the Acoustic Nonlinearity Parameter of Adhesive Bond

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In this work, we employed a wave mixing technique with an incident longitudinal wave and a shear wave to measure the Acoustic Nonlinearity Parameter (ANLP) of adhesive bonds. The adhesive transfer tape (F-9473PC) was used as an adhesive material: two aluminum plates bonded together by the tape. For high signal to noise ratio, proper interaction angle and frequency ratio between the two incident waves were carefully selected so resonance occurs primarily in the adhesive layer, which somewhat suppressed the resonance in the aluminum plates. One of the most significant features of this method is that the measurements need only one-side access to the sample being measured. To demonstrate the effectiveness of the proposed technique, the adhesively bonded aluminum sample was placed in a thermal chamber for chemically aging. The ANLP of the thermally aged sample was compared with that of a freshly made adhesive sample. The results show that the ANLP varies with aging time and temperature.

Acknowledgement:

NSF CMMI-1613640
Identification of a Crack Tip Position Using Low-frequency Ultrasonic Waves Caused by Directivity and Scattering

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In our previous research, we experimentally examined transmission of ultrasonic waves through contact surfaces of two metal blocks stacked and compressed in order to simulate a closed crack as in Ref.[1]. The experiments showed that an ultrasonic wave transmitted over a contact solid interface consists of not only the transmitted fundamental frequency component but also much lower-frequency spectra[2]. The magnitude of the low-frequency components is a function of the relative angle between the transmitting and receiving transducers and is expected to use for developing a comprehensive method allowing unskilled engineers to detect cracks successfully. Thus, we proposed a new ultrasonic testing method using the low-frequency components[3], which may not depend on the installation condition of ultrasonic transducers. However, since the actual positions of cracks made by bending tests were difficult to measure, we could not verify the accuracy of the proposed inspection method. In this research, using specimens with a crack whose tip position is more easily measured beforehand, we investigated effectiveness of the proposed ultrasonic method for identifying the tip position of a crack.

We carried out experiments using two kinds of specimens: one with a crack perpendicular to their upper surfaces, and the other with a crack parallel to their upper surfaces. These cracks were made by wire electric discharge machining, and the position of each crack tip was accurately measured beforehand. Results of both types obtained by the proposed method using the low-frequency components show that the crack tip position can be successfully identified by that method.

References:
Flash thermography model-based inversion using physical geometric context
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Flash thermography is based on using a thermal camera to observe the cooling of a surface after exposure to a heat pulse. Flaws and/or delaminations can be found from the cooling profile. Many traditional analysis approaches treat each pixel independently, but such approaches cannot compensate for lateral heat flows. By using known heat conduction solutions (Green’s functions) we can perform a model-based thermographic inversion that compensates for such lateral flows.

Such an approach is relatively simple in flat geometries where there is no curvature and an orthographic correction can be applied to map the thermal camera image to the specimen surface. For specimens with more complicated shapes such as non-flat composite panels with stiffeners or (in the extreme case) sharp bends, not only is mapping the thermal image onto the specimen more complicated, but the physics of heat propagation is different on a curved surface compared to a planar surface. We present progress in developing approximate thermal Green’s function for curved anisotropic materials. We demonstrate how the thermal image sequence can be projected back in virtual space through a 3D model of the specimen onto a surface parameterization, such as shown in Figure 1. Then we show how model-based thermographic inversion can be applied to the parameterized surface, so as to calculate the inversion in geometric context including local thickness and curvature. This allows the model-based inversion to exploit both heat conduction physics and local geometry to provide better detection, localization, and interpretation of flaws.

Acknowledgement:

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Figure 1. Projection of thermal image data onto specimen surface

References:
2D Surface Parameterizations for Temporal and Multi-Modality NDE Data Fusion

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Data fusion [1] is in the academic NDE literature and has been fairly widely demonstrated in the laboratory, but has not garnered wide industrial adoption. One of the major challenges to data fusion applications is in registering the NDE data to the physical part, for real parts with non-trivial geometries. While data registration to a 3D model is not a new problem, nor a particularly hard problem, projecting NDE data onto a 3D model is not entirely trivial. Moreover, in many cases the physical object may not match the 3D model; practical NDE data fusion systems will have to accommodate inconsistent or changing part geometries.

One way to accommodate inconsistent geometries is by projecting the NDE data onto a surface parameterization of the 3D model rather than onto the 3D model itself. Because large 3D deformations usually result from bending, the surface parameterization will in general be less affected by distortion due to mechanical loading than the 3D shape. The surface parameterization also provides a context for applying data fusion algorithms, model-based inversion algorithms, and condition tracking algorithms.

In this presentation we will discuss some of the challenges in defining surface parameterizations, including the need for seams and overlap, and the irreconcilable requirements that may be placed by different stakeholders on the parameterization. We will discuss existing tools for creating such parameterizations and the need for an algorithmic process that can instantiate a desired parameterization on-demand from measured specimen geometries. Finally, we will discuss some of the new capabilities in NDE data fusion and model-based inversion that are enabled by projecting 3D NDE data onto a consistent 2D parameterization.

References:
Annular Phased Array Probe for Testing of Aero Engine Discs

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Ultrasonic testing of airplane jet engine disks pose high challenges in finding very small flaws in highly scattering materials as titanium alloys and nickel based super alloys. At the moment this testing is performed as multizone testing meaning that a series of scans is performed with focusing conventional probes at various depths of the disk. We propose to apply annular phased arrays (APA) together with dynamic depth focusing DDF [1]. This approach in combination with specially designed signal processing algorithm and probe shape will allow to detect defects equivalent to FBH 0.2 mm in contrast to the currently achievable FBH 0.4 mm. With the help of sound field simulations it is shown, that a non-planar APA of special curvature gives better results compared to commercially available transducers with plane faces. The sound field of the designed and produced transducer was characterized and agrees with the predictions of our simulations. It is demonstrated that the transducer can be successfully applied in the variants (i) standard phased array operation, (ii) transmission as axicon [2,3] and reception with fixed focus and (iii) reception with DDF. In a test specimen made of titanium alloy an FBH 0.2 mm could be detected (see figure 1).

Figure 1. APA probe during scanning of an aero engine disk test piece (left), a B-scan of the indicated area (middle) and magnification of the B-scan containing an FBH 0.2 mm (right).

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References:
Nondestructive Analysis of Alkali-Silica Reaction Damage in Concrete Slabs Using Shear Waves

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Alkali-silica reaction (ASR) is the chemical reaction that occurs in concrete. It is caused by the interaction of alkalis in Portland cement and silica in aggregates and results in microcracks within the material. This type of damage has been the focus of nondestructive evaluation efforts in recent history, but no work was done on in-situ structures or large-scale samples.

To address these limitations, an ultrasonic linear array device, MIRA, was utilized for this research. An experimental investigation was performed on four slabs with various levels of alkali-silica reaction at the Electric Power Research Institute (EPRI) [1]. One-period impulses with a target of 50kHz center frequency were selected in this study. We propose the use of the Hilbert Transform Indicator (HTI) for quantification of ASR damage [2]. A higher HTI value would be indicative of damaged concrete, while a low value represents sound concrete. In general, values below 90 are regarded as an indicator of sound concrete while values above 100 indicate the presence of damage [3].

The ability of the HTI values to distinguish between areas of damaged concrete is exhibited by the color map results shown in Figure 1. The maps show that the control specimen, Slab 0, was in good condition, while slabs 1 and 2 exhibited higher levels of damage as indicated by the HTI values. It should be noted that extreme damage conditions were not present in any of the slabs.

Acknowledgement:

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References:
This paper presents the design and development of the distributed ultrasonic wave-guide temperature sensors using a stepped-helical structure. Distributed sensing has several applications in various industries (oil, glass, steel) for measurement of physical parameters such as level, temperature, viscosity, etc. These wave-guide having special embodiment such a notch or bend for obtaining ultrasonic wave reflections from the desired locations (Gage-lengths) where local measurements are desired. In this paper, a multi-location measurement wave-guide, with a measurement capability of 18 locations, in a single wire has been fabricated. The distribution of these sensors is both in the axial as well as radial directions using a stepped-helical spring configuration. Also, different high temperature materials have chosen for the wave-guide. Both lower order axi-symmetric guided ultrasonic modes (L(0,1) and T(0,1)) were employed. These wave modes were generated/received (pulse-echo approach) using conventional longitudinal and shear transducers respectively. Also, the both wave modes were simultaneously generated/received and compared using shear transducer for developing the distributed helical wave-guide sensors. The effect of dispersion of the wave modes due to curvature effects will also be discussed.
B-scan Technique for Locating and Imaging Fatigue Cracks Around Fastener Holes Using a Spherically Focused Ultrasonic Probe

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Ultrasonic shear-wave inspection has been utilized for cracks initiating at fastener sites in multi-layer aircraft structures. This effort aims to develop and transition an angled-beam shear-wave technique for crack localization at these fastener sites. This requires moving beyond detection to achieve reliable crack location and size, thereby providing invaluable information for maintenance actions and service-life management. The technique presented is based on imaging cracks in “true” B-scans (depth view projected in the sheets along the beam path). The crack traces that contribute to localization in the true B-scans depend on small diffracted signals from the crack edges and tips that are visible in simulations and experimental data acquired with sufficient gain. For experiments and simulations, each indication in C- and B-scans is analyzed to determine its origin and to characterize the signal-crack interaction (Fig. 1a-d). The most recent work shows that cracks rotated toward and away from the central UT beam also yield crack traces in true B-scans that allow localization in simulations (Fig. 1d-e), even for large obtuse angles where experimental and simulation results show very small or no indications in the C-scans. Similarly, for two sheets joined by sealant, simulations show that cracks in the second sheet can be located in true B-scans for all locations studied: cracks that intersect the front or back wall of the second sheet, as well as relatively small mid-bore cracks. These new results that will be discussed are consistent with previous model verification and sensitivity studies that demonstrate crack localization in “true” B-scans for a single sheet and cracks perpendicular to the UT beam.

Figure 1. Simulated C-scan (1a) for a rotated crack (-22.5°) that intersects the back wall showing the indications associated with the bore hole and crack. The white arrow in the C-scan indicates the position in a low-amplitude indication corresponding to the beam that hits the upper crack tip (blue arrow in 1b). The crack dimensions are shown in 1c, and are followed by the true B-scans obtained for two levels of applied gain (15 and 21 dB). Experimental (blue background) and simulated C-scans (green background) are shown with simulated B-scans (1e) for the crack rotated with respect to the UT beam for angles between ± 22.5°.

