Multi-Stage Damage Detection Method Based on Lamb Waves

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A multi-stage damage detection method based on Lamb waves is proposed for plate-like structures, which is not only for locating the damage position accurately, but also for determining the damage size precisely. Considering a layout of PZT wafers in a square grid arrangement, the multi-stage damage detection method is based on the same PZT layout to achieve the damage detection in multiple stages with improving accuracy. Firstly, an aluminum plate with a hole is identified numerically by finite element method based on the multi-stage method. After the group velocity of Lamb wave in an aluminum plate is obtained numerically by the time of flight (ToF) and cross-correlation method, the position and size of holed-damage can be assessed by the first stage detection. The second stage is carried through one more data obtained by the same layout of PZT wafers, and the size of hole can be estimated more precisely. The third stage only depends on the need of improving detection results of the second stage. Meanwhile, the influences of the detection area of the layout of PZT wafers with the diameter of the hole on the detection accuracy are discussed for the first stage, and an assessment is provided for how to choose the detection size of PZT layout and when to use the second stage detection. Secondly, an experimental verification is carried through the multi-stage detection method applied in an aluminum plate with a hole. Therefore, the proposed method based on PZT wafers can conduct a multi-stage damage detection in the same PZT layout, and it can reach to a more accurate assessment quantitatively without requiring more PZT wafers. It means our method is easily carried out and saving cost in damage detection of plate-like structures.

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References:

Correction of Reconstruction Artifacts Induced by Deflection of Linear-detectors

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Artifacts will be introduced into the reconstruction for fan-beam CT system if the central projection line is not perpendicular to the detector array, and the image quality will degrade consequently. In this study, the reasons for the formation of such artifacts are analyzed based on the classic filtered back projection algorithm, and a novel method is proposed to calculate the geometric parameters necessary based on sinogram features. The image quality can be improved obviously with these parameters embedded into the revised algorithm. The newly proposed method requires no correction phantom, thus avoiding the additional correction scan. Computer simulation and experimental results demonstrate that the method is easy, fast, and effective for practical utilization.

Fig.1 FBP reconstruction results with only COR correction (left) and the partial enlargement (right)

Fig.2 Reconstruction result using correction method proposed in this study left and the partial enlargement (right)

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References:

Acoustic Nonlinearity Parameter Due to Microstructural Defects

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Nonlinear ultrasonic techniques have been widely used for nondestructive evaluation (NDE) of damage induced by microstructural defects in polycrystalline materials. For quantitative NDE of such damage, it is necessary to develop models that relate the acoustic nonlinearity parameter (ANLP) with microstructural defects. In this study, we focus on three commonly observed microstructural defects, namely, partial dislocations, stacking faults and dislocation pile ups. By investigating how the wave motion interacts with these defects, analytical models are derived that relate the ANLP with defect characteristics, such as the Burgers vector, pinning length, separation distance, stacking fault energy, etc. These new models will not only enrich our understanding of wave-defect interactions, but also enable quantitative interpretation of nonlinear ultrasonic measurements.

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An Interpretation of Acoustic Nonlinearity of ASR-Affected Cement-Based Materials

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While nonlinear acoustic techniques show a significant sensitivity to the detection of alkali-silica reaction (ASR) damage, an interpretation of results based on the reaction chemistry does not exist. To provide better insights into ASR damage, this study combines the knowledge of cement-based materials and nonlinear acoustics to interpret the hysteresis nonlinearity measured by a nonlinear acoustic technique, nonlinear impact resonance acoustic spectroscopy (NIRAS). It is suggested that the early-stage increase of hysteresis nonlinearity (especially for mortars exposed to the accelerated mortar bar test) is mainly due to the dissolution of minerals at the interfacial transition zone region. However, at later ages due to mechanisms such as the increased viscosity and yield stress of gel caused by further polymerization of silicon and the dissolution of calcium, hysteresis nonlinearity decreases.
High frequency laser ultrasound, in the high Gigahertz regime, has been used to study ultrathin polymer films on the 1-10 nm scale [1]. We have been looking at thicker (100-1000nm) films where the properties are more like the bulk material. This has been achieved by depositing a thin film stack on top of a polymer layer. The thin film stack has a mechanical resonance which radiates narrowband elastic waves into the polymer film. These are reflected from the glass substrate and return to the transducer. The return phase leads to constructive or destructive interference changing the apparent frequency of the transducer. This change can be used to map the film thickness. We will present images of large areas of polymer thin films deposited by the spin coating method. We will discuss methods to determine the thickness and how this can be used to investigate thin film fabrication processes.

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References:
Metallic nano particles have interesting optical and mechanical properties which can be exploited to build nanoscale sensing systems. The optical properties are exploited in techniques such as Raman spectroscopy and localized surface plasmonic measurements. Our interest stems from the possibility of using nanostructures as sources and receivers of ultrasound. Their small size means they cannot be resolved optically, which means they cannot be imaged in optical microscopes, although some indirect information can be determined from their optical scattering. In this paper we show that by exciting and imaging GHz frequency vibrations in the particles they can be measured and imaged (in an optical microscope) at resolutions far higher than native optical resolution of the instrument. We will discuss the optical and mechanical properties of particles, the expected behavior as predicted by analytical and finite element models. We will show experimental validation of these models and discuss how the particles can be localized, used in experiments to enhance the resolution below the optical diffraction limit[1] and form the basis of sensing systems in the future.

![Time resolved signals and frequency content for different regions in the image, showing that a single optical object is actually two nano particles in close proximity.](image)

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**References:**

Non-Destructive Acoustic Imaging of Living Cells

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There is an emerging need to be able to measure properties of living cells in a nondestructive way so that these cells can then go on to grow and be used in therapeutics. Many existing techniques require the use of labels, such as fluorescent dyes, to see contrast in the cells. These dyes are either toxic or modify the long-term function of the cell so the cells cannot be used for other things.

We are developing an ultrasonic microscope capable of inspecting living cells, with good contrast and without the use of labels [1].

The microscope uses a specially designed transducer substrate to control the generation of sound waves, manage the thermal impact on the cells and efficiently pass the probe beam to allow integration of the acoustic waves.

We will present the technique, its capabilities and limitations, show images of various types of fixed and living cells, and discuss how this technique could be used in the future.

Imaging of live 3T3 cells with phonons. (a) Optical image of the scanned area. (b) Brillouin shift measured from (a) sampling every 1 μm, taking ~1.5 s per point and a total of 38 minutes total acquisition time

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References:
Selective laser melting (SLM) is an additive manufacturing technique used to build parts layer-by-layer by fusing metallic power. The parts can have complex geometries which cannot be made using traditional manufacturing methods. The fusion process is complex and hard to control, this leads to defects being present in the parts. To certify parts for operation in tough or safety critical environments every part must be inspected.

We are developing in-situ ultrasonic inspection techniques to assess build quality during the build process. This will allow smart fabrication where flaws can be found, then the build process can be stopped (saving time/money) or paused so that repair or reworking can be performed to correct the defect before the build continues. Laser ultrasound can be used to detected defects and to inspect the microstructure of the material [1]. Working on SLM material is challenging due to the high surface roughness. We will present results of a laser ultrasonic technique – spatially resolved acoustic spectroscopy (SRAS) – on as deposited material from a build chamber compatible instrument. We will discuss the possibilities for defect and microstructure control and the challenges remaining for online inspection.

Optical and acoustic velocity map from as deposited SLM sample obtained with SRAS.

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References:
A theoretical approach for guided waves in layered structures with applications in bone quantitative ultrasound

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Guided wave motions generated by a time-harmonic load in layered structures are computed by the use of reciprocity theorems. The calculation includes interface waves in two bonded half-spaces, Rayleigh-Lamb waves and Love waves in a layered half-space, and guided waves in a general multi-layered structure. Based on the reciprocity relations between an actual state, wave motion generated by a time-harmonic load, and a virtual state, an appropriately chosen free wave traveling in layered structures, scattered amplitudes of the guided waves due to the load are derived. Models for guided waves propagating in long bones are also studied in the current work. The obtained results are critical for exploring the potential of using ultrasound-based methods for long-bone characterization.

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Research on High Precision Measurement of Small Diameter Pipe Diameter with High Speed

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When the double-immersed ultrasonic probe is used to measure the outer diameter of the small-diameter pipe, there is an unmeasurable deviation between the rotation center of the probe and the axis of the tested pipe, and the self-axis of the probe group cannot completely coincide with each other, resulting in the measurement error of the outer diameter. The error exceeds the requirements of the small diameter pipe for nuclear industry. Through error analysis, we propose a new signal processing algorithm, which divides the exact period of the discrete interface echo sound path and calculates its confidence interval at each phase angle for series of periodic signals of calibration pipe. The discrete interface echo sound path and corresponding confidence interval are show in Figure 1. After that, using the same acquisition parameters measure the question pipe, and compared to the confidence intervals, to obtain the dimension difference between the question pipe and the calibration pipe with high precision. The algorithm does not require the high precision of the mechanical installation and improve the measurement accuracy of small diameter pipe to ± 4μm. The self-developed TESC-200 pipe high-speed inspection system at 4000RPM verify the effectiveness of the algorithm.

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Figure 1. Discrete interface echo sound path and its confidence interval.
This paper investigates collinear mixing of Lamb waves. The focus is on establishing the optimal relationship between the group velocities of the two primary waves that will yield the largest amplitude for the mixed wave under resonant mixing conditions. Since the energy of an elastic wave is transmitted with its group velocity, it is important to consider the relationship between group velocities in practical applications where pulses with finite length are often used. All possible combinations of backward and forward primary and mixing waves are considered in detail. The corresponding signal forms of generated mixing waves are predicted. Based on the studies, a set of necessary conditions are derived that must be satisfied by the pair of primary Lamb modes if they are to generate resonant mixing waves. Conditions are also derived for achieving the maximum amplitude for the mixed wave. Numerical experiments are conducted in Comsol to validate the theoretical analysis using two Lamb wave pulses. Outcomes of this study provide useful tools for designing tests for nondestructive evaluation of plates and pipes by using nonlinear Lamb waves.