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When a commercial launch vehicle composite overwrapped pressure vessel (COPV) failure occurred on the launch pad at the Kennedy Space Center (KSC), a representative of the launch vehicle provider contacted NASA Johnson Space Center (JSC) White Sands Test Facility (WSTF) for assistance. The industry standard inspection method for COPV liners, dye penetrant (PT), could not be used on the liner interior after wrapping and autofrettage testing and had limitations on the minimum flaw size that could be reliably detected. At the time, JSC/WSTF had developed laser profilometry (LP) and eddy current (EC) flaw scanning capability for COPV liners. The LP system had been successfully applied throughout the International Space Station nitrogen and oxygen recharge system (NORS) COPV development, qualification, and flight vessel production program. Sensitive EC methods had been recommended for this application in previous NASA Engineering and Safety Center (NESC) assessments\(^\text{1}\) since PT methods have limited sensitivity for detection of critical flaw sizes in COPV liners. Additional EC development was needed and the requisite capability assessment\(^\text{2}\) (probability of detection, POD) was required for equipment qualification and co-funded by the NASA Office of Safety and Mission Assurance (OSMA). In addition to interior and exterior EC flaw detection, the system would also provide liner interior EC thickness mapping to identify liner thickness reduction after overwrapping and autofrettage testing. The COPV NDE scanner demonstrated outstanding capability, showing improvement over the state-of-the-art in most areas. The system produced an estimated 90/95 POD at a detectable flaw size of 0.0094 in x 0.0047 for fatigue cracks. This exceeded the capability of PT even under less than ideal conditions. An innovative phase filtering and analysis technique was developed to enable reduction of much of the noise allowing differentiation between pits and fatigue cracks and EDM notches in many cases. The EC thickness measurement probe was successfully demonstrated to accurately map the liner thickness over the range of 0.060 to 0.140 inch, calibrated to within 0.0004 inch of a NIST traceable calibration tool. The integrated LP system was found to measure and map internal surfaces within an accuracy of approximately 0.002 inch. The LP system provided high-resolution laser imaging of the liner interior (same scan), eliminating the need for separate borescope imaging.

Acknowledgement:

Development significantly benefitted by collaborations with Laser Techniques Company and UniWest. Both organizations are based in Washington state. Statistical support was provided by Spencer for Hire of Albuquerque, NM. Testing was supported by the JSC and WSTF materials evaluation laboratories. Funding for this work was provided by the NESC and OSMA.

References:

Development of Composite Calibration Standard for Quantitative NDE by Ultrasound and Thermography

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Inspection of aircraft components for damage utilizing ultrasonic Non-Destructive Evaluation (NDE) is a time intensive endeavor. Additional time spent during aircraft inspections translates to added cost to the company performing them, and as such, reducing this expenditure is of great importance. There is also great variance in the calibration samples from one entity to another due to a lack of a common calibration set. By characterizing damage types, we can condense the required calibration sets and reduce the time required to perform calibration while also providing procedures for the fabrication of these standard sets. We present here our effort to fabricate composite samples with known defects and quantify the size and location of defects, such as delaminations, and impact damage. Ultrasonic and Thermographic images are digitally enhanced to accurately measure the damage size. Ultrasonic NDE is compared with thermography for comparison.

Three different methods for artificially creating delaminations have been developed and the results will be presented. The samples have also been impacted with a 0.25 inch dia impactor with varying levels of energy.

An impact sample ultrasonic image and digitally enhanced image.

Acknowledgement:
This work is done under a Phase II sub-contract from Innoveyda Corp. Prime contract from US Air Force No. FA8117-15-C-0007.
Coda Waves or diffuse field has been touted to be an NDE method which does not require the damage to be in the path of the ultrasound. The object is insonified with ultrasound and instead of catching the first or second arrival, the waves are allowed to bounce multiple times. This aspect is very important in structural health monitoring (SHM) where the future damage detection location is unknown. Researchers have used it in the interrogation of seismic damage and metallic materials. In this work we have applied the technique to composite material and the results are presented. The coda wave and acoustic emission signals are recorded simultaneously and collaborated. Development of small damage in the form of micro-crack is the objective of this work.

Acknowledgement: This research was partially supported by the NSF Industry/University Cooperative Research Program of the Center for Nondestructive Evaluation at Iowa State University.

Figure: Differential feature amplitude increasing with increasing damage level under four point bending.

Reference:
Using Guided Ultrasonic Wave Inspection to Quantify the Wide of Delaminations in Composite Laminates

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Delamination is a key limitation of composite materials. Delamination is attributed to intrinsically low interfacial strength of laminated composites and may result in loss of integrity of the structure. Several analytical approaches have been suggested to predict delamination. This paper presents a guided wave inspection approach to quantify the width of a delamination in a carbon fiber reinforced polymer (CFRP) composite plate.

A 2D numerical model for predicting A0 Lamb wave propagation behavior in a cross-ply [0/90]s composite laminate plate containing a delamination is simulated using a commercial FEM software. It is demonstrated from the dispersion curve of Lamb waves that the phase velocity of A0 mode in the sub-laminates above and below the delamination area are different as depicted schematically in Figure 1. The wave propagates with the same velocity in the main laminate. In the delamination area, waves propagate separately with individual velocities in the two sub-laminates above and below the delamination. After passing the delamination, the waves then propagate in the same velocity again in the main laminate. The phase difference between the waves travelling from the upper and the lower sub-laminates can be expressed as:

\[ \Delta \phi = \omega \left( \frac{D_L}{C_{P-L}} - \frac{D_L}{C_{P-U}} \right) \]

Figure 2(a) shows the waves travelling from upper and lower sub-laminates. Figure 2(b) shows that the phase difference between the two waves increasing linearly with the delamination width. Figure 2(c) shows the change of amplitude of the superimposed signal with the delamination width. When the phase difference is 180°, the signal amplitude is smallest.

The effectiveness of the method was also verified experimentally, on a GFRP plate sample.

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References

Evaluation of Crack’s Depth Using Eddy Current Testing and GMR Sensors

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In this paper we use the eddy current testing [1] (ECT) method to determine the depth of superficial cracks [2] by measurement of the secondary magnetic field perturbation when an excitation current with surface uniform density is launched perpendicularly to the crack orientation. The secondary magnetic field is measured using giant magneto-resistor (GMR) detectors.

The experimental part of this work was performed by inspection of the secondary field obtained by scanning a large number of slits machined on aluminum plates. The field component represented in the figure was obtained with sinusoidal excitation and was measured on the direction of the linear slits. The measured component presents a single maximum on the center of each one of the seven defects.

Amplitude of the secondary field component measured in the direction of the excitation primary field.

The observed data permits to conclude that the field maximum amplitude measured at the center of slits is correlated to the depth of the defect, for slits of the same length. For slits of different lengths, and under the supposition that the excitation frequency is low enough to consider that the primary field penetrates the entire thickness, we need to consider the division of current beneath and around the defect. That study shall be made in the final paper.

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References:
This paper presents technologies used for condition assessment of bare concrete decks and asphalt overlaid decks as well as asphalt pavements. The study for bare concrete decks was funded by the National Cooperative Highway Research Program – Ideas Deserving Exploratory Analysis (NCHRP-IDEA) program. The objective of the research and development was to develop a faster, more accurate technology to determine internal conditions of bridge decks. A Sonic Surface Scanner (S3) prototype with a pair of transducer wheels was originally developed. Later the S3 system was expanded as part of a Strategic Highway Research Program SHRP 2 R06 (D) research project for asphalt pavement delamination (National Center for Asphalt Technology - NCAT study at Auburn University) so that up to three pairs of transducer wheels could be added to the system for more rapid testing. The S3 system can be set to perform either Impact Echo Scanning on all wheels for condition assessment of bare concrete decks or simultaneously perform Impact Echo Scanning and Spectral Analysis of Surface Waves (IE/SASW) scanning for condition assessment of concrete decks underneath overlays such as asphalt or on concrete/asphalt pavements. In this paper, case studies are presented from a bare concrete deck from an asphalt overlaid deck and pavements. Comparisons were made in which comparison/ground truthing techniques (chain drag acoustic sounding, coring, hydro-blasting, etc.) were used to valid the IE/SASW scanning results. The research investigations were performed as “blind” studies. Actual known bridge deck and pavement conditions revealed to the research team after initial data analysis and reporting of detected delamination conditions was completed using the Sonic Surface Scanner shown below in Figure 1.

Figure 1. Sonic Surface Scanner (S3) for Impact Echo/Surface Wave Testing of Concrete and Asphalt Decks and Pavements
Temperature Sensitivity Study of Eddy Current and Digital Gauge Probes for Nuclear Fuel Rod Oxide Measurement

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Novel fuels are part of the nationwide effort to reduce the enrichment of Uranium for energy production. Performance of such fuels is determined by irradiating their surfaces. To test irradiated samples, the machinery must operate remotely. The plate checker used in this experiment at Idaho National Lab (INL) performs non-destructive testing on fuel rod and plate geometries with two different types of sensors: eddy current and digital thickness gauges. The sensors measure oxide growth and total sample thickness on research fuels, respectively. Sensor measurement accuracy is crucial because even 10 microns of error is significant when determining the viability of an experimental fuel. One parameter known to affect the eddy current and thickness gauge sensors is temperature. Since both sensor accuracies depend on the ambient temperature of the system, the plate checker has been characterized for these sensitivities. The eddy current probes were tested previously in a non-radioactive environment and are noted to have sensitivity to temperature. The manufacturer of the digital gauge probes has noted a rather large coefficient of thermal expansion for their linear scale. It should also be noted that the accuracy of the digital gauge probes are specified at 20°C, which is approximately 7°C cooler than the average hot-cell temperature. In this work, the effect of temperature on the eddy current and digital gauge probes is studied, and thickness measurements are given as empirical functions of temperature.

Figure 1. Eddy current sensor (Left) and digital gauge (Right) thickness variation with temperature.

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This work was supported by the INL and the DOE office of NNSA (National Nuclear Safety Administration)
Least-squares reverse time migration (LSRTM) for damage imaging using Lamb waves

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Reverse-time migration (RTM) is an effective damage imaging technique for both metallic and composite plates [1, 2]. Incorporating least-squares inversion into migration can generate images with improved resolution and suppressed artifacts [3, 4]. Large-area monitoring and accurate damage quantification are two primary goals of ultrasonic, guided wave-based structural health monitoring (SHM). Development of a least-squares reverse time migration (LSRTM) technique is promising since it could expand the imaging area for a given sensor array while maintaining relatively high resolution. Furthermore, the imaging technique can estimate damage reflectivity, which can be used to quantify its severity [5]. A LSRTM technique is introduced in this research for damage imaging in an isotropic plate using $A_0$ mode Lamb waves. A finite difference algorithm based on the Mindlin plate theory was used to simulate the flexural wave propagation. To form the theoretical foundations for guided wave-based LSRTM, a modeling operator and its adjoint are defined. The damage images show that LSRTM can enhance imaging resolution, reduce artifacts, and improve damage reflectivity estimation over iterations.

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References:
Inspection of As-Cast Steel Slabs Using an EMAT Array

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A new EMAT system has been developed that is capable of driving a number of EMAT coils with controllable phase delays, allowing for focusing and steering of the acoustic field. This preliminary work describes a 4-channel pulser system, with each channel capable of driving currents of up to 1.75 kA for a pulse with a rise time of 1 µs. The system has been demonstrated to generate bulk compressional waves in a 23 cm thick as-cast steel slab, which can be detected by an EMAT, either opposite to or on the same side as the generating array. Some degree of beam steering and focusing has been demonstrated, with the signal amplitude enhanced by a factor of approximately 3.5 when compared to using a single generation coil. The system is capable of generating surface and guided waves in addition to bulk wave modes, and the design of the system is such that it has the potential to be employed at elevated temperatures in a casting environment.

Figure 1. A-scan data comparing the transmitted signals generated by a single generation coil and a 4-element EMAT array.

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Phased Array Ultrasonic Assessment of High Temperature Hydrogen Attack

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This study assesses Phased Array Ultrasonic Testing (PAUT) capabilities for detecting localized High Temperature Hydrogen Attack (HTHA) in low alloy steels using portable and battery powered equipment with parallel architecture and integrated Beam Forming, Full Matrix Capture, Total Focusing Method and Adaptive Total Focusing Method algorithms. Optimized via modeling and simulations, linear and matrix 5-15 MHz PAUT probes are designed and manufactured. The probes are integrated with solid and comfortable (flexible) wedges and are used to generate straight beam longitudinal and angle beam shear waves. Encoded real time data collection on vessels and piping with expected HTHA is performed. Data analysis is conducted using reflected, diffracted, and back scattered signals and 2D/3D visualization of the indications. Examples for reliable detection, characterization, and sizing of HTHA damage in early stages are provided. Selected PAUT results are correlated with metallographic images and measurements1.

Acknowledgement:

This work is supported by BP Products North America.

References:
On the Use of Ground Penetrating Radar to Detect Rebar Corrosion in Concrete Structures

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We continue our investigations into the use of ground penetrating radar (GPR) to detect and quantify corrosion-induced metal loss in steel reinforcing bars (rebar) embedded in concrete structures. Past experimental work in 2012 on a highway bridge in central Iowa [1] suggested that GPR could be used to differentiate an intact rebar from one having substantial metal loss due to corrosion. That study made use of the amplitudes of GPR signals reflected by rebar, as obtained using a commercial instrument operated in pulse/echo mode. There it was assumed that a rebar containing a thinned region (i.e., presenting a smaller metal target to the incoming microwave pulse) would reflect more weakly than an un-thinned rebar, thus resulting in a GPR signal having a smaller peak amplitude. Several rebar having abnormally small peak amplitudes were detected in the course of the highway bridge inspection.

Two new studies are summarized in this presentation. In the first, we compare recent GPR measurements on the same bridge to those obtained in 2012. The newer measurements use both the 1.6 GHz antenna used in the earlier work and an alternative higher frequency antenna (2.6 GHz). We discuss similarities and differences between the old and new results at 1.6 GHz, and also summarize the effect of the frequency change on the newer measurements.

Many factors can contribute to the strength of the GPR echo seen from a given rebar, including the rebar’s length, its distance from and tilt angle relative to the antenna, and the location and size of the metal-loss region. In the second section of the presentation we discuss new laboratory measurements to systematically investigate these geometric effects. In 2016 we studied such effects using a simplified measurement setup where only an air layer separated the antenna from the rebar [2]. Here we discuss similar measurements simulating rebar embedded in concrete. For our concrete “phantom” we use a layer of moist sand in between two parallel concrete blocks. When the moisture content is properly chosen, the EM properties of sand are similar to those of cured concrete. The block/sand/block sandwich then serves as a concrete-like medium in which a rebar can be inserted and readily repositioned. Results of GPR measurements using this new sandwich approach are reported and compared with those of the earlier “air layer only” measurements.

Acknowledgment:

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References:

Model-Assisted Probability of Detection for a Flat Bottom Hole in an Aluminum Block Using UTSim2 and Least Angle Regression Sparse Polynomial Chaos Expansions

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Probability of detection (POD) is a widely established method for measuring reliability of nondestructive (NDE) systems¹. Typically, POD is determined experimentally, while it can also be enhanced by utilizing computational measurement simulations and model-assisted POD (MAPOD) techniques²,³. Recent development of high-fidelity measurement simulation models provides an opportunity to significantly reduce the empirical information needed for POD. Unfortunately, the computational cost of performing the high-fidelity simulations can be high. Moreover, current MAPOD methods require a large number of model evaluations²³. In particular, propagating uncertain input parameters through the computational models is typically achieved using Monte Carlo sampling (see Fig. 1). Hence, the usage of high-fidelity simulations in combination with state-of-the-art MAPOD techniques can be computationally/time-wise prohibitive. This paper describes the application of stochastic surrogate models to handle the uncertainty propagation. More specifically, the least angle regression sparse polynomial chaos expansions⁴⁵ are utilized to efficiently propagate the uncertain parameters through the computational measurement model. The approach is demonstrated on MAPOD analysis for a flat bottom hole (FBH) in an aluminum block using ultrasonic simulation testing with UTSim2. The uncertain parameters to be studied include the probe angle and F number, as well as the FBH orientation. The proposed approach is compared with the conventional method of using Monte Carlo sampling in terms of accuracy and computational cost.

Figure 1: Flowchart showing the main elements of model-assisted probability of detection.

References:

A new definition of acoustic nonlinearity parameter and its measurement using an air-coupled receiver

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In order to determine the absolute material nonlinearity, there are many things required including the separate calibration of receiving transducer and the absolute displacement measurement of fundamental and second harmonic waves with consideration of attenuation and diffraction corrections. Most of previous studies, however, measured the so-called relative nonlinearity parameter by using the amplitude spectra of fundamental and second harmonic waves without complicated measurement procedure. More recently, the ratio of relative nonlinearity parameter is also measured by dividing the target nonlinearity by that of a reference sample with similar thickness and acoustic properties. These relative nonlinearity measurement techniques have some drawbacks and impose limitations in practical applications. Contact piezoelectric transducers are most commonly used as receiving transducers of longitudinal waves in the through-transmission setup. Piezoelectric contact transducers, while easy to use in many ways, is heavily influenced by contact conditions between the transducer and sample surface, so that application of a consistent force is crucial to measurement repeatability. Noncontact reception is highly desirable and air-coupled transducers have a potential advantage in this respect. However, current calibration techniques such as self-reciprocity methods are not directly applicable because of high ultrasonic attenuation loss in air. Consequently, all the measurements with air-coupled receivers so far were limited to relative measurements. In this study, a novel measurement technique is proposed with air-coupled transducers for material nonlinearity determination in an absolute manner without receiver calibration. For this purpose, a nonlinearity parameter equation is newly defined and its validity is tested through nonlinearity measurements. The proposed method releases the requirement of similarity between the reference and target samples in both thickness and acoustic properties. The method also takes into account the effects of attenuation and diffraction for both samples. The results show that the nonlinearity parameter of target samples with different thicknesses can be obtained with reasonable accuracy without depending on the type of reference samples used.

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Portable Vibro-acoustic Testing System for *In situ* Microstructure Characterization and Metrology

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There is a need in research reactors like the INL to inspect irradiated materials and structures. The goal of this work is to develop a portable scanning infrastructure for a material characterization technique called vibro-acoustography (VA) that has been developed by INL [1] for nuclear applications to characterize fuel, cladding materials, and structures. The proposed VA technology is based on ultrasound and acoustic waves; however, it provides information beyond what is available from the traditional ultrasound techniques and can expand the knowledge on nuclear material characterization and microstructure evolution.

VA is a three-dimensional (3D) imaging modality based on ultrasound-stimulated acoustic emission. VA uses the force caused by the beating of two frequencies to generate an acoustic emission signal. Due to absorption or reflection, the energy density in the object at an acoustic focal point changes to produce a “radiation force.” This force locally vibrates the object, which results in an acoustic field that depends on the characteristics of the object at that point. This acoustic field is detected for every point in the object; the resulting data is used to make an image of the object’s mechanical properties. This technology is fundamentally different from traditional ultrasound imaging. More specifically, VA is: (a) based on the “radiation force,” a nonlinear phenomenon in sound propagation, and (b) sensitive to both high and low frequency dynamic responses of the object. The combination of these two response types provides information about characteristics of the object beyond what is possible by traditional ultrasound imaging. High spatial resolution is achieved, since the radiation force is localized to the focal point of the ultrasound beam. Low-frequency information, which is a representative of structural characteristics, is gained through the radiation force mechanism at a low (beat) frequency.

This paper will report on the development of a portable scanning that can be set up to characterize materials and component in open water reactors and canals *in situ*. We will show some initial laboratory results of images generated by vibro-acoustics of surrogate fuel plates and graphite structures and discuss the design of the portable system.

**Reference:**

Progress on the Development of a Linear Phased Array Transducer for Harsh Environments

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Ultrasonic inspections in conditions such as elevated temperature, pressure and radioactivity generate difficulties for current commercially available phased array ultrasonic transducers. Industry standard piezoelectric material for commercial transducers can not be used in high temperature environments because of operational temperatures in excess of the Curie temperature. In nuclear environments the nuclear heating effects on the piezoelectric can induce short-duration, high amplitude spikes in received waveforms. Various other materials that are used in commercially available transducer construction can suffer degradation from heat, as well as embrittlement and transmutation because of cumulative radiation effects [1][2]. The research being performed will lead to a phased array ultrasonic transducer that will be used to detect component characteristics such as cracks/flaws, bowing and thickness variations in an Advanced Test Reactor (ATR) loop, where it will operate in deaerated primary water (DPW) at a temperature of 700 °F and fast (>1 MeV) neutron fluence of $1 \times 10^{20} \text{n/cm}^2$. Work completed includes multiple brazing and high temperature adhesion techniques being evaluated as well as various brazing/high temperature paste materials using ultrasonic measurements to asses bondline thickness and surface coverage. Crosstalk of multi-element high temperature cable was performed. An off-the-shelf phased array linear transducer was purchased and was able to detect a simulated flaw in a room-temperature mock scenario where it was coupled to a 3 mm thick steel plate at a distance of 20 mm from the sample target with a 1 mm diameter drill flaw. This setup simulates the space constraints set by the inspection position within the loop. There is still work that needs to be completed, but the milestones that have been completed to date show that the feasibility of constructing a phased array transducer for harsh environments is possible.