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Figure 1 The coordinate system and sketch of Lamb wave propagating in infinite plate
Theoretical and Experimental Investigation on Interaction of Guided Lamb Wave with Disbond in Adhesively Bonded Joint

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Disbond in the adhesively bonded joints may lead to decrease of the interfacial strength of the joints. Guided Lamb wave-based approach was investigated in this research for the nondestructive evaluation of bonded aluminum-epoxy-aluminum joint. In this approach, Semi-analytical Finite Element (SAFE) \cite{1} analysis was performed firstly to obtain the dispersion curve of all the propagating and evanescent Lamb wave modes. Both the properties of multilayer geometry structures and viscoelastic material property of epoxy adhesive layer are included in the SAFE model. Secondly according to the stress and displacement continuity at the step transition of the disbonded area, the Normal Mode Expansion \cite{2} analysis was adopted to derive the magnitude of each reflected and transmitted guided wave mode when Lamb wave enters and exits the disbond area. It is discovered that under some mode-frequency combination, the incident wave energy, except the energy dissipation due to viscoelasticity, is fully transmitted through the disbond area (as shown in Figure 1a using incident mode 1 with frequency $< 1.5$ MHz for example). Nevertheless, in several mode-frequency combination regions (as shown in Figure 1b using incident mode 8 for example), the transmitted energy is distributed among several modes with different propagating velocities, leading to the decrease of signal amplitude or change of time-of-flight of transmitted wave packets. Angle beam ultrasonic transducer was used as transducer/sensor to generate/acquire ultrasonic waves in the experiment, whose results well validate the results from the numerical analyses.

![Figure 1](image_url)

\textbf{Figure 1.} Simulated energy transmission after disbond with incident (a) mode 1 and (b) mode 8".

References:

Research on Automatic Ultrasonic Identification of Leaking Fuel Rod

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Experiments are carried out on both intact rods and failed ones (wet sand in the tube), the Lamb wave energy will leak into the wet sand in the shell, and attenuate about 9dB. We analyzed the propagation path and echo travel time of Lamb wave, when the one piece pitch and catch probe through the gap of the fuel assembly. By comparing the A-scan signal and B-scans images of fuel rods before and after the leaking, the method of ultrasonic inspecting and data analyzing are determined, which can locate the failure fuel rod accurately and quickly without dismantling the fuel assemblies. According to the methods, two failure ones were successfully identified from 121 fuel assemblies during the first in-service inspection of Hainan Nuclear Power Station, and two of the leaking fuel rods were accurately located.

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![Figure 1. Lamb wave propagation through the intact fuel rods](image)

(a) Lamb wave propagation path           (b) B-scan and A-scans images of fuel rods

References:
A novel approach to guided wave motions in hollow cylinders with application to nondestructive evaluation

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Guided waves generated by time-harmonic sources in an elastic hollow cylinder are studied by the use of reciprocity theorems. In this approach, the reciprocity relations between the actual field, guided wave motions due to the sources and a virtual field, an appropriately chosen free wave traveling along cylinders, are found. It is shown in the current work that the far field displacements of guided wave modes are derived by a simple analytical approach. In particular, closed-form solutions of torsional waves in rods and pipes are obtained. Scattering of lowest guided wave modes by a surface defect is then considered. The principle motivation of the present investigation is to develop advanced methods for nondestructive evaluation of piping and tubing structures.

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Vibro-Acoustic Amplitude and Frequency Modulations during Fatigue Damage Evolution

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Vibro-Acoustic Modulation method (VAM) utilizes effect of the nonlinear interaction between higher frequency ultrasonic wave (carrier signal) and much lower frequency structural vibration (modulating signal). This interaction is taken place at the nonlinear interfaces (cracks, bolted connections, delaminations, etc.) manifesting itself in the spectrum as side-band components around the carrier. There are numerous studies applying VAM for nondestructive testing and structural health monitoring. Most of them utilize resonance structural bending vibrations as the modulating signal and measure a ratio of sideband to carrier spectral components defined as Modulation Index (MI). The present VAM study utilizes in-plane non-resonance very low frequency (10 Hz) tensile oscillations for monitoring fatigue and stress-corrosion damage evolution in steel. Experiments consistently demonstrated significant increase in MI during 70% – 80% of the fatigue life. Additionally, newly developed algorithm separates Amplitude and Frequency Modulations during the damage evolution demonstrating FM dominance at initial micro-crack growth stages and transition to AM dominance during macro-crack formation.

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Quantitative Performance Analysis of Ultrasonic Detection of Corrosion Rate Changes

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The cost of corrosion has been estimated to be several billion dollars/year to the USA alone. Numerous corrosion induced component failures have occurred in the past and they have caused devastating consequences. Industry spends much money on corrosion monitoring to improve safety and sustainability of assets. Compared to conventional methods such as weight loss measurements and electrochemical measurements, ultrasonic testing makes it possible to monitor corrosion online and in a non-intrusive way.

Corrosion rates are calculated from ultrasonic wall-thickness measurements by linear regression. The presence of measurement noise induces uncertainties in the rate estimates. In this paper the authors analyse data from a state-of-the-art ultrasonic corrosion monitoring setup with a thickness measurement repeatability between 20 and 40 nm \cite{1}. From the measurement data it is determined how quickly statistically significant changes in corrosion rate can be detected. It is shown that acidic corrosion of carbon steel that results in corrosion rates of several mm/year can be detected over a timeframe of approximately 10mins. Based on the underlying thickness measurement capabilities of the ultrasonic system it can be predicted how long it will take to detect different changes in corrosion rates. For small rates that are commonly reported to be of interest in real plant processes (i.e. 0.1 – 0.2 mm/year), the current system will detect the corrosion within 1 – 2 hours (see figure below).

![Figure 1. Detection times for different corrosion rates.](image)

References:
Automated Defect Detection for Fluorescent Penetrant Inspection using Machine Learning

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Fluorescent Penetrant Inspection (FPI) is a well-established NDE method used widely in the aerospace industry. Over 90% of metallic aerospace components receive at least one FPI during production. FPI involves applying a fluorescent dye to the surface of a component. The dye penetrates any surface breaking defects making them visible when excess dye has been removed. Whilst automated processing has been common in industry for a number of years, inspection is still performed manually meaning results are highly influenced by human factors. Our research has demonstrated that even with a small number of training examples, Machine Learning and Computer Vision Techniques, such as Random Forest, can be used successfully to perform automated defect detection on parts processed using FPI. We have produced results which demonstrate performance comparable to that of a human operator. The methods used are able to correctly identify defects, as small as 0.7mm, from dye associated with false indications, such as poor wash-off or geometrical indications, without an excessive number of false calls. In this talk, we will give an overview of the methods used so far before presenting results obtained from each, demonstrating the capabilities and limitations.
Composites laminates have been widely used in various industrial structures, such as aviation and aerospace vehicles, wind turbines, pressure vessels etc. During manufacturing processes and under working conditions, many types of damage may be generated in composite laminates inevitable. Although most of composite structures are designed by damage tolerance criterions, it is quite important to detect and evaluate these defects before catastrophe happens. Structural health monitoring (SHM) has attracted much attention for locating and evaluating damages to reduce the failure risk of structures. Many damage imaging methods have been proposed and improved by researchers, among which Lamb wave-based damage detection method is an efficient technology for composite laminates. However due to the dispersive and multimodal characters of Lamb wave, and the complexity of composite laminates, such as anisotropy and heterogeneity, most of the damage detection methods used for isotropy structure cannot be used directly for composite.

In this study, we proposed a novel phase reversal method (PRM) for damage detection in composite laminates. PRM is not affected by the anisotropy and dispersion of the composite, due to the phase spectrum is considered. In numerical analysis, Lamb wave was actuated into a composite laminate with an aperture, and the reflect waves from the crack were measured at different location. Then PRM was introduced for estimating the scattering wave. Then the damage index was defined as the magnitude of the superposed phase reversed signals. The result verifies the applicability and efficiency of PRM in damage imaging for composite laminates.

**Keywords**

Composite laminates, Damage imaging, Phase Reversal Method
Realistic Film Grain Noise Simulation in Industrial Radiography based on Microscopic and Spectral Investigations

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Before performing actual radiography in industry, output images are simulated to qualify NDT procedures as well as to assess and improve test setups with the aim to minimise cost and potential ionisation hazard [1]. For that purpose, it is crucial to simulate radiographic images as realistically as possible. To increase the validity of these simulations, authentic film noise modelling is an important feature because image noise influences the human detectability of visual signals such as defects: noise downgrades the defect visibility significantly. Hence, noise, being an important part of the final image, should be modelled realistically too.

In this talk, a model relying on experimental film noise data is presented. The basis of this data are light microscopic investigations of homogenously exposed and developed films. Film samples differentiating between various optical densities and magnifications were considered and spectral analyses were conducted. The resulting empiric database of spectral properties supports the simulation of realistic noise characterised by an accurate film graininess. Outstanding advantages of the new method compared with the state of the art will be highlighted such as the consideration of the correlation between noise and shadow image as well as internal correlation of the simulated noise, the fast generation of any number of unique noise samples and the exploitation of real film noise data. Application and validation of the new technique are undertaken within industrial radiography. It will be shown that noise generated by the presented method is visually not distinguishable from original noise. The novel noise generation method presented in this talk increases the validity of radiographic simulations hugely and therefore allows more realistic assessments of radiographic test setups.

Figure 1. Radiographic input image, optical density dependent segmentation areas and generated noise output image with detailed area indicated by frame.

References:
(022)

Why Industry 4.0 and Additive Manufacturing requires new approaches in NDE

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The term “Industry 4.0” describes a transformation process of industrial manufacturing covering organizational aspects like horizontal organization of production in (often regional) value networks, vertical integration of production in networked global manufacturing systems and end-to-end engineering of integrated products and services across the value chain and life cycle. Additive Manufacturing (AM), Artificial Intelligence (AI) and the Industrial Internet of Things (IIoT) are the most dominating technical innovations enabling this transformation.

An individualized customer-centric design and production at the same cost level as in traditional mass manufacturing is the promise of this approach. If the product or component is individualized by purpose, established quality tools like statistical process control, sample testing, probability-of-detection or Six Sigma do not work any longer. It provokes a paradigm change in quality management and non-destructive testing. The new paradigm of quality management in Industry 4.0 is covering aspects like:

- Tracking material data along the value chain (from raw material over processing to use in products and finally towards recycling)
- Component properties based on micro/meso and macro parameters are digitized and updated in digital models using simulation tools to draw conclusions
- Blending process parameters, material data, environmental data with non-destructive testing data generated and processed in real-time using machine learning and big data tools
- Including sensors for life time condition and structural health monitoring

This development is, on one hand, a unique chance to reposition non-destructive inspection methods as an approach to generated valuable data. On the other hand, speed, process integration, digitalization and automated processing + evaluation of data becomes more important than ever. Before Fraunhofer, IKTS is developing Industry 4.0 methods like AM or process monitoring with special focus on ceramic technologies and systems including advanced NDE methods. The presentation will include some recent results and new opportunities in this field.

References:
Projection of 2D Data Registration in 3D CAD Space for Rapid Automated NDE

Andrew Simms, Carl Magnuson, and David Forsyth; NDE Division, Texas Research Institute Austin Inc., Austin, Texas

As international space flight advances, there is a need for astronauts to perform NDE inspections independent from mission control on Earth due to communication constraints. These communication constraints include message data bandwidth limitations, signal travel time delay, and other delays due to planetary orbits. For example, rover communication between Mars and Earth is limited to a speed between 3,500 and 12,000 bits per second, is delayed by a 1.5 to 5 hour signal travel time, and is only available for at most 3 hours every day [1]. It is for these reasons that it is necessary for astronauts to use a rapid automated NDE tool to quickly and efficiently detect defects onboard a spacecraft or a space station that is far from Earth. The goal of this project is to increase the speed and efficiency of NDE by creating a projection of NDE data in 3D space. TRI Austin is using the three-dimensional surface geometry of a part and the prerecorded three-dimensional ray data, which contains the position and orientation of the ultrasonic transducer, to reconstruct the location of every A-scan in the inspection of objects with complex curvature. This information is generated in the scan plan for an inspection, but not typically saved or utilized. This registration process is a necessary step in data fusion. Now in 3D space, NDE data can be fused with other NDE data and metadata relevant to the inspection. For example, part geometry and materials properties can have a significant effect on NDE data. In the use case of a remote NDE operator with limited connectivity, previous inspections and metadata about the inspection subject can be fused with data from the new inspection to provide a better characterization of the subject. In a more typical use case not constrained by data bandwidth, tracking defect growth over time is a common NDE task that is eased by spatially registering data. The Digital Twin concept [2] requires NDE results registered to the part coordinate system for use in assessment of current and future structural integrity.

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References:

Application of the thermoelectric effect for monitoring over aging effects on Ti–6Al–4V alloy

Martín R. Barajas-Álvarez, Alberto Ruiz, Héctor Carreón, Víctor H. López

A research was conducted to study the effects of over aging on the thermoelectric coefficient of Ti–6Al–4V alloy. Bimodal microstructure containing fine precipitated particles were obtained by over aging a Ti–6Al–4V alloy plate of 12.7 mm thick. Over-aging heat treatment were conducted for 0.5, 1, 10, 50, 100, 200, 480 and 720 h at a holding temperature of 545 °C in different samples. Vickers microhardness and tension test were performed on unaged and over aged samples, respectively. Tension test show a decrease in the mechanical properties as aging time increases due to the precipitation of very fine $\alpha_2\text{Ti}_3\text{Al}$ particles. Thermoelectric power shows a gradual reduction as holding time increases from 0.5 h to 200 h. After 200 h the thermoelectric power starts to rapidly increase for aging times of 480 and 720 h. These data can provide useful information for future work related to thermoelectric properties of Ti–6Al–4V alloy.

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References:

Concrete structures are susceptible to multiple defects developing such as alkali-silica reaction (ASR) as they age and degrade. ASR is a reaction forming a gel that occurs over time between alkaline cement paste and reactive, noncrystalline silica in aggregates [1]. With the continuing extension of nuclear power plant’s life span, it is significant to monitor the structural integrity of concrete structures after 40+ years. Compression strength, modulus of elasticity, flexural stiffness, shear strength, and tensile strength are performance characteristics susceptible to the development of ASR. Current methods for monitoring for defects and degradation within thick concrete structures require damaging the concrete. Oak Ridge National Laboratory, in collaboration with the University of Pittsburgh, has developed a nondestructive evaluation (NDE) and reconstruction technique that enables deep image reconstruction of damaged concrete. Frequency-banded synthetic aperture focusing technique (F-SAFT) is an augmented SAFT reconstruction that segments the time-series data into different frequency bands using wavelets immediately before performing SAFT reconstructions [2]. This paper presents the NDE instrumentation and reconstruction techniques applied to thick-reinforced concrete structures and concludes with preliminary results.

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Figure 1. Reconstruction of Thick-Reinforced Concrete Structure.

References:

Better understanding of propagation and scattering of elastic waves in polycrystalline materials is very important for the field of non-destructive evaluation. Recent three-dimensional finite element (FEM) models [1, 2] have provided accurate representation of wave behaviour, but they were applicable to polycrystals with statistically equiaxed grains. This study aims to extend the modelling to microstructures with elongated grains and to evaluate the approximations of analytical models [3]. The study uses grain-scale spatial representation, in significant sample volumes of large numbers of grains, to describe polycrystalline materials. Different grain elongation ratios are adopted to investigate the grain elongation effect on the attenuation and dispersion of longitudinal plane waves. The evaluation and correction of numerical errors and statistical uncertainties are performed to overcome computational constraints and to achieve reliable results. To compare with the FEM modelling the accurate autocorrelation functions of the elongated microstructures are incorporated in the analytical models. An example of results (Figure 1) shows a significant directional difference in the attenuation between elongated and shortened directions. Good agreement between the analytical and numerical models is achieved.

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This work is supported by the China Scholarship Council and the Beijing Institute of Aeronautical Materials.

References:


In high temperature pipework the detection of creep damage is important to prevent catastrophic failure which may occur if creep cracks grow above a critical size. Current methods of non-destructively testing for creep damage can be either time consuming or difficult to apply in an industrial setting; there is a need for development of new or improved inspection techniques. Guided wave testing is a rapid long range inspection technique which is routinely used as a screening tool for defects such as corrosion in pipelines. Initial guided wave testing of pipes with suspected regions of creep damage has suggested that guided wave testing may be sensitive to creep damage. This was not initially expected as the scale of the individual creep pores is much smaller than the wavelength used in typical guided wave testing. In this presentation the geometry of creep voids in ex-service pipe samples is determined from macrographs of their cross section. In the long wavelength regime the effect of creep damage may be modeled as a change in the effective material properties of the pipe, which significantly reduces the computational complexity and allows the generation of full scale guided wave models. The effective properties of creep damaged material have been calculated by modeling the stiffness of a section of material with voids representative of the expected levels of creep damage. Utilizing finite element guided wave models the sensitivity of guided wave testing to localized regions of creep damage, modelled as a change in material properties, is then investigated.

Acknowledgement:

This work is funded through the EngD studentship program by the Research Centre for Non-Destructive Evaluation (RCNDE) and the Engineering and Physical Sciences Research Council (EPSRC). Additional support is provided by an industrial partner Guided Ultrasonics Ltd. (GUL). P. Huthwaite is funded on EPSRC fellowship EP/M020207/1.
Evaluating the use of the Failure Forecast Method for Improved Fatigue Remnant Life Predictions

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Michael Todd, Jacobs School of Engineering, University of California San Diego, California, United States

Remnant life predictions for engineering components subject to fatigue loading are vital for determining whether it is safe to continue operation, both during and beyond the original design life. Recent technological advances have made permanently installing sensors increasingly viable; the realization of frequent on-load measurements enables the monitoring of trends in damage growth rate, information that was previously unobtainable with infrequent periodic inspections. It is proposed that the rate of damage growth can be used to gauge the integrity of an engineering component and remnant life predictions can be made using the Failure Forecast Method [1], a methodology which makes use of the accumulation of data and does not rely on estimates of operating conditions or material properties. This study compares the accuracy of remnant life estimates using the ‘monitoring approach’ of near-continuous data interpreted using the Failure Forecast Method against the conventional ‘inspection approach’ of infrequent data sets interpreted in isolation using Paris’ Law. Statistical analysis using a set of fatigue crack growth test data as an example reveals that remnant life predictions made using the Failure Forecast Method has the potential to be significantly more accurate and less conservative compared to predictions made using information obtained with periodic inspections and nominally-known operating conditions.