References:
Multi-mode reverse time migration damage imaging using ultrasonic guided waves

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The sensitivity of Lamb wave modes to a particular defect or instance of damage is dependent on various factors, e.g. the local strain energy density due to that wave mode\textsuperscript{1}. As a result, different modes will be more useful than others for detecting and quantifying, dependent on damage type. For example, prior work in the field has shown that out-of-plane modes may have a higher sensitivity than in-plane modes to surface defects in plates\textsuperscript{2}. Furthermore, the excitability of a certain data acquisition system and the corresponding resolution for damage imaging also varies with frequency. The aim of the present work was to develop a quantitative multi-mode damage imaging technique that enables higher resolution imaging, general sensitivity to unknown damage types, and detectability using different data acquisition systems due to a wider range of applicable frequencies. A reverse-time migration (RTM) imaging algorithm\textsuperscript{3} was combined with an accurate numerical simulator, the three-dimensional (3D) elastodynamic finite integration technique (EFIT)\textsuperscript{4}, to provide multi-mode damage reflectivity imaging. The obtained results demonstrate the possibility to recover the damage reflectivity using \textit{A}0 and \textit{S}0 Lamb wave modes and to address the mode conversion effect.

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References:


Acoustic Emission Monitoring of Damage in Ceramic Matrix Composites: Effects of Weaves and Features

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Ceramic matrix composites (CMCs) are a class of high temperature materials with better damage tolerance properties compared to monolithic ceramics. The improved toughness is attributed to weak interface coating between fiber and matrix that allows for crack deflection and fiber pull-out behavior. Thus, CMCs have surpassed monolithic materials for high temperature applications in gas turbines. The current standard weave for CMCs is an 8-harness satin balanced weave; however, other architectures such as uni-weave materials (tape layup) are also being considered due to fiber placement control. In addition, engineering components require additional features in the CMC laminates such as notches and holes for attachments. Past work has shown that acoustic emission could differentiate the effect of changing interface conditions as well as heat treatment effects. The focus of the present work is to investigate the effects of different weaves and features on damage behavior of CMCs as observed via acoustic emission technique. The results of the tensile testing with acoustic emission monitoring will be presented and discussed.
Multilevel Fast Multipole Algorithm (MLFMA)-accelerated Nyström Method for
Ultrasonic Scattering - Numerical Results and Experimental Validation

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An important aspect of ultrasonic measurement models is how the scattering of ultrasound
from flaws/defects is modeled. State-of-the-art scattering models used in ultrasonic NDE
modeling include the Kirchhoff and the modified Born approximations. Although these models
are computationally fast and memory efficient, each has its own limitations. It is, therefore,
important to consider full-wave scattering models that yield accurate results for the complex yet
practical defects that cannot be modeled accurately using the approximate methods. Some
progress has been made in developing full-wave models for 2D flaws [1]. However, full 3D
modeling is still very challenging because of the large simulation times and memory
requirements. We applied a boundary integral equation method, called the Nyström method, to
model elastic wave scattering from complex defects in 3D [2] and used a fast algorithm,
multilevel fast multipole algorithm (MLFMA), to reduce computation time and memory
requirement. We have shown our model to be in good agreement with benchmark data from the
world federation of NDE centers (WFNDEC) [3]. Here, we present numerical results
demonstrating the improvements in simulation times and memory requirements that can be
achieved using our model over other full-wave scattering models. A comparison of our model
and the Kirchhoff approximation with WFNDEC benchmarks has shown that both models agree
with experimental data very well in case of large specular reflector-like defects at normal
incidence [3]. In contrast, significant errors were observed in the Kirchhoff approximation at
oblique incidence angles. In this paper, we will present further experimental comparisons,
particularly for those defects which cannot be modeled accurately by the Kirchhoff
approximation such as small spherical inclusions, multiple inclusions, etc.

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References:

High Temperature Ultrasonic Immersion measurements using BS-PT based piezoelectric transducer without a delay line

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Ultrasonic technology offers the potential for in-coolant NDT measurements and imaging required for the safe operation of small modular reactors. Previous studies have shown that signal to noise ratio (SNR) becomes a critical issue for transducers operating even at hot stand by temperature (260°C). Particularly, reduction in the signal strength as a function of temperature reduces the ability to distinguish ultrasonic response from the defect due to background electrical noise. This reduction in signal strength can cause reduction the probability of detection in a high temperature (HT) environment.

In the current work, BiScO₃-PbTiO₃ (BS-PT) based 2.25 MHz air-backed immersion transducer is developed and tested. Dielectric constant characterization of BS-PT is performed and a high curie temperature in excess of 400°C is reported, suitable for hot stand by inspection in liquid metal reactors. BS-PT, wear plate and transducer casing are bonded together using a thin layer of high temperature epoxy and cured at 150°C for one hour. For electrical conductivity, a solder is replaced by a high temperature conductive paste cured at 125°C for four hours. Fabrication challenges regarding development of HT transducer will be discussed.

Ultrasonic immersion measurements are performed in water up to 92°C. Increase in temperature of water generated gas bubbles which adhered to the wear plate of the transducer resulting into significant attenuation of the ultrasonic signal. Using silicon oil, temperature dependence of ultrasonic NDT system is evaluated up to 150°C with 1018 low carbon steel sample as a reflector. The immersion measurements in water and silicon oil are repeated for three thermal cycles for durability testing of the probe. Sensitivity of the probe is calculated with respect to the baseline sensitivity at room temperature. SNR as a function of temperature is reported for immersion measurements in both water and silicon oil for three thermal cycles.

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Self-diagnostic sensor mode for high temperature SHM using electromechanical impedance method: A coupled field modeling approach

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The applications of ultrasonic transducers in high temperature (HT) environment is expanding rapidly in nuclear power industry, gas turbines and the space exploration technology. Piezoelectric based transducer is used as a sensing element for structural health monitoring of these critical infrastructures.

Temperature dependence of the adhesive used for bonding piezoelectric material to the specimen affects the transmitted and received signal critically. Also, piezoelectric material is bonded to a matching layer in a conventional HT contact and immersion transducers. Reduction in acoustic coupling as a function of temperature causes attenuation of the transmitted ultrasonic signal reducing the sensitivity of these transducers.

In the present work, application of electromechanical impedance (EMI) method is proposed for self-diagnosis of such a weak bond state between the piezoelectric material and the substrate. A coupled field model is developed for the piezoelectric material using commercial finite element software. Frequency domain finite element approach is used to compute electrical admittance of the bonded structure to establish a baseline EMI signature. The deviation from the baseline spectrum due to weak bond state is quantified for the frequency shift and magnitude reduction using a damage index. Root mean square deviation (RMSD) index and correlation coefficient deviation metric (CCDM) are discussed for the evaluation of the damage index. The sensitivity of the damage index towards the frequency bandwidth of the sensor is also studied to quantify challenges in the self-diagnostic sensor mode using EMI method.

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_Hearing the defects: A low-cost binary classification based learning algorithm to reduce human factors in Ultrasonic NDT measurements_

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Methods such as coin tap tests in early days of NDT relied profoundly on the human senses. These tests helped for qualification of a defect from the sound created by the components. Acoustic impact technique became the modernized version of tap tests in NDE 3.0 version. Under the paradigm of NDE 4.0, current work proposes a low-cost signal processing approach to improve the efficiency of the NDT operator and hence the probability of detection by providing an audio assistance.

The ultrasonic frequency content in the reflected signal from the sample under inspection cannot be heard by a human ear. In the current work, the discrete time signal is stretched in time domain to reduce the frequency content of the signal to an audible range of the human ear. Pulse echo contact measurements are performed with 2.25MHz ultrasonic transducer on a 1018 low-carbon steel block with a benchmark artificial defect-side drilled hole (SDH). The diameter of the SDH varies from 0.46 mm to 3.9 mm. Scattering amplitudes of sixteen SDHs is acquired experimentally. The measurement for each SDH is repeated 6 times to reduce the variability due to contact pressure. Threshold based binary classifier with an upper and a lower bound is trained to distinguish the response of a SDH from a low amplitude noise floor and a large amplitude backwall echo signal. The SDH response within the bounds is categorized a hit, emitting a sound to enhance alertness of the NDT operator.

The signal to noise ratio of the experimental data is further reduced by adding the low frequency random noise. Denoising technique using Savitzky-Golay (SG) filtering is then applied to the noisy signal before passing through classifier based learning algorithm. The effectiveness of the algorithm as a function of reducing SNR is measured in terms of computational time for potential use in continuous condition monitoring methods.

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Origami based ultrasonic array element layout for beam focusing using principles of acoustic beamfolding

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Ultrasound beam focusing has many applications in medical ultrasound and industrial imaging. A conventional ultrasonic array can focus the ultrasound by varying the time delay between firing of piezoelectric elements. This results in constructive interference of waves resulting into beam focusing and steering. In such beam forming technologies, controlling firing of each transducer is non-trivial and complex for real time implementation. The objective of the current work is to propose an element layout for ultrasound beam forming without introducing time delays and apodization applied to the driving pulses.

Origami, the ancient art of paper folding has recently provided pathway for topological changes in the mechanical structures for improving the efficiency. In the current work, using finite element method, topological changes in a linear array layout are modeled and compared with linear element configuration. A straightforward mechanical folding of linear element array in a single plane is shown to result in a focused beam without application of time delay and weights applied to the driving pulse. The feasibility of such acoustic beam folding principle is also being studied for generating a non-linear ultrasound beam into a hyperelastic material.

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References:
Optimization of time reversal focusing through various signal processing techniques

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Time reversal vibration focusing, as shown in Figure 1a, has been shown to excite local nonlinear characteristics of cracked media such as steel and glass [1] and is used to evaluate materials for micro-cracking. This research optimizes the time reversal focus of energy in terms of amplitude and quality by exploring several signal processing techniques applied to the reversed impulse response, shown in Figure 1b. Techniques explored here include deconvolution or inverse filtering [2], one-bit time reversal [3], and a new technique termed “clipping”. A parameterization study comparing the maximum focal amplitude and focal temporal quality of time reversal focal signals for these techniques with different settings will be presented. Focal signals are explored in a system comprised of a steel sample with a piezoelectric transducer and a scanning laser Doppler vibrometer (SLDV). This optimization of time reversal focusing will provide for optimal nonlinear crack detection since nonlinear techniques rely on high amplitude excitation of the crack.

Figure 1. a). Time Reversal focus in time domain. b). Reversed impulse response.

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References:
Preliminary Design of High Temperature Ultrasonic Transducers for Liquid Sodium Environments

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Advanced reactor concepts include fast reactors (including sodium cooled fast reactors), gas cooled reactors, and molten salt reactors. Common to these concepts is a higher operating temperature (when compared to light water cooled reactors), and the proposed use of new alloys with which there is limited operational experience. Concerns about new degradation mechanisms, like high temperature creep and creep-fatigue, that are not encountered in the light water fleet and longer operating cycles between refueling intervals indicate the need for condition monitoring technology. Specific needs in this context include periodic in-service inspection technology for the detection and sizing of cracking, as well as technologies for continuous monitoring of components using in-situ probes.

This paper will discuss research on the development and evaluation of high temperature (>550°C) ultrasonic probes that can be used for continuous monitoring of components. The focus of this work is on probes that are compatible with a liquid sodium cooled reactor environment, where the core outlet temperatures can reach ~550°C. Modeling to assess sensitivity of various sensor configurations and experimental evaluation have pointed to a preferred design and concept of operations for these probes. The paper will describe these studies, and ongoing work to fabricate and fully evaluate survivability and sensor performance over extended periods at operational temperatures.

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Industrial applications of additive manufacturing components are increasing rapidly. Consequently, quality control of the parts become important for safe use of these materials. Material properties, surface conditions, and size of defects are some the main concerns in nondestructive evaluation of additive manufactured parts, and the problem is only compounded given the potential for complex part geometry. Numerical modelling can allow the interplay of the various factors to be studied leading to improved measurement design. This paper presents finite element simulation verified by experimental results of ultrasonic waves scattering from artificial flat bottom holes in additive manufacturing materials. A focused beam immersion ultrasound transducer was used for both the modelling and simulations in the additive manufactured samples. The samples were SS17 4 PH steel samples made by laser sintering in a powder bed.

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References:

Detecting Damage in Stainless Steel Using Nonlinear Resonant Ultrasound Spectroscopy

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During disposal, spent nuclear fuel rods are placed into stainless steel containers and may be stored this way for decades. In order to ensure there is as little radiation leakage as possible, the structure of the stainless steel needs to be evaluated and damage detected. In particular, one type of damage these containers are particularly susceptible to is stress corrosion cracking (SCC). Traditional (linear) evaluation methods can detect open cracks but often a closed portion of the cracks extends further, compromising the air tight seal sooner. To this end, NRUS (Nonlinear Resonant Ultrasound Spectroscopy) is used here to quantify crack sizes. This research is currently focusing on quantifying crack size in cylindrical 304L stainless steel rods that are immersed in a heated 42% MgCl₂ solution to induce SCC in an accelerated manner to simulate the damage that is likely to occur on the actual containers.

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Flexible probe for measuring local conductivity variations in Li-Ion electrode films.

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Electrical conductivity is a fundamental characteristic determining the performance of lithium-ion batteries. However, methods to measure the conductivity nondestructively have proven difficult. This is due to the presence of a metallic conductive current collector as well as dominating effect of the contact resistance between the film and the probe. In previous research we developed a micro-four-line probe [1] that can measure thin-film electrodes without removing the current collector. We found that the conductivity of even high-quality electrodes is not homogenous, and has variation on length scales much larger than the size of the active material particles.

Even though the micro-four-line probe worked well, we continue to improve the design. The previous design was fabricated in a clean room on a rigid glass substrate. This limited the geometry of the sample and made adaptation to industrial use difficult. To address this problem, we switched to a flexible polymer substrate, as shown in the figure, which allows for increased sample size and potential low-cost manufacturing. In addition, changes were made to the computer-controlled probe holder and stage, again with an aim toward lowering cost and increasing usability. The stage is used to move the probe over the surface of the sample in order to produce a conductivity map.

We will report conductivity results using the new probe for both anodes and cathodes, including the effect of cycling. Results will also be compared to related work on ionic conductivity of the same electrodes. The hope is that this probe technology can be adapted to manufacturing use as well as to assist other researchers in understanding limiting mechanisms in battery performance.

Figure 1. Flexible conductivity probe.

References:
A new approach to obtaining acoustic impact-echo data from rapid sounding of concrete bridge decks has been developed to significantly increase the speed at which concrete bridge decks can be evaluated [1]. Because data acquisition can occur at highway speeds, stationary traffic control is not necessary, the traveling public is not impacted, and inspection personnel are not exposed to live traffic. This promising approach has the potential to greatly reduce the cost and therefore increase the frequency of acoustic impact-echo testing in support of engineering decisions about bridge deck maintenance, rehabilitation, and replacement. Beyond applications to project-level bridge deck management, applications to network-level bridge deck management may also become possible as a result of this new technology.

Advanced signal processing algorithms have been developed for acquiring acoustic impact-echo and spatial positioning data at highway speeds and performing automated interpretation of the acoustic responses. In particular, the algorithms that differentiate intact concrete from delaminated concrete are critical for successful deployment of this technology. This paper will discuss development of the signal processing algorithms associated with classifying acoustic responses obtained during highway-speed impact-echo testing. These algorithms enable the use of low-cost microphones for measuring acoustic responses and dynamically account for changing measurement conditions. The process of creating feature vectors and then selecting thresholds in conjunction with acoustic responses will be presented. The algorithms run quickly on standard computing platforms to enable automated generation of impact-echo maps that can be overlaid on aerial bridge deck photographs for convenient visual analysis and interpretation by bridge engineers. Statistics such as the overall percentage of the interrogated bridge deck surface area that exhibits delamination can then be estimated from the generated maps. Because data can be acquired at high speeds and multiple passes can be conducted at relatively low cost, analysis of the sensitivity and repeatability of the scanning technique can also be performed.

Acknowledgement:

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References:

1. B. A. Mazzeo, and W. S. Guthrie. “Highway-Speed Acoustic Evaluation of Deteriorated Concrete Bridge Decks,” American Concrete Institute Convention, Detroit, March 27, 2017.
Implementing Statistical Analysis in Multi-Channel Acoustic Impact-Echo Testing of Concrete Bridge Decks

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The United States has over 600,000 bridges, approximately 40% being at least 50 years old. Because of internal corrosion of the reinforcing steel and its subsequent expansion, many concrete bridge decks exhibit delamination, or internal cracking in the concrete around the reinforcing steel. This cracking eventually leads to the formation of potholes that pose a major safety hazard, further accelerate bridge deck deterioration, and dramatically shorten the remaining service life of the bridge [1]. Bridges can be maintained and rehabilitated for a fraction of the cost of replacement, but because bridge maintenance and rehabilitation are still expensive, allocating limited budgetary resources in a rational manner using nondestructive evaluation techniques is important.

Although the most common method of detecting delaminations in concrete bridge decks involves manually dragging a large chain across the deck and listening for acoustic responses associated with delaminations, this type of manual chaining is inherently subjective and slow and frequently exposes inspectors to safety risks associated with working near live traffic. Instead, acoustic impact-echo testing with automated signal processing can be performed using a multi-channel impact-echo trailer, as reported in previous work [2]. Due to potential variation among the channels, changing conditions within the tested lanes, and imprecise field calibrations, a reliable data classification technique is needed to produce delamination maps that accurately reflect bridge deck conditions.

In this paper, a statistical approach to delamination detection is explored. The approach is based on the observation that variations in the acoustic responses of intact concrete and delaminated concrete can be used to identify delaminated areas. Based on this observation about the heterogeneity of the impacts, classification of delamination occurs through a multi-channel statistical analysis using Otsu’s method [3]. Application of this analysis to multiple sets of data yields apparent improvements in the accuracy of acoustic impact-echo results.

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References:

Determination of Mechanical Properties of Battery Films from Acoustic Resonances

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Measuring the mechanical properties of lithium-ion battery films, such as thickness and elasticity, is important for predicting and improving homogeneity of the films and subsequent performance of the battery [1]. Problems with film heterogeneity could be identified and addressed early on through accurate, non-destructive inspection of the electrode as it is being manufactured. There are several techniques currently used to measure the mechanical characteristics of films, including nanoindentation and laser-induced surface acoustic waves. However, their use for analyzing battery electrodes is fairly limited.

This research investigates the use of acoustic measurements as an alternative means of non-destructive quality control that could be adapted for on-line use. Here we report on our efforts to distinguish between films with different mechanical properties using acoustic resonances. A clamped film is excited using a pulsed infrared laser to produce an acoustic resonance in a confined area, and a microphone measures the acoustic response. Because the resonance depends on properties such as thickness and density [2], the resonance frequency shifts with changes in these properties. Figure 1 shows the resonance peaks of three battery films with different coating thicknesses. As the thickness increases, the resonance frequency decreases. These results show that acoustic tests can demonstrate observable differences between films with different properties.

Figure 1. Power spectral density of three battery films with different coating thicknesses.

Acknowledgement:

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References:

Deep sub-wavelength ultrasonic imaging

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There is much interest in improving the resolution of ultrasonic inspection, which suffers from large wavelengths typically in the range of millimeters, due to low value of speed of sound. The authors are interested in achieving this through holey metamaterial lenses (see ref. [1] for example). Previous work by our group has demonstrated an experimental subwavelength resolution of $\lambda/5$ [2]. This paper will discuss the optimization of the structural parameters of a holey structured meta-material lens to achieve a deep sub-wavelength resolution and imaging up to $\lambda/25$. The optimization is performed using numerical simulations and analysis of the physics of the wave propagation through the holey structured metalens.

Reference:
Vertical Electrical Impedance Evaluation of Asphalt Overlays on Concrete Bridge Decks

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Overlays are placed on concrete bridge decks to improve ride quality as well as prevent ingress of corrosive agents, such as de-icing salts. When overlays fail, they can allow leakage of corrosive agents to the internal steel reinforcement, which can result in non-visible corrosion of the steel and eventual failure of the bridge deck. While there are a variety of tools that have been developed for non-destructive evaluation of concrete bridge decks, such as sounding, infrared thermography, and half-cell potential [1], these techniques often fail when they are applied to concrete bridge decks that have overlays. In particular, asphalt overlays, because of their thickness, impermeable sealant layer, and substantially different modulus than the underlying concrete, limit the effectiveness of many of these non-destructive evaluation methods.