References:
A comparative study on the accuracy of elastic micromechanical homogenisation methods in textured polycrystals

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⁴. Department of Earth Sciences, University of Cambridge, UK;
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In this talk, we present a comparative study on several elastic micromechanical homogenisation methods[1], about their accuracies in predicting elastic stiffness of polycrystalline materials with crystallographic texture (i.e. non-uniform crystal orientation distribution). Two well-established experimental techniques, namely neutron diffraction and the resonant ultrasound spectroscopy (RUS), are employed to obtain highly accurate texture information and elastic constants in industrial metal samples, which are made of hexagonal (titanium) and cubic materials (stainless steels) and possess orthotropic sample symmetry. The texture information is then input to classical homogenisation models - including Voigt-Reuss-Hill, Hashin-Shtrikman (H-S), and self-consistent - to predict the polycrystal elastic constants, as well as to the finite element method and a spherical convolution model to evaluate the directional variations of Young's modulus in 3D. These predictions are compared to the benchmarking RUS measurements, and the results suggest that for hexagonal materials, the Voigt-Reuss bounds are already very tight and give good estimations, while for cubic materials, the upper H-S bound most closely resembles the RUS results, and the simple Hill model is also reasonably close. The best performers for estimating the directional Young's modulus are the convolution model for hexagonal materials and H-S upper bound for cubic. Note that these studies concern the elastic behaviours in the static or low-frequency ranges. The findings point to a reliable and reasonably accurate way to evaluate the macroscopic elasticity from known texture for the studied material types, and they are put into practice with two industrial steel samples with no pre-known structural information. Their texture information is estimated from longitudinal ultrasound wave speed measurements [2], and elastic constants are calculated thereafter from the H-S bounds and verified against shear wave speed measurements.

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Scattering of torsional guided waves from small surface cracks in pipes

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Guided wave testing is widely used in pipeline inspection for the detection of relatively large corrosion defects in the order of several percent of the pipe cross-sectional area (CSA). Recent work has shown that permanently installed monitoring systems can reduce this to around 1% but need the incorporation of frequent data collection and baseline subtraction techniques. This suggests that guided wave monitoring might be applicable to crack detection, where critical crack size is likely to be <1% CSA. Crack growth rate monitoring using permanently installed sensors has been shown to be a promising method to predict failure time of components. Little work to date have been conducted on guided wave reflection from small cracks in thin-walled pipes (T<12mm). This paper looks at the amplitude reflection ratio of plane SH0 waves from small cracks. Through a finite element model, a torsional wave was generated to approximate plane SH0 wave incident on the surface crack in a pipe. Since the reflected signal was recorded at a point less than one pipe circumference away from the crack, the measured signal was similar to the scattered SH0 wave. Both analytical and numerical results show that the backscattered SH0 amplitude ratio, R, has power relationships to the incident wave frequency (f⁻¹.5), waveguide thickness (T⁻¹), sampling distance (r⁻⁰.⁵) and geometric mean of the crack surface area (a⁻³). In addition, R is shown to be dependent on the shape factor of the crack, where the maximum reflection being obtained when the crack length, c is approximately 3 times the crack depth, d. Numerical studies predicted that a 2mm x 4mm (depth x circumferential extent) plane crack located ~200mm away from the sensors will result in R=0.3% at a frequency of 100kHz. These numerical findings were validated experimentally and indicate that guided wave monitoring for relatively small cracks is a promising technology.

Acknowledgement:

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Figure 1. Scattering of the T(0,1) waves by a rectangular surface crack. The direction of the backscattered SH0 wave is shown with the arrow.
Validation of the performance of guided wave SHM systems is vital if they are to be widely deployed; testing the sensitivity of a system by introducing different types of damage at varying locations is very costly and cannot be performed on a system in operation. A performance validation methodology has recently been proposed involving the use of measurements on the structure in its initial state onto which defect reflections obtained from finite element (FE) simulations are superimposed. A blind trial was recently conducted in order to test the performance of an independent component analysis (ICA) based SHM algorithm for guided wave measurements of pipes. A number of defects were introduced into a pipe setup including welds and a 90 degree bend. The growth of three of the defects in the test pipe was replicated by superimposing synthetic defects, obtained from FE simulations of the damage, onto readings acquired during environmental cycling of the pipe prior to the introduction of damage. Very good agreement was observed between the results obtained using the purely experimental data collected during the blind trial and those obtained from the synthetic data sets, both corresponding well with the true defect growth. The results obtained during the investigation therefore validate the proposed performance prediction methodology. The methodology can take data from any installed monitoring system to predict its damage detection performance. This makes it possible, for example, to assess whether a defect of a given size at a particular location would be detected reliably at a given data collection frequency. This enables the system to be tuned to meet particular requirements and it could be used in a safety case to provide assurance that had a defect of a given size and location been present, it would have been detected.
Investigation of Ultrasonic Guided Wave Propagation in Rail Tracks based on Floquet-Bloch Theory

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Ultrasonic guided wave technology shows great potentials in the field of health monitoring and safety control of rail tracks due to the long-range capability and full cross-section coverage. However, widely practical applications have been hindered by the complicated signal integration due to the multimodal and dispersive nature. It is desirable to investigate the characteristics of wave propagation along the rail track in both free and prestressed states. In this study, we proposed Floquet-Bloch theory to analyze the dispersive characteristics of a standard rail with 56E1 profile. The dispersion curves of guided wave along a rail are obtained from the modal analysis. Then, three-dimensional finite element modelling is carried out to simulate the transient wave propagation along the same rail. Based on wavenumber-frequency analysis, the guided wave modes are separated and identified by comparing with the predicted dispersion curves. An effective ultrasonic guided wave mode along the rail web is identified and excited to investigate the wave-defect interaction. The direct relation between the reflection energy and the defect size demonstrates that such a guided wave mode is efficient to assess the integrity of the rail track.

Acknowledgement:

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Digitizing the MRB Process for Composite Aerospace Structures

Dr. Carl W. Magnuson (TRI Austin), David Forsyth (TRI Austin)

Nondestructive testing (NDT) has progressed in capability from handheld needle gauge instruments to fully robotic multiple axis sub millimeter positional control accompanied by sensor arrays and real time data processing and visualization. In addition, there are many recent advances in the modeling of NDT, forward and inverse, and the ability to predict the reliability of NDT and integrate it into risk assessment.

In this talk, we will show demonstrations of automated interpretation of data from NDT of composite aerospace components. Automated Defect Analysis (ADA) algorithms have been developed and tested on test specimens and production components. A complete inspection technique including the interaction of the inspector with the ADA has been developed, providing significant reduction in time to interpret large data sets.

We will also show how the ADA results can be mapped onto the part coordinate system. Now that the NDT data has become part of the “digital thread”, information from design and manufacturing can be accessed, and results from the automated analysis of NDT data can be directly imported into finite-element analysis (FEA) models. We will show an example of mapping manufacturing inspection data to the part coordinate system to model the effect of defects on structural performance. Digitizing the entire inspection and evaluation of structural performance will drastically speed the material review board (MRB) process.

Funding provided from AFRL under contracts FA8650-10-D-5210 Task Order 0011: “Automated NDE Analysis of Composite Ultrasonic Inspection Data for Manufacturing Quality Control” and FA8650-16-C-5701:”Digital Analysis of Defects for Critical Autoclave Components”.

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Surface-Breaking Flaw Detection in Ferritic Welds using Quantum Well Hall Effect Sensor Devices

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In this paper, the potential of using Quantum Well Hall Effect sensors for the electromagnetic NDE of metallic materials is demonstrated [1] [2]. An overview of the QWHE principles, the potential benefits QWHE sensors can provide for surface-breaking flaw detection and how they could be implemented into a practical NDE inspection system are discussed. An initial benchmarking study is also presented, quantitatively comparing the performance of established surface-breaking flaw NDE methods (magnetic particle testing, alternating current field measurement and eddy current) with prototype QWHE devices [3] [4] on a series of ferritic steel welded test-pieces with known flaws.

Acknowledgement:

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References:

Characterization by non-destructive magnetic technique of steam reformer tubes

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Abstract:
Heat resistant austenitic stainless steel tubes are commonly used in pyrolysis and steam reformer furnaces. These structures are exposed to high pressures and high temperatures, causing microstructural changes which lead on magnetic properties variations [1,2]. In this study, the microstructural changes have been measured based on their magnetic properties alterations, which took place on both regions of the tube, bulk thickness and external surface [2]. For this purpose, an eddy current testing (ECT) with external magnetization has been developed to characterize the samples. Thus, the ECT system was used to evaluate samples extracted from a steam reformer tube, exposed to temperatures ranging from 550°C to 950°C during 90,000 hours. Figure 1 shows the diagram of the developed eddy current system that was used to characterize the samples. The ECT system consist of a current generator to drive the probe, an amplifier and a data acquisition system to acquire the data with sampling rate of 1.2 MS/s. The probe consists of an excitation coil, and a Hall sensor is placed at the bottom axial center of the excitation coil in order to detect the magnetic field which is perpendicular to the surface of the sample. Two features, i.e. the amplitude and phase-shift, were used to analyze the experimental results to measure magnetic changes of the samples. Thus, by using this NDT technique, the magnetic influence of the external surface and the bulk were evaluated, which allow to classify samples with different microstructural conditions of steam reformer tubes.

Figure 1. Block diagram of the eddy current system.