This paper presents the use of vertical electrical impedance measurements to non-destructively detect compromised areas of an asphalt overlay. Using a previously developed multichannel apparatus [2], vertical impedance measurements were obtained on 4 asphalt overlaid bridge decks. Collected impedance measurements were compared to surface cracking measurements, chloride concentrations measurements, and half-cell potential measurements obtained from the same 4 bridge decks. Results indicate that vertical impedance measurements are highly correlated with defects in asphalt overlays. Maps of this damage (Figure 1) can be presented to bridge deck managers to assess and address the deterioration. These results indicate that vertical impedance measurements can be used to quantitatively evaluate the cover protection offered to concrete bridge decks by asphalt overlays.

Figure 1. Vertical electrical impedance map from a scan of an asphalt overlaid bridge deck.

Acknowledgement:
This work was supported by Utah’s Department of Transportation and the U.S. Army Dugway Proving Ground.

References:
On the Usage of Ultrasound Computational Models for Decision Making Under Ambiguity

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Computer modeling and simulation is becoming pervasive within the nondestructive evaluation (NDE) industry as a convenient tool for designing and assessing inspection techniques. This raises a pressing need for developing quantitative techniques for demonstrating the validity and applicability of the computational models. Computational models provide deterministic results based on deterministic and well-defined input, or stochastic results based on inputs defined by probability distributions. However, computational models cannot account for the effects of personnel, procedures, and equipment, resulting in ambiguity about the efficacy of inspections based on guidance from computational models only. In addition ambiguity arises when model inputs, such as the representation of realistic cracks cannot be defined deterministically, probabilistically, or by intervals. In this work, we describe a framework that represents signals from both experiments and simulations as stochastic quantities. We use this framework to demonstrate the ability of computational models to represent field measurements for two cases: (1) all the model input parameters can be characterized by probability density functions; (2) some of the model input parameters are ambiguous and cannot be described by probability density functions. In particular, we consider the case of modeling branched cracks such as intergranular stress corrosion cracks, when the shape of the crack is poorly defined. Results show that computational models are capable of realistic representations when measurement conditions are ideal. However, one should be conservative in their use for decision-making under unknown field measurement noise, material variability, and crack morphology complexity.

Acknowledgement:

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Advances in Model-Based Software for Simulating Ultrasonic Immersion Inspections of Metal Components

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The use of models to simulate ultrasonic inspections has played a key role in R&D efforts for over 30 years. At Iowa State University’s Center for Nondestructive Evaluation (CNDE), such work began in earnest with the development of the Thompson-Gray measurement model which allowed the pulse/echo A-scan response from small reflector in a test specimen to be predicted from knowledge of: (1) the far-field scattering amplitude of the reflector; and (2) pertinent information about the inspection system being used, including the radiation pattern of the transducer and the measurement system efficiency function for the conversion of electrical energy into sound. Over the years, a series of wave propagation models, flaw response models, and microstructural backscatter models have been developed at CNDE to address inspection problems of interest. One use of the combined models is the estimation of signal-to-noise ratios (S/N) in circumstances where backscattered echoes from the microstructure (grain noise) act to mask sonic echoes from internal defects. Such S/N models have been used to address questions of inspection reliability, such as how to optimize the choices of transducer properties and inspection design to insure that critical defects are reliably detected.

Under the sponsorship of the National Science Foundation's Industry/University Cooperative Research Center at ISU, an effort was initiated in 2015 to repackage existing research-grade software into user friendly tools for the rapid estimation of S/N for ultrasonic inspections of metals. The software combines: (1) a Python-based graphical user interface (GUI) for specifying an inspection scenario and displaying results; and (2) a Fortran-based engine for computing defect signal and backscattered grain noise characteristics. The later makes use of several models including: the Multi-Gaussian Beam Model for computing sonic fields radiated by commercial transducers; the Thompson-Gray Model for the response from an internal defect; and the broadband Independent Scatterer Model for backscattered grain noise. The Stanke-Kino model is used for the computation of attenuation for equiaxed microstructures, with extensions to elongated grains made via correction factors computed using Yang-Lobkis-Rokhlin attenuation formulas. Methods pioneered by James H. Rose are used for computing microstructural backscatter coefficients.

This presentation provides an overview of the ongoing modeling effort, with emphasis on recent developments including the treatment of microstructures having elongated grains, and the ability to simulate ultrasonic B and C-scans. With some restrictions, the software can now treat both normal and oblique-incidence immersion inspections of curved metal components having microstructures in which grain size and shape vary with depth. Both longitudinal and shear-wave inspections are treated. The model transducer can either be planar, spherically-focused, or bi-cylindrically-focused. Defect types include flat-bottomed-hole (FBH) reference reflectors, and spherical pores and inclusions. Simulation outputs include estimated defect signal amplitudes, RMS grain noise amplitudes, and S/N ratios as functions of the depth of the defect within the metal component. At any particular depth, the user can view simulated A, B, and C-scans displaying the superimposed defect, grain-noise and electronic-noise waveforms. As will be demonstrated as part of this poster presentation, the software typically requires only a few seconds to complete a simulation when running on a typical laptop computer.
Analysis of parameters influencing Critically Refracted Longitudinal directivity

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Residual stresses can be generated during fabrication processes, such as, welding, rolling etc. They have obvious influence on the performance of the material, like cracking and corrosion. To better control residual stresses, the initial distribution of them in materials must be clear. The critically refracted longitudinal (LCR) wave is widely used for residual stress detection in recent years\cite{1-3}, for it is very sensitive to the possible stress and less sensitive to the texture of the material. Although LCR wave is widely applied, the factors that would influence LCR beam are seldom discussed. This article discussed transducers’ parameters that can make contribution to the directionality of LCR wave by numerical method, with the aim to acquire proper LCR wave direction for industrial application. Orthogonal test method\cite{4} is used to figure out which parameter influences LCR’s beam mostly. The simulation of sound field of 2D “water-steel” model is obtained by Spatial Fourier Analysis method\cite{5}. The angle, the length and the center frequency of the transducer are studied with Orthogonal method, the result show that the length and the center frequency of the transducer plays the most important function for the directivity of LCR. The center frequency of the transducer can influence the directivity of LCR wave is already well known, but the length of transducer can obviously influence the directivity of LCR wave is seldom discuss, which is very interesting. The results give a guidance for industry application.

Acknowledgment:

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Reference:
Re-inventing NDE as Science, or how student ideas will help to adapt NDE to the new ecosystem of science and technology

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Seeing the invisible, hearing the silence, looking into things without destroying – these are slogans for high technology of the 60th and 70th. The physics driven science has made significant progress in understanding the interaction of radiation and fields with matter. This allowed for seeing defects and measuring material properties without destroying, and/or even without touching from a distance. Revolutionary inventions have made, and instantly applied in the energy and transportation industries, for instance. NDT/NDE is still an indispensable job for technicians to increase the safety and extend the life of our industrial infrastructure.

Since then, scientist have worked hard to solve more difficult problems, to overcome the limitations in sensitivity and reliability, and to convert NDE from a detecting technique into a reliable measurement technique; however, this happened with only limited success and incremental innovation. An analysis of the papers submitted to the Journal of NDE in the last 24 months shows the limited degree of innovation in this area.

In the meantime, the priorities in sciences and technology have changed from understanding things to making things. The progress in genetics, biotechnology, microelectronics and 3D printing, for example, is breathtaking. Smart Robots with senses and the ability to make decisions, self-driving cars, artificial organs for humans, food, fuel, and materials from algae colonies are topics that get public attention. Portable, high-end computers in the hands of everyone (cellphones, tablets) to solve almost every problem and allow everyone to communicate with everyone in the world in real-time are highlights of today. This gets attention by the public and, with this, also comes research funding.

NDE has to find its new place in the ecosystem between biotechnology and the internet of things by identifying new challenges, and making technology available for everyone, not only highly-trained technicians. There are many technical solutions around and something could be purchased in a supermarket without noticing that this is NDE.

Equipping robots with senses to see into structures, making materials smart with sensing and actuation capabilities, NDE by unmanned vehicles in the air or the deep sea are new challenges; however, for instance, helping to solve all-day problems for everyone would be the future. Identifying leaks, measure corrosion damage, diagnose defect in cars by the emitted noise, measure paint quality and thickness, looking through walls, or analyzing materials; all this are questions that can be answered by NDE techniques and can today be made available for low costs for the brought public.

The author initiated in his NDE introductory class student projects where small groups of students had identify all day problems that can be solved by NDE techniques and suggest technical solution based on today’s technology what for example available with cellphones. The results where exiting.

After discussing the ecosystem and the present situation of NDE as science, several of these ideas will be presented. The winner of the competition of ides will present his ides during the following session. Let us listen to the ideas and needs of the young generation to re-invent NDE !!!
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 water types that are used for rinse of the parts prior to FPI inspection, along with a variety of conductivity levels within the various water types. It is believed that the conductivity level of the rinse water can have an adverse effect on the FPI process. To assess the effect of conductivity of the rinse water, this study examines the condition of regular city, or tap water verses deionized water, as well as the effects of different levels of conductivity within deionized water on FPI detection.
Increasing the probability of Sub-millimeter defect detection for Eddy Current Arrays.

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Eddy Current Array (ECA) systems are often used to generate C-scan type images, which can show the size, and location of any surface breaking, crack-like defects present. Most ECA systems work by a process which involves generating the eddy currents with one coil and measuring the induced voltage on one or more adjacent coils. Coils in an ECA are often multiplexed and the position of the array is encoded. A C-scan is generated, typically using the magnitude of the voltage induced on a detection coil.

Here we have used a two-coil probe to scan Stainless Steel and Titanium samples with varying defect sizes as small as 0.25mm in their surface length, to try and demonstrate a principle of using multiple measurements to improve the signal to noise ratio of a C-scan produced by the send-receive eddy current coil pair. In these experiments, we have measured the voltage across the driving coil as well as that induced in the detection coil. We have demonstrated that combining the magnitude and phase components of the measured voltages, can result in a significantly improved signal to noise ratio when scanning for very small defects.

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This work was performed with support from the EtherNDE Ltd, and the EPSRC funded UK Research Centre for Non-Destructive Evaluation, United Kingdom.
On the Possibility of Use of Fractional Order Derivatives to Eddy Current Non-Destructive Testing

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The fractional order derivatives and integrals are known since 1695 year when Leibniz and L'Hospital initiated the discussion aimed at calculus based on fractional order derivatives and integrals. For a long time, areas for applications of this calculus were not found. The lack of applications has been caused by difficulties referring to possibilities of clear physical and technical interpretation of fractional calculus formulae. Nowadays the number of papers using fractional order derivatives refer to electrical engineering (unfortunately, many among them contain severe errors). There exist several definitions for fractional order derivatives and integrals. The following are commonly used: Gruinvald-Letnikov, Caputo, Riemann-Liouville [1-5]. After choice, the useful definition the calculations must be done. On the beginning one should define the linear, fractional order elements of electric circuit used in non-destructive testing (i.e. elements applied for construction of the eddy current NDT transducer). The physical units attached to them depend on the order of derivatives. To avoid inconsistencies referring to Kirchhoff's laws the "dedicated" coefficients are introduced to formula describing each element. Then fractional order differential equations describing circuits are processed. By introducing of fractional derivatives to equations modeling operation of eddy currents diagnostic system one obtains additional possibilities in forming of resultant properties of system mathematical models. Those new "degrees of freedom" allow to tune the model parameters to make its operation highly accurate. As the essence of the proposed approach one can treat creation of circuits with desired frequency characteristics. Thus, one obtains theoretical standards (in form of fractional order differential equations and referring frequency characteristics) for designing of innovative diagnostic systems based on the eddy-current technique. Comparing these standards to frequency characteristics obtained during testing of faulty elements one can identify the defect parameters as well. The eddy currents testing is carried out in precisely defined range of frequencies. That is why the Ostaloup's approximation of fractional derivatives in frequency domain [6] has been used. The necessary elements of theory of fractional calculus and theory of eddy currents method using fractional derivatives of time are included to paper. The examples referring to multi-frequency eddy current testing system are also provided. The proposed approach can be used in case of other testing methods based on differential equations (e.g. ultrasonic testing).

References:
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Evaluation of Reinforced Concrete Structures Using the Electromagnetic Method

Tomasz Chady, Paweł Frankowski, Paweł Waszczuk and Adam Zieliński, West Pomeranian University of Technology, Piastów 17, Szczecin 70-310, Poland

Reinforced concrete has been a universally dominant construction material for over a century, although structures made of this material are often exposed to many types of damage and deterioration due to different causes and external conditions. The most important problem is corrosion of the reinforcement [1–3]. Currently, most of the inspection methods of rebars in a concrete are indirect nature or they are partially destructive. Moreover, none of the well know systems allows for direct and non-destructive evaluation of the rebar corrosion.

Due to the importance and relevance of the problem, the number of proposed solutions is relatively large and growing rapidly. However, all the methods have significant disadvantages. Many of the methods are used to examine a level of concrete carbonation, not directly progress of the corrosion. Such methods include: tests with the Schmidt sclerometer, tests with the Windsor's probe, chemical methods (e.g. the Rainbow Test), a half-cell potential method and a measurement of concrete resistivity. To the next group belongs methods, where the results interpretation is complicated, or there are extended hardware requirements. This group includes methods like: a radiography, ground-penetrating radars (GPR), an impact-echo (IE) method, an ultrasonic pulse velocity (UPV) method. The last group of methods were being mentioned in the literature as potentially useful, but due to many reasons they have not been implemented yet for industrial scale. To this group belong: a thermography, a vibration analysis, a measurement of magnetic field changes or an eddy current inspection.

The purpose of this paper is to present the new, direct and non-destructive method, which allows to detect cracks and corrosion of the reinforcement bars. Both cracks and corrosion lead to the loss of adhesion between reinforcing bars and concrete. The rusty steel bars are surrounded by iron oxides. The volume of the iron oxides is usually several times bigger than a volume of the steel, therefore it significantly insulates the rebars from the concrete. The main idea of the described method is to use transducer generating a magnetic field, which affects the rebars. The rebars respond is measured and utilized for the identification of the tested structure. Details of the method will be provided in the full paper.

References:
Utilizing Today’s Technology (i.e. smartphones) to Improve NDT

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During the class “Principles of Nondestructive Testing” in the spring semester of 2017 at Iowa State University the instructor initiated student projects where small groups of students had to identify all day problems that can be solved by NDE techniques and suggest a technical solution based on today’s technology, for example smartphones or tablet computers. In a competition for the best presentation, the following paper had been selected:

With an increasing demand for quality good in the modern era, non-destructive techniques are being used more and more. Unfortunately, many companies and academic researchers are more focused on utilizing the current physics of these techniques to collect what is considered “good” data instead of pushing for new uses or applications of NDE. Our goal as undergraduate students was to come up with innovative ways NDE will utilize the technology that is available in the modern era.

Our presentation examines the construction industry with an emphasis on bridges and how non-destructive evaluation techniques can be used to improve the field. In the present day, most bridges need to be inspected every six months for significant defects. The primary inspection technique is just to use visual inspection, which can leave many significant subsurface flaws undetected. With various non-destructive techniques, such as acoustic emission, ultrasonic testing, and eddy current testing, many critical flaws can be found with making bridges safer means of transportation. While detecting flaws is crucial, having a portable testing system is necessary to conduct these tests on an object as massive as a bridge. The idea behind the iNspect project is to create an application for a smart phone that is compatible with numerous NDE techniques and their respective equipment in order to create more effective tests that are convenient for inspectors. The easiness of the tests would allow for an environment where operators can conduct precise measurements and be able to replicate the results.
Concrete structures are subjected to various degradation mechanisms including alkali-silica reaction (ASR), freezing-thawing cycles and corrosion during their service life. Prolonged and repeated exposure to these mechanisms can cause distributed cracks in the structures. This paper reports work to characterize distributed cracks in concrete using multiple scattering behavior of ultrasonic surface waves. A series of numerical simulations are performed to understand surface wave scattering phenomenon caused by distributed cracks in concrete, distinguishing that caused by internal aggregate network (Fig. 1). The numerical simulation results reveal that incident surface waves undergo complicated multiple (random) scattering within the cracked region. A frequency-wavenumber (f-k) domain signal filtering approach is proposed to extract the randomly scattered wavefields set up by the aggregate network and distributed cracks. The analysis approach is then evaluated using a series of experiments on laboratory-scale concrete specimens. The experimental results demonstrate that distributed cracks in concrete can be successfully characterized where the crack density is closely related to the extracted scattered wavefield energy, and further that the scattered wavefield response from aggregates can be distinguished.

**Figure 1.** Numerical modeling of sound concrete: (a) shear wave velocity distribution of the physical domain of concrete and (b) absolute displacement field response at a time step.

**Acknowledgement:**

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Train track buckling and rail joint failures are some of the leading causes of train derailments. In both cases, the stress state of rail is a key parameter in defining derailment risk, where measuring longitudinal (axial) rail stress in particular is key. Past efforts to estimate longitudinal stress with nondestructive measurements have shown promise and demonstrated good performance in laboratory test environments, but have yet to be demonstrated to be broadly effective when applied in the field. Thus, new methods for monitoring longitudinal rail stress are needed. Impulse resonant vibration measurements offer great potential as a nondestructive means to monitor rail: vibration properties depend on geometry, structure, material properties and environment, including stress state. In this effort, we investigate the viability of using impulse vibration measurements to monitor stress state of continuously welded rail. As impulse vibration applied to the rail head generates many individual and separable vibration modes, each with unique properties, we propose to measure and identify special “indicator” modes that are especially sensitive to axial rail stress, but are insensitive to other confounding conditions such as rail support conditions and ambient rail temperature. Dynamic finite element (FE) analysis are carried out to understand the characteristics of the vibration modes in two different, but commonly used, geometries of commercial rail; both vertical stretch and transverse flexural families of vibration modes are considered. The results demonstrate that certain modes are sensitive to the axial stress state of the rail but less sensitive to the support conditions, for example the presence and type of underlying rail tie, and thus are good candidates for rail stress measurement. Experimental vibration data is collected from a full scale mounted rail sample, confirming the presence of the specific vibration modes predicted by the FE simulation and proving the ease of measurement. Based on these preliminary findings, an analysis approach to determine stress state of continuously welded rail without prior knowledge of conditions in situ is proposed.

Acknowledgement:

The work presented here is made possible by funding from the American Association of Railroads.
Active infrared thermography is increasingly used for nondestructive testing of various materials. Properties of this method are creating unique possibility to utilize it for inspection of composites. These materials are replacing traditionally used metal components and become a core of modern constructions. In the case of active thermography, an external energy source is usually used to induce a thermal contrast inside tested objects. Usually the conventional heating methods (like halogen lamps or flash lamps) are utilized for this purpose. In this study, we propose to use a cooling unit. The proposed system consists of a thermal imaging infrared camera, which is used to observe surface of the inspected specimen and a specially designed cooling unit with thermoelectric modules (Peltier modules). The photo of the cooling unit prototype is shown in Fig. 1. The entire system is portable and can be battery powered. Inspected elements are not exposed to elevated temperature and even during long tests will not be damaged. Additionally, the camera can be also cooled down, what results in lower noises of a detector. Preliminary test of the system was carried out with a glass fiber reinforced composite plate with artificial internal defects (holes manufactured in a single, internal layer of a fiberglass mat). The example of achieved thermograms is shown in Fig. 2. One can observe indications of the internal defects having diameter from 2 to 5 mm. Details of the proposed system and results of extended tests will be provided in the full paper.

Figure 1. Photo of the cooling unit prototype.

Figure 2. Example of thermogram obtained for the GFRP test sample with artificial internal defects having diameter from 2 to 5 mm.
Simulation tools for guided wave based Structural Health Monitoring at CEA LIST

Olivier Mesnil, Alexandre Imperiale, Edouard Demaldent, Vahan Baronian, and Bastien Chapuis, NDE department CEA LIST, Saclay, France

Structural Health Monitoring (SHM) is a thematic derived from Non Destructive Evaluation (NDE) based on the integration of sensors onto or into a structure in order to monitor its health without disturbing its regular operating cycle. Guided wave based SHM relies on the propagation of guided waves in plate-like or extruded structures. Using piezoelectric transducers to generate and receive guided waves is one of the most widely accepted paradigm due to the low cost and low weight of those sensors. A wide range of techniques for flaw detection based on the aforementioned setup is available in the literature but very few of these techniques have found industrial applications yet. A major difficulty comes from the sensitivity of guided waves to a substantial number of parameters such as the temperature or geometrical singularities, making guided wave measurement difficult to analyze.

In order to apply guided wave based SHM techniques to a wider spectrum of applications and to transfer those techniques to the industry, the CEA LIST develops novel numerical methods. These methods facilitate the evaluation of the robustness of SHM techniques for multiple applicative cases and ease the analysis of the influence of various parameters, such as sensors positioning or environmental conditions.