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Quasi-DC Potential Drop Measurements for Materials Testing

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Potential drop measurements are well established for use in materials testing and are commonly used for crack growth and strain monitoring. Traditionally, the experimenter has a choice between employing direct current (DC) or alternating current (AC), both of which have strengths and limitations. DC measurements are afflicted by competing spurious DC signals and therefore require large measurement currents (10’s or 100’s of amps) to improve the signal to noise ratio, which in turn leads to significant resistive Joule heating. AC measurements have superior noise performance due to utilisation of phase-sensitive detection and a lower spectral noise density, but are subject to the skin effect and therefore not well-suited to ferritic materials. A quasi-DC monitoring system is presented which uses very low frequency (0.3-30 Hz) which combines the positive attributes of both DC and AC while mitigating the negatives. Bespoke equipment has been developed that is capable of low-noise measurements in the demanding quasi-DC regime; an overview of the system is described. The combination of the quasi-DC methodology and the specially designed electronics yields exceptionally low-noise measurements using typically 100-400 mA; at 400mA the quasi-DC system is shown to achieve a 13-fold improvement in signal to noise ratio compared to a 20A DC system. The reduction in measurement current from 400mA to 20A represents a ~3900 fold reduction in measurement power, effectively eliminating resistive heating and enabling much simpler experimental arrangements. Several example experiments are presented to illustrate the utilisation of the technique for materials testing.
The influence of static and dynamic magnetoelastic effects on low-frequency potential drop measurements

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Potential drop measurements are well established for use in materials testing and NDE applications. Utilizing low frequency AC for potential drop measurements is attractive as it provides superior noise performance and lower power measurements than DC. AC measurements are subject to the skin effect; the skin effect is dependent on magnetic permeability, which in ferrous materials is strongly dependent on elastic strain, so changes in applied load will influence measurements. In the very low frequency ‘quasi-DC’ regime, the skin effect is suppressed, yet as the frequency is increased the influence of the effect gradually begins to emerge. The sensitivity to applied load may either be considered to be providing useful information or acting to undermine stability. Studies into the influence of both static stresses and dynamic cyclic stresses are presented, encompassing background theory, finite element simulations and experimental results. Particular emphasis is placed on the rarely observed ‘magnetoelastic skin-effect’, which is distinct from the electromagnetic skin-effect; mechanically induced magnetisation becomes concentrated to the component surface during cyclic loading, which in turn influences the spatial distribution of magnetic permeability and therefore the potential drop measurements. Fatigue experiments are presented where the apparent resistance increases by over 10% due to the magnetoelastic skin effect, illustrating the importance. Developing an understanding of these phenomena provides a first step towards exploiting potential drop measurements for load monitoring or mitigating any undesired consequences.
Study on the Magnetic Nonlinear Mixing Frequency Technique and Its Application in Mechanical Properties Assessment

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Assessment of the mechanical properties is of high importance, both for safety and economical in the modern industrial. The majority of conventional non-destructive evaluation techniques are insensitive to the degradation in the microstructure of the metal. However, it is well known that the nonlinearity of magnetic hysteresis in ferromagnetic materials is completely depended on the material microstructure [1] and the mixing frequency method can precisely measure the nonlinear effect [2]. We investigate a new micromagnetic method that exploits the magnetic mixing frequency technique to induce the magnetic nonlinearity. Figure 1 shows a typical example of mixed B-H loop with a set of minor loops superposing on the saturation loop. Then, the minor loss coefficient and the magnetic nonlinear factor are used to characterize the mechanical properties of materials. An experiment result of case harden which assessed by the magnetic nonlinear factor is shown in Figure 2. Also, the magnetic nonlinear mixing frequency method was used to evaluate the fatigue damage of the steel. Compared to the traditional non-destructive evaluation methods, the studied method has an advantage in assessing the subtle changes in microstructural mechanical properties. It has the potential to be used as a non-destructive technique.

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References:
The monitoring of polycrystalline materials with large grains is made challenging by the presence of different orientations of principal axes of grains. The arising scattering increases the noise level and attenuates signals from defects, so the resulting signal-to-noise ratio (SNR) is often not good enough for the test to be viable. The SNR can be enhanced by scanning the specimen with multiple focused transducers at different depths. However, this is not practical for permanently installed monitoring systems where transducers are located at fixed positions. In this case, unfocused transducers are desirable because they enable large area coverage from a single transducer position. To get a satisfactory SNR with a permanently installed monitoring system, we need to find the optimal frequency and diameter of the unfocused transducers. In this study, a procedure of choosing the optimal transducers is presented. The independent-scatterer model [1] is used for grain noise prediction, the signals from a defect at one position are computed using finite element simulation and overall signal to noise maps for defects at different locations are produced via scaling the signals by squared particle velocity and scattering induced attenuation. Two possible optimisation criteria are given and the effects of anisotropy factor, defect size, transducer diameter and frequency on SNR are investigated. Finally, two representative examples are discussed. The main conclusions are: 1) if regions close to the top surface are to be monitored, a relatively high frequency is needed to limit the dead zone; 2) for highly scattering materials and large inspection depths, a low frequency is required and the depth range can be increased by increasing $D/\lambda$ at a cost of increasing the fractional surface area that must be covered with transducers; 3) a narrow depth range far from the surface can be monitored with 1-2% surface area covered with transducers, which has application in weld monitoring.

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References:
**Expected scattering of incident shear waves from 2D random rough surfaces using stochastic Kirchhoff theory**

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Analytical elastodynamic Kirchhoff formulae are derived using a stationary phase approach to analyze the stochastic scattering of shear waves from 2D rough surfaces. Shear waves are widely used in NDE inspections to detect rough cracks with higher sensitivity than longitudinal waves. The theoretical expected values are compared with results from Monte Carlo simulations and Finite Element models. Good agreement is found for a range of incident/scattering angles within the limits of the validity of the Kirchhoff approximation (KA) for the case of shear waves. Results for both single realizations and the full statistical simulations are compared with those for longitudinal wave incidence provided by [1,2]. It is found that shear-wave incidence brings novel effects to the stationary phase method for a KA surface, associated with the bounds on incident and mode-converted longitudinal wave angles. The importance of mode-converted surface waves is also discussed.

**Acknowledgement:**

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**References:**


Acoustoelastic Evaluation of Ultra-High Performance Concretes

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In the last decades ultra-high performance concretes (UHPC) have been successfully developed, which have superior mechanical, physical and chemical properties, allowing new designs and applications in Civil Engineering. Usually, a concrete with a compressive strength of over about 160 N/mm² is classified as an ultra-high performance concrete (UHPC). To reach the high strength and packing density, very fine aggregates and a low water-cement ratio are used. As a basis for nonlinear ultrasound applications and to analyze the micromechanical properties and damage processes in UHPC, the associated third order elastic constants (TOEC) are experimentally determined in this study [1]. To extract the nonlinear elastic constants, the relative velocity changes of longitudinal \( \frac{dV_2}{V_2^0} \) and shear acoustic waves \( \frac{dV_2}{V_2^0}, \frac{dV_3}{V_3^0} \) travelling through the samples are measured during uniaxial compression loading by a phase sensitive measurement system (RITEC RAM 5000 SNAP). As an example, Figure 1 shows the relative velocity changes for a UHPC-sample in relation to the applied stress fitted by linear regression. Additionally, third order elastic constants for high performance concretes (HPC) and steel samples are experimentally determined and compared with values reported in literature [2]. The results reflect the characteristic damage-free microstructures of the UHPC and show simultaneously typical properties of ordinary concretes.

![Relative velocity changes as a function of uniaxial pressure (UHPC-sample).](image)

Figure 1. Relative velocity changes as a function of uniaxial pressure (UHPC-sample).

References:


Keywords: Acoustoelasticity, Ultra-high performance concretes, Third order elastic constants, Ultrasonic waves, Micromechanics, Material nonlinearity
High-Frequency Nondestructive Hall Coefficient Measurements Using Inductive Sensing for Characterizing Shot-Peened IN718

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The authors have recently developed a new technique for nondestructive Hall coefficient measurement based on inductive sensing of the Hall-Corbino current produced by alternating current injected into the component under test [1]. This technique offers numerous advantages over conventional alternating current potential drop techniques allowing inspection at sufficiently high frequencies, such that the penetration of both the injected primary current and the secondary Hall-Corbino current is limited by the electromagnetic skin depth. In this study, we investigated the feasibility of characterizing shot-peened fully hardened IN718 based on inductive Hall impedance measurements. The nondestructively measurable physical property (Hall coefficient and electric conductivity) profiles were estimated from the destructively (XRD) measured elastic strain (residual stress) and plastic strain (cold work) profiles available in the open literature. The estimations were based on gauge factors obtained in previous studies where the influences of residual stress and cold work on the electrical conductivity and Hall coefficient of fully hardened IN718 were established. The estimated Hall coefficient and electrical conductivity profiles were used to numerically calculate, using finite element simulations, the change in the inductively sensed Hall impedance due to different levels of shot-peening over a wide frequency range. The results from these simulations indicate that the electromagnetic field produced by the Hall-Corbino current is evanescent around the injection electrodes, therefore the inductively measured Hall impedance exhibits a significant change in shot-peened components at a much lower frequency than expected based on the electromagnetic skin effect. Preliminary data obtained with the current Hall coefficient measurement system between 300 kHz and 30 MHz on fully hardened IN718 coupons surface treated to four different shot-peening levels of 4A, 8A, 12A and 16A Almen intensity shows reasonable agreement with estimations based on XRD results available from earlier published studies.

Acknowledgement:

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References:

Characterisation of EDM notch and fatigue crack using ultrasonic arrays

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Using ultrasonic arrays to detect and characterise surface breaking cracks (SBCs) is very important in the Nondestructive evaluation (NDE) field. Typically, SBCs are approximated by machined slots and used to examine and assess defect detection and characterisation methods. In this paper, real SBCs are fabricated and used to examine the performance of defect detection and characterisation using the full matrix capture (FMC) and total focusing method (TFM) [1]. In the SBC fabrication process, a single edge notch beam (SENB) aluminum specimen is first made following ASTM standard E1820 and an EDM starter notch is made at the middle of the specimen. A fatigue crack is then propagated from the end of the EDM starter notch by subjecting the specimen to 3-point bending. The specimens are finally machined to remove the EDM notch and only leave the fatigue crack. Using this method, a range of SBCs with different sizes are manufactured and used to examine the performance of the FMC and TFM for SBCs detection and characterisation. For the SBCs with a size greater than 2 wavelengths, the image features from crack tip and corner echo are used to measure the size and this is termed the image based sizing method [2]. After assessing on real fatigue crack, an EDM notch with equivalent depth measured by above-mentioned technique are added on the same specimen for assessment comparing. The results show that the tip echo from a fatigue crack is 16dB weaker than the tip of an EDM notch. A fatigue crack also tends to be influenced by crack opening and closure condition.

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Figure 1. Ultrasonic array FMC/TFM image on real fatigue crack and EDM notch.

References:
Ultrasonic Characterization of Polymer Matrix Composite Impact Delamination Field

J. T. Welter, J. C. Aldrin, J. N. Wertz, D. Zainey, V. Kramb,

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Computational Tools, Gurney IL
University of Dayton Research Institute, Dayton OH

Characterization of delamination fields in 3D for impact damaged composites is necessary to achieve the USAF objective of damage tolerance for polymer matrix composites. A review of the literature shows that these fields exhibit a range of 3D morphologies. The most common ones observed in the literature can be generalized as ‘cone’, ‘inverted cone’ and ‘diamond’ shaped when viewed in a 2D cross-section. Results of an extensive literature review of delamination morphology will be provided. Oblique angle pulse echo ultrasound inspection has been hypothesized as a potential technique to address this nondestructive characterization need, and modeling results presented last year support this hypothesis. Experimental results will be presented showing that the received signals are much lower than predicted by the idealized model, and lower than could reasonably be detected without a priori knowledge of the delamination field. An alternative to oblique angle pulse echo ultrasound inspection will be illustrated. Initial results, and a discussion of remaining challenges will be presented.

Acknowledgements:

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Assessment of Systematic and Random Errors of Time Of Flight Diffraction Defect Sizing

John Jian, Alan Stansfield, Darren Chapman, Inspection Group, Nuclear Generation, EDF Energy, Gloucester, UK

Time Of Flight Diffraction (TOFD) has been widely used for defect sizing and it is believed that its sizing accuracy is better than that for conventional pulse echo techniques if it is used properly, and a good signal to noise ratio achieved \[1, 2\]. Commercially available TOFD systems assume a constant probe index point for the lateral wave, the back wall echo and indication signals. There are associated systematic errors, and calculation shows that index points for different signals vary, and this is a source of systematic errors that needs to be assessed.

In this paper, a way to assess random errors and systematic errors for various TOFD calibration techniques and for both curved and flat inspection surfaces has been studied. A tool has been developed and verified, which allows for rapid error assessment and aids in the optimization of the measurement setup. Experimental trials have been completed and inputs of essential parameters to the tool have been determined. Analysis has been performed using the tool and best practices have been established.

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Guided Wave Inspection of a Complicated Component

John Jian, Alan Stansfield, Darren Chapman, Inspection Group, Nuclear Generation, EDF Energy, Gloucester, UK

Hartlepool and Heysham 1 Advanced Gas-cooled Reactor (AGR) power stations in the UK contain boilers of a unique ‘pod’ design. There are 32 pod boilers and each has a spine with lots of attachments along its length, and a big section change mid-length. Access to the spine for inspection is restricted to the top 2 meters and conventional guided wave technique has been applied to boiler spine inspections since 2003, predominantly using the torsional guided wave mode T(0,1). Compared to guided wave inspection of oil pipelines, whose structures are simple and generally straight, the boiler spine guided wave response is very complicated and very challenging. Site inspection responses across the 32 spines are quite individual, although they were manufactured to the same drawing. Some spines have weak signal from the mid-section change and some spines have weak signals that are reflected from the spine end. It has been observed over several years that there is a high degree of variability in the guided wave responses for some spines.

A signal processing technique has been developed and has been applied to process historic site inspection data on the 32 boiler spines. Two major reflections are expected from the section change at the middle of the spine (known as the 12.3 region) and from the far end of the spine. With the new technique, the signal to noise ratios and variability of signal amplitude and temporal profile have been reduced greatly for these two signals. This has led to an enhanced defect detection capability to support the return to service safety case. Figure 1 shows some results from the new technique for comparison with the torsion mode, and Table 1 shows the improved signal to noise ratios obtained with the new technique compared with the conventional method.

Table 1 Comparison of results of new technique with current technique

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<td>9.8</td>
</tr>
<tr>
<td>SNR @12.3 - EDF</td>
<td>15.0</td>
<td>11.5</td>
<td>4.9</td>
<td>8.6</td>
<td>7.6</td>
<td>9.1</td>
<td>6.5</td>
</tr>
<tr>
<td>SNR @end - EDF</td>
<td>18.4</td>
<td>7.2</td>
<td>7.3</td>
<td>2.6</td>
<td>4.3</td>
<td>8.5</td>
<td>7.8</td>
</tr>
</tbody>
</table>

Figure 1 Guided wave inspections on HRA 2A1. Left: Torsion mode; right: new technique.

References:
Flexible wedge phased array transducers, recent development and innovation

P. Dumas, S. Oster, A. Membre, L. Fournier, Imasonic rue des savourots, 70190 Voray sur l’Ognon, France

Since several years Imasonic is investigating the concept of phased array transducer with flexible wedge, for various industrial applications. Result obtained with the first generation of these transducers has been presented at QNDE 2016. This concept improves the quality of the coupling for components with complex or variable geometry, and in some cases, makes it possible to do certain inspections that currently have no solution.

A new generation of these probes has been developed, more compact, more resistant, compatible with different kind of phased array probes.

This article presents the recent developments and results obtained, in particular:

- Development of new flexible membranes
- Evaluation of acoustic performances and mechanical resistance
- Implementation of an air bubble trap system
- Development of mechanical support dedicated to manual or automated use
- Manufacturing of compact, integrated versions, with fast membrane replacement system

The detailed results will be presented, as well as the possibilities for the future developments.
Super Resolution Array Imaging for the Inspection of Embedded Rough 2D & 3D Defects

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Ultrasound Non-Destructive Evaluation (NDE) plays a crucial role in the accurate detection and characterisation of defects. There is a constant drive within the nuclear industry to improve upon the characterisation capabilities of current techniques in order to improve safety and reduce costs. Particular emphasis has been placed on the ability to characterise very small defects which could result in extended component lifespan and help to reduce the frequency of in-service inspections.

Significant research has been focused on ultrasonic array imaging techniques which utilise full-matrix capture (FMC) data sets, such as the Total Focussing Method (TFM), to characterise defects. Super Resolution (SR) algorithms, also known as sampling methods, are a new family of imaging algorithms, which also use FMC data. These algorithms have been shown to demonstrate the capability to resolve scatterers separated by less than the diffraction limit when deployed in NDE inspection scenarios.

The majority of work to date on SR algorithms has focused on idealised cases with defects with simplified geometries. Realistic defects, however, can be far from simple. One of the major challenges facing the characterisation of defects is that of roughness. All real defects exhibit some degree of roughness. It has been shown that the extent of roughness can significantly impact the scattered field from a defect and hinder accurate sizing using conventional techniques. The work presented here aims to investigate the capabilities of a range of SR imaging algorithms in characterising rough defects, whilst comparing their performance to conventional TFM. Ultrasonic array inspection has been simulated using both full 2D Finite Element (FE) analysis and 3D hybrid-FE modelling for a range of defect sizes, orientations and extent of roughness. A Monte Carlo approach has been applied for the 2D cases to allow statistically significant conclusions to be drawn. The effect of introducing a third dimension to the roughness on the capabilities of the imaging algorithms was then investigated and the findings compared to the 2D results.

Acknowledgement:

The work is funded by EPSRC through an EngD studentship from the Research Centre for Non Destructive Evaluation and supported by Rolls-Royce plc. Additional funding for the EngD project is provided through the Royal Commission for the Exhibition of 1851 Industrial Fellowship programme.
High speed and high accuracy inspection technique for heat exchanger tube of carbon steel

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In the chemical plant, many carbon steel heat exchangers using cooling water (freshwater) are installed, but pitting corrosion occurs from the cooling water side of the heat transfer tubes, and finally it penetrates and leaks (see fig.1). In order to suppress this, it is important to adequately manage the thickness of the carbon steel heat transfer tubes in addition to various measures at the design stage and operation stage. IRIS (Internal Rotary Inspection System) has become a major maintenance inspection technique for the heat exchanger tubes. It is known that IRIS has a high precision of evaluation thickness, however there are a few disadvantages, such as slow inspection speed. Therefore, we have developed a new inspection technique based on new concept called Magnetic Flux Resistance (MFR) to achieve high speed and high accuracy inspection for carbon steel tube. Table.1 shows comparison result of characteristics of IRIS, RFECT (Remote Field Eddy Current Testing), MFL (Magnetic Flux Leakage) and MFR. MFR is expected as a most useful inspection technique for heat exchanger tube of carbon steel.

- High wall thickness measurement accuracy is ensured. (+/- 0.2mm)
- High speed inspection is possible. (500 tubes or more a day)
- Inspection of pipes with outer diameter of 19.05 mm or more is possible.
- Even if the scale remains on inner surface of tube, it does not affect the measurement accuracy.
- No medium like water is necessary to measure.
- It is possible to inspect with full number or high extraction rate.

Table 1. Characteristics of MFR

<table>
<thead>
<tr>
<th>Method</th>
<th>IRIS</th>
<th>MFL</th>
<th>RFECT</th>
<th>MFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement principle</td>
<td>Ultrasonic</td>
<td>Magnetic Flux Leakage</td>
<td>Eddy Current</td>
<td>Magnetic Flux Resistance</td>
</tr>
<tr>
<td>Accuracy</td>
<td>±0.1mm</td>
<td>×</td>
<td>×</td>
<td>±0.2mm</td>
</tr>
<tr>
<td>Speed</td>
<td>100 tube/day</td>
<td>500 tube/day</td>
<td>500 tube/day</td>
<td>500 tube/day</td>
</tr>
<tr>
<td>Small DIA tube</td>
<td>≤ φ19.05</td>
<td>≤ φ19.05</td>
<td>≤ φ19.05</td>
<td>≥ φ19.05</td>
</tr>
<tr>
<td>Influence of scale</td>
<td>Inspection impossible</td>
<td>Reduced accuracy</td>
<td>Reduced accuracy</td>
<td>Ensured accuracy</td>
</tr>
<tr>
<td>Medium</td>
<td>Water</td>
<td>Unnecessary</td>
<td>Unnecessary</td>
<td>Unnecessary</td>
</tr>
<tr>
<td>Remarks</td>
<td>Low sampling rate</td>
<td>Screening inspection</td>
<td>Screening inspection</td>
<td>100% inspection: High sampling rate</td>
</tr>
</tbody>
</table>

Fig.1 Typical corrosion of carbon steel tubes in cooling water service
Laser induced ultrasonic phased array inspection of complex-shaped component with adaptive total focusing method

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³SMRT Trains Pte Ltd, Singapore

There has been an increasing interest to inspect components with complex geometries. A few strategies have been developed, including flexible transducer array, comfortable wedge, etc. In these approaches, the surface profile of the component is constructed by the ultrasonic, optic or mechanical measurements, and is then used to obtain the correct delay law for ultrasonic array imaging. However, most of these approaches required direct access to the complex surface, while there are lots of scenarios where the existing coupling mechanisms cannot be applied such as hazardous environments. Therefore, the inspection needs to be carried out remotely.

For remote inspection, laser ultrasound has its advantage due to its non-contact feature. More recently, laser ultrasonic technique has been combined with phased array techniques and Total Focusing Method (TFM) to image internal flaws remotely [1]. In this work, such method is further developed for complex surfaced component using multiple ultrasonic wave modes generated by laser. A laser induced phased array is applied on the specimen and full matrix data is captured. The Rayleigh wave, with the energy creeping along the surface, is used for the surface profiling, and bulk waves are used for the TFM imaging based on the obtained surface profile. Finite Element simulations and experiments are designed on an aluminum sample with sinusoidal front surface and side-drilled through-holes (SDHs), illustrating the imaging procedure. The good agreement between numerical and experimental TFM images proves the proposed concept of laser induced phased array inspection for specimens with complex-shaped geometries. The approach presented in this study can also be exploited in other online or in-service scenarios where conventional ultrasonic phased array inspection cannot be applied, such as coating quality evaluation in fabrication and online monitoring of additive manufacturing.

Acknowledgement:

This research work was conducted in the SMRT-NTU Smart Urban Rail Corporate Laboratory with funding support from the National Research Foundation (NRF), SMRT and Nanyang Technological University; under the Corp Lab@University Scheme.

References:

Finite Difference Simulation of Ultrasonic Waves for Complex Composite Laminates

Erik Frankforter, National Institute of Aerospace, Hampton, VA, United States
Cara Leckey, NASA Langley Research Center, Hampton, VA, United States

The development of ultrasonic nondestructive evaluation (NDE) simulation tools has the potential to reduce both individual part inspection time and overall certification time for composite parts and structures. This reduction may be enabled by providing simulation-based inspection guidance and increased confidence in the veracity of inspection results. To this end, this paper outlines ongoing work in the development and application of a finite difference simulation approach which can be applied to composite structures with realistic geometries. A Lebedev finite difference scheme is being used, as it has been shown to produce stable results at boundaries in triclinic media, which has been identified as a challenge for some methods [1]. In this work, the Lebedev finite difference scheme is applied to curved and geometrically complex composites. Special attention is paid to material interface conditions during the application of a heterogeneous finite difference scheme, where the same finite difference approximations are employed at both interfaces and bulk media. It was found that the application of a conservation-based method for specifying elastic parameters [2] at interfaces became increasingly important as the apparent degree of anisotropy increased, as seen in geometrically complex composite parts. A modeling framework for moving towards realistic complex parts is discussed along with initial results.

Acknowledgement:

No funding acknowledgement for this paper

References:

Acoustoelasticity of additively manufactured stainless steel

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Acoustoelasticity describes the relationship between stresses in an elastic body and the small-amplitude elastic wave speeds within the stressed body. This relationship is manifest in the nonlinear material behavior that occurs when an elastic body contains an initial stress state. Thus, measurement of the wave speeds provide insight into the nonlinearity of the material, namely the so-called third-order elastic constants (TOECs) [1]. In this presentation, we report preliminary TOEC measurements of powder bed fusion additively manufactured (AM) samples using the acoustoelastic technique. Experimental details of longitudinal and shear wave speed measurements will be provided. This initial study seeks to quantify the differences in the magnitudes and anisotropy of the TOECs between AM and traditionally manufactured samples. Lastly, the wave speed results are compared against a micromechanical based homogenization model [2] in order to establish the model’s applicability to AM samples.

Figure 1. Acoustoelastic effect showing the stress dependence of longitudinal and shear wave speeds as a function of uniaxial stress. Results obtained from model predictions [1].

References:
Towards Quantitative Characterization of 3D Morphology of Impact Damage in Polymer Matrix Composites for Ground Truth Representation

Michael D. Uchic¹, Sarah M. Wallentine¹, Daniel M. Sparkman¹, Sean P. Donegan¹, Josiah M. Dierken², Norman D. Schehl², David A. Zainey²
¹Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson AFB, OH 45433
²University of Dayton Research Institute, Dayton, OH

Quantitative nondestructive characterization of the 3D morphology of delaminations and matrix cracks generated from impact damage in polymer matrix composites (PMCs) is a problem of current interest for AFRL. For example, AFRL research efforts have explored the use of both normal and oblique angle ultrasound testing to quantitatively measure the volumetric shape of delamination substructures under representative impact loading, and selected results have been presented at QNDE over the past few years.

For any quantitative characterization study, obtaining a ground truth representation through independent methods is an essential step in error estimation. A previous study by some of the authors at QNDE 2017 demonstrated the use of an automated serial sectioning system to characterize impact damage in laminate PMC plates and provided an initial qualitative comparison between the destructive serial sectioning and traditional ultrasonic NDE characterization methods. While serial sectioning is inherently destructive, the previous study showed that modern systems are capable of providing an unrivaled combination of resolution and volumetric coverage, i.e., micrometer resolution for impact damage that spanned over 18 mm in width. The use of high resolution optical imaging enables robust computer-automated image segmentation and classification of the micrometer-thick delaminations that can span many millimeters. However, due to time constraints only a limited portion (~ 5%) of the impact-damaged region was characterized in this previous study.

This presentation will discuss the findings from a follow-on ground truth characterization effort that characterized the entire volume associated with a low-energy (< 5 Joules) impact-damage site via normal-incident pulse-echo ultrasound, X-ray computed tomography, and automated serial sectioning. The experimental and digital workflow to transform samples into a volumetric representations will be discussed. In addition, an analysis of the damage structure, as well as methods to mesh realistic damage representations for image based modeling will be presented.

Acknowledgements:

Portions of this work are funded by U.S. Air Force contract FA8650-14-D-5224 (UDRI).
A low power miniaturized ultrasound system using spread spectrum technology

Paul Gammell, Gammell Applied Technologies, Exmore, Virginia

Commercial Time Delay Spectrometry (TDS) systems have been used for decades in audio acoustics\(^1\). In the ultrasonic frequency range TDS is an accepted standard for calibration of hydrophones for medical device evaluation\(^2\) and have also been used for materials characterization\(^3\).

In contrast to pulsed systems, which concentrate the ultrasound energy into a brief high intensity pulse of under a microsecond, TDS spreads out a wide bandwidth of energy as a low amplitude signal over several microseconds. This eliminates the complications of handling a high voltage signal. When the received signal is compressed by a Fourier transform the familiar A-scan is produced with a signal to noise improvement due to the compression gain that is equivalent to coherently averaging several hundred pulse-echo signals. The resolution of the A-scan is predictable, being inversely proportional to the frequency range over which the signal was swept.

This pulse-compression technique enabled a system to be developed that produces a quality a-scan through an attenuating medium while energizing the transmitting transducer with a signal that is under 5 volts peak-to-peak. This TDS system has been developed for the ultrasonic sensing module of a prosthetic hand. The combination of small size, low power, and high sensitivity suggests a variety of additional applications.

Among the potential applications are remote monitoring and smart materials. In addition, the low power (less than 5 volts) would allow a system to be used in hazardous environments. Since the system can be produced cheaply, applications where the ultrasound system is expendable are also a possibility.

References:
1. Model TEF-25, Gold Line, PO Box 500, West Redding CT 06836
2. IEC 62127-2, Appendix H
Evaluation of Bolt Torque Levels using Nonlinear Wave Modulation Spectroscopy

Carter L Neblett, Manton J Guers and Dean E Capone
Graduate Program in Acoustics, Pennsylvania State University, State College, Pennsylvania

Structural health monitoring techniques have been investigated for evaluating the integrity of bolted joints in engineering structures. For example, nonlinear acoustic techniques have been used to study bolted lap joints having imperfect contact at the interface using multiple discrete excitation frequencies [1]. Likewise, impact excitation has been used to produce contact acoustic nonlinearity at bolted joints [2].

The goal of this work was to examine torque levels of a bolted joint using nonlinear wave modulation spectroscopy with impact excitation. A photograph of the test structure is shown in Figure 1. An ultrasonic shaker was used to supply the probing signal near the bolt location and an impact hammer was used to excite the natural vibration modes of the structure. Some of these modes produced significant displacements at the bolts leading to nonlinear sidebands around the ultrasonic probing frequency. Figure 2a shows an example of the modal excitation and Figure 2b shows the corresponding nonlinear sideband content around the probing signal frequency. Both discrete sideband peaks and broadband sideband levels were examined to determine a damage metric related to varying bolt torque levels.

Figure 1. Experimental Setup

Figure 2. (a) Modal excitation due to impact excitation; (b) Corresponding sidebands around the probing signal frequency

Acknowledgement:

This work was performed with support from the Walker Graduate Assistantship program of The Pennsylvania State University Applied Research Laboratory.
Observation of ultrasonic wave propagation in centrifugally cast stainless steel

Shan Lin, Central Research Institute of Electric Power Industry, Yokosuka-shi, Kanagawa-ken, Japan

Cast stainless steel (CSS) is widely used in nuclear power plants, particularly PWR primary coolant systems. The JSME Fitness-for-Service Code [1] requires periodic in-service inspection of welds in such systems by ultrasonic testing (UT), but anisotropy and heterogeneity of CSS make flaw detection and sizing difficult. Phased array ultrasonic technique (PAUT) is considered the most promising technique to solve such difficulties. In order to take advantage of PAUT to CSS, it is crucial to deeply understand how waves propagate in CSS. In this study, a 2-MHz linear array transducer is used to generate waves which propagate within a specimen made of centrifugally cast stainless steel (CCSS) at different directions, and a normal beam longitudinal transducer is used to receive waves propagating in the specimen. The observation results show that wave propagation direction is different from the supposed direction and the difference depends on the supposed direction.

References:
In-situ monitoring of rectangular bar specimens

Manton J. Guers\textsuperscript{1} and Bernhard R. Tittmann\textsuperscript{2}; Penn State University, \textsuperscript{1}Applied Research Laboratory; \textsuperscript{2}Engineering Science & Mechanics Dept., 225 Science Park Road, State College, PA 16803-2213 USA

Previous work \cite{1} investigated using a guided wave methodology for the in-situ monitoring of rectangular bar specimens (Figure 1) subjected to harsh environmental conditions. As shown, a trapezoidal horn is used to transition between the rectangular specimen and the wire waveguide. The previous work indicated that internal voids could be detected using the proposed methodology. The work presented in this paper examined the sensitivity of the in-situ monitoring approach for detecting other physical changes of interest including temperature gradients, material hardening, geometric swelling, and bending. The semi-analytical finite element (SAFE) technique was used to determine the theoretical change in group velocity due to changes in material properties and specimen cross-section.

![Figure 1. Illustration of in-situ monitoring method with rectangular bar specimen.](image)

References:

Nondestructive Evaluation of Interfacial Bond Strength in Single Lap Joints via Swept-Frequency Ultrasonic Phase Measurements

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Daniel F. Perey, William T. Yost, and K. Elliot Cramer, NASA Langley Research Center, Hampton, VA, USA
Mool. C. Gupta, Department of Electrical and Computer Engineering, University of Virginia, Charlottesville, VA, USA

As adhesive bonding is a preferred method of joining advanced composite structures for modern aerospace and automotive designs, the need for a quantitative nondestructive evaluation (NDE) method for adhesive bond strength has sharply increased. For many years, adhesively bonded joints have been examined with conventional NDE methods, but none have proved able to detect weak or “kissing” bonds, except where major bonding defects occur. Here, the problem of weak interfacial bonding is investigated with a novel swept-frequency ultrasonic phase measurement method. High-resolution, swept-frequency ultrasonic phase measurements are obtained at each frequency through the use of a constant-frequency pulsed phase-lock-loop instrument. The method is tested on single lap joints fabricated with polished glass adherents and adhesive cured with ultraviolet (UV) light. The cohesive and adhesive bonding properties are modified by varying the adhesive’s exposure time to UV light and thereby changing the degree of cure. After fitting the measured phase response to a model of the ultrasonic response of the bonded joint, the stiffness constant of the adhesive/adherent interface is found. The interfacial stiffness constant is shown to have a strong linear correlation with measured mechanical tensile strength. As such, high-resolution swept-frequency phase measurements are shown to have a sensitivity to interfacial bond strength without the presence of gross bonding defects, allowing for bond strength quantification rather than a simple identification of “good” or “bad” bonding. This method has the potential to be a quality control and service life assessment method for both newly-fabricated and in-service bonded joints for the aerospace, automotive, and other industries.

Acknowledgement:

This work was supported by a NASA Space Technology Research Fellowship and the NASA Langley Professor Program.
Additive manufacturing (AM) process for metallic parts is an important emerging technology. Platforms such as powder bed available for producing complex parts are usually slow. For fast AM process of large components, suitable platforms are laser or electron beam wire or powder feed systems, and more recently cold spray systems. In additive manufacturing, components are built up layer by layer, which allow one to manufacture highly complex structures including walls, hollows to reduce weight, or internal fluid or gas channels. Quality control of such complex parts is a challenge and new strategies have to be developed. For this purpose, laser ultrasonics is very attractive due to its non-contact nature and is well adapted to online implementation during the AM process.

In this study, NDE inspection is performed off-line on metallic parts produced by the cold spray AM process. Laser ultrasonics is used to detect flaws using the synthetic aperture focusing technique (SAFT), and through-thickness distributed porosity is investigated using the backscattered signal. Also, laser shockwave is used to characterize bond strength at the interface between the deposition and the substrate. Laser-ultrasonic measurement can also be performed during post heat treatment of cold spray AM metallic parts to follow softening, recrystallization and sintering. Inspection results from either the top layer or the underside of the substrate are reported and discussed.
Qualitative Detection of Boron Nitride in Ceramic Matrix Composites

Greg Ojard\textsuperscript{1} and Michael Taylor\textsuperscript{2}
\textsuperscript{1}United Technologies Research Center, 411 Silver Lane, East Hartford, CT 06108 USA\textsuperscript{2}Phoenix LLC, 2555 Industrial Drive, Madison, WI 53713 USA

The current state of the art for interface coatings of ceramic fibers in ceramic matrix composites is Boron Nitride. The performance of this weak interface in deflecting cracks around the fibers is what differentiates ceramic matrix composites from monolithic ceramics. The location and distribution of Boron Nitride is nominally assumed to be uniform during the processing. Performance of the coating is only noted by posttest destructive analysis: mechanical and microstructure. Conventional nondestructive approaches have not been able to discern any information about the distribution of Boron Nitride in the composite: qualitative or quantitative. Based on the understanding of the physics of neutron absorption and scattering, the presence of Boron Nitride would affect the transmission of neutrons and changes in concentration should be detectable. With this insight, a series of ceramic matrix composites where inspected to determine the effectiveness of neutron radiography for observing the presence, (or absence), of Boron Nitride. The results demonstrated are encouraging. In addition, this nondestructive tool appears to be providing new insight into a process issue that was a weak point in past engineering trials of ceramic matrix composites.
The concept of using permanently attached sensors, commonly called structural health monitoring (SHM), to detect damage in fixed wing aircraft structures has been the subject of research efforts for the past 40 years. Significant investment in development of sensing systems, algorithms to analyze received data, and in various laboratory-based testing, to include on-aircraft flight experiments, has occurred during this time. However, to date these in-situ sensing systems have not realized their potential to be a viable approach to determine if damage is present in structure. This presentation (and affiliated paper) addresses the major hurdles for the use of in-situ sensors for damage detection in fixed wing aircraft structures and provides a detailed discussion of solutions to overcome these hurdles. This includes how to ensure the SHM sensing systems are compliant with the requirements of the USAF Aircraft Structural Integrity Program (ASIP) and additional testing that needs to be completed to satisfy implementation requirements, including those published in the latest revision of the military standard that governs ASIP, MIL STD 1530D. The integration of modeling and simulation (M&S) in the validation process is addressed with a representative example that illustrates the feasibility of using M&S to make the process for validation feasible. In addition, several different use scenarios will be covered, each with distinct validation processes for their intended use. Included in the presentation is the current plans of the Air Force Research Laboratory (AFRL) plans to realize a validated system that addresses the requirements put forth by the USAF ASIP community. By satisfying these requirements, the intent is to have a system ready for eventual use when a suitable application emerges in the management of USAF aircraft.
Nondestructive Evaluation (NDE) and the closely related Nondestructive Inspection (NDI) is a key component in the management of the integrity of US Air Force structures and propulsion systems. Many current inspection processes have their origin linked to the acquisition of the weapon system which results in the use of methods and approaches that are approaching 40+ years of age. New capability in instrumentation is based on solid state electronics, generating the opportunity to use inspection data for more than only determining if a defect above a certain size is present. In addition, the readily available digital data from an inspection enables the potential to fully automate the documentation of an inspection facilitating the work of an inspector by mitigating the need to send significant time manually documenting an inspection reports. To introduce the potential of digital data capture, several use scenarios are introduced, including reporting, facilitated analysis, and raw data capture. Justification for each use scenario is described, along with challenges to realize this capability. The presentation introduces the two follow-on presentations that will delve into the automated reporting and the facilitated analysis of NDE data to provide end-users with increased efficiency in managing the safety of USAF systems and additional diagnostics to guide their maintenance and risk management. This will include a brief introduction to several strategic initiatives under within the USAF and how they are expected