The first numerical tool is the guided wave module integrated to the commercial software CIVA, relying on a hybrid modal-finite element formulation to compute the guided wave response of perturbations (cavities, flaws...) in extruded structures of arbitrary cross section such as rails or pipes [1].

The second numerical tool is based on the spectral element method [2] and simulates guided waves in both isotropic (metals) and orthotropic (composites) plate-like structures. This tool is designed to match the widely accepted sparse piezoelectric transducer array SHM configuration in which each embedded sensor acts as both emitter and receiver of guided waves. This tool is under development and will be adapted to simulate complex real-life structures such as curved composite panels with stiffeners. This communication will present these different numerical tools and their main functionalities.

References:
Large concrete blocks of 1.5 m x 1.5 m x 0.3 m were damaged with different impact energy for evaluation of the integrity of buildings after collisions with aircraft or trucks. Complex crack fields were formed by the impact experiments. The cumulative crack lengths and the crack shapes were evaluated in 3D data sets of laminographic high energy X-ray measurements. Axial computed tomography measurements could not be performed since 1.5 m concrete could not be penetrated with the available high energy radiation of 7.5 MV. The laminographic inspection was based on coplanar linear scanning of source, object and detector (200 µm pixel pitch, 0.4 m x 0.4 m active area) in vertical and horizontal direction. The projections were stitched from measurements at different detector positions, which enabled the extension of the effective detection area (detector tiling). The effective detector area in horizontal direction was 160 cm x 40 cm and in vertical direction 40 cm x 120 cm. A special digital cross laminography method was developed obtaining high resolution volume data by combining the coplanar laminograms in horizontal and vertical direction. The reconstructed crack fields were segmented from background by threshold optimization. The obtained results are distorted by the typical structure of the concrete (cement and gravel) and the reinforcement. The cracks are interrupted and noisy. A template matching algorithm based on cross correlation of flat cuboid segments with the measured voxel data was used to improve the segmentation and evaluation of the crack fields.
Analytical modeling of the evolution of the nonlinearity parameter of sensitized stainless steel

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Austenitic stainless steels have a wide range of uses in the energy industry due in part to their corrosion resistance. However, these alloys are susceptible to sensitization – chromium diffusion to the grain boundary to form M23C6 carbides – when exposed to a certain range of high temperatures over a threshold period. The chromium-depleted zones locally adjacent to the grain boundaries are susceptible to stress corrosion cracking (SCC). Previous research has shown that nonlinear ultrasound is sensitive to the development of sensitization in welded 304 and 304L stainless steel (Figure 1). As carbide precipitates form at the grain boundaries, the equilibrium separation distance of grains increases. We propose an analytical model to predict the behavior of the nonlinearity parameter, $\beta$, in sensitized stainless steel in relation to the increase in grain boundary separation. We assume that the adhesion force between grains can be described by a Lennard-Jones potential, and utilize a second-order approximation of elastic constants to calculate the relative change in $\beta$ with increased precipitate growth. This model was compared to data from the experimental results of [1] and the predictive nature of this analytical model is demonstrated through comparison with existing data on carbide formation in stainless steel.

Figure 1: Normalized $\beta$ for increasing heat treatment at 675°C for annealed stainless steel 304 and 304L. [1]

Acknowledgement:

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References:
Introduction to Special Session on “Ultrasonic Transducers for Harsh Environments”

B. R. Tittmann, Session Chairman; Penn State University, University Park, PA 16802

Ultrasound offers measurements of parameters encountered in harsh environments such as steam generators, heat exchangers and nuclear reactors. But there is a lack of piezo-materials tolerant of high temperatures and irradiation. Field deployability is an issue with new materials and methods being proposed. This session is dedicated to presentations of progress towards devices and methods for ultrasound in harsh environments. Three of the presentations deal with new material candidates, two deal with phased arrays for guided waves and one with signal processing methods for in-situ creep specimen monitoring.

Pennsylvania State University was awarded an Advanced Test Reactor National Scientific User Facility (ATR NSUF) project to evaluate promising magnetostrictive and piezoelectric transducers in the Massachusetts Institute of Technology Research Reactor (MITR) for 18 months. The transducers experienced an integrated neutron fluence of about 8.68 E+20 n/cm^2 for n >1 MeV, temperatures over 420 °C, and a gamma fluence of 7.23 Gy/cm2. Three piezoelectrics were chosen with Aluminum Nitride (AlN), Zinc Oxide (ZnO), and Bismuth Titanate (BiTi) and two magnetostrictive transducers with Remendur and Galfenol as the active elements. Although most sensors performed well in this environment, it was not without some troubles. This is demonstrated and explained in the context of pulse-echo signals. Overall, this is the longest exposure experiment conducted to the researchers' knowledge on the chosen sensor materials and the first instrumented lead test for many of these materials. Thus, the potential usefulness of ultrasonic transducers in a nuclear reactor environment has been demonstrated.

One of the presentations discuss the use of AlN for the design of a one-dimensional phased array transducer. BiTi in powder form was selected as main ingredient for SolGel processing and was found to be a useful candidate for spray-on deposition. Three of the presentations elaborate on progress on the use of the Spray-on methods. Thus this Session presents a few steps forward in the progress toward ultrasonic transducers for harsh environments.
Detecting damage in storage tanks is performed commercially using a variety of techniques. The most commonly used inspection technologies are magnetic flux leakage (MFL), conventional ultrasonic testing (UT), and leak testing. MFL and UT typically involve manual or robotic scanning of a sensor along the metal surfaces to assess the integrity of the structure. For inspection of the tank bottom, however, the storage tank is commonly emptied to allow interior access for the inspection system. While there are costs associated with emptying a storage tank for inspection that can be justified in some scenarios, there are situations where emptying the tank is impractical. Robotic, submersible systems have been developed for inspecting these tanks, but there are some storage tanks whose contents are so hazardous that even the use of these systems is untenable. Thus, there is a need to develop an inspection strategy that does not require emptying the tank or insertion of the sensor system into the tank. This paper presents a guided wave system for inspecting the bottom of double-shelled storage tanks (DSTs), with the sensor located on the exterior side-wall of the vessel. The sensor used is an electromagnetic acoustic transducer (EMAT) that generates and receives shear-horizontal guided plate waves using magnetostriction principles. The system operates by scanning the sensor around the circumference of the storage tank and sending guided waves into the tank bottom at regular intervals. The data from multiple locations are processed together using the Synthetic Aperture Technique (SAFT) to create a color-mapped image of the vessel thickness changes. The target application of the system described is to inspect the DSTs located at the Hanford site, which are million-gallon vessels used to store nuclear waste. Other vessels whose exterior walls are accessible would also be candidates for inspection using the described approach. Experimental results are shown from tests on multiple mockups of the DSTs being used to develop the sensor system.
Automatic Non-destructive System for Quality Assurance of Welded Elements in the Aircraft Industry

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The manufacturing process and production standards are very restrictive during the fabrication of aircraft components. It is crucial to ensure the highest standards of safety and durability. This is important especially for critical components of the machines, which often are subjected to extreme operating conditions [1]. Contemporary inspection systems are mainly based on human controllers experience to detect flaws. For objective reasons mistakes might happen in the defect assessment and detection process. Proper estimation of geometrical parameters of the welded metal sheets, that are exploited in the aircraft is also essential for determining its future reliability. Due to mentioned reasons researchers form the West Pomeranian University of Technology in Szczecin in close cooperation with Pratt & Whitney Rzeszow S.A., developed an automated scanning system for welded metal elements, based on a 3D laser triangulation scanner. Developed non-destructive automatic system for quality assurance of welded elements in aircraft industry consisted of: (1) 3-D measurement sensor, (2) profilometer controller, (3) drive controller, (4) work station and (5) rotational platform. Control of the entire system, 3-D data acquisition and user interface were developed in LabView environment. The laser profilometer data is processed by specially designed software. The implemented algorithm is divided into stages. In the first stage the data is filtered and the welded joint is detected. The detection is based on a fitting technique using b-Spline curves. Due to the round shape of the inspected object, the weld geometry must be corrected and straighten to allow further analysis. After correction and weld location the jointed sheets of metal are detected and separated. It allows the sheet alignment parameters to be assessed. The alignment is calculated using a Singular Value Decomposition approach for plane fitting operations and then a 3D angle is then processed using the fitted plane coefficients. Finally, other parameters that help assess the quality of the joint are evaluated. The parameters are welds straightness – measured by the highest residue value form a fitted straight line, height and width uniformity – measured by the standard deviation of height and thickness. The parameters are then checked to determine if the part is up to a set benchmark standard. The developed non-destructive automatic system for quality assurance of welded elements in the aircraft industry is a useful and helpful tool in flaw detection. Its implementation helped to ensure the high standards of welded elements. The data gathered during the inspection process contributes to improvement of the components reliability. The used hardware devices and the developed software algorithms had given the possibility of expending the system’s capabilities, which is intended to be a next step in the nearest future.

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References:
We present preliminary results of the work on a project aimed at developing and demonstrating methods for transmission of information in nuclear facilities by acoustic means along existing in-place metal piping. Acoustic communication (AC) using guided elastic waves provides a capability to transmit information across boundaries, such as the containment building walls consisting of several feet-thick reinforced concrete. AC provides information transmission capability at a nuclear facility during an accident scenario, when the loss of electric power disables conventional communication channels.

After conducting review of common nuclear plant layouts, we have identified chemical volume control system (CVCS) austenitic stainless steel pipes as the most viable candidates as metallic information transmission pathways. The CVCS charging line pipes penetrating containment building walls are found in most nuclear plant designs. The CVCS pipes under consideration for AC are schedule 160 pipes with 3” diameter. In a working power plant, these pipes are typically covered with 2” to 4” mineral wool insulation. We presently consider AC characteristics of CVCS pipes without insulation, with insulation as the next level of complexity to be added later.

Initial research efforts have focused on identification of frequency bandwidth, which allows for signal reception after propagation along a straight section of a CVCS pipe for a distance of at least 5 feet. This is the minimal distance for information transmission through containment building wall. Signal transmission of using 500KHz piezoelectric transducers (PZT’s) has been investigated in preliminary studies. Using a simple system consisting of a waveform generator and power amplifier on the transmission side, a low-noise amplifier, a filter, and data acquisition system on the receiver side, signal transmission over 5-foot straight pipe section has been demonstrated. Performance of electromagnetic acoustic transducers (EMAT), which are more resilient to ionizing radiation compared to PZT’s, is currently under consideration.

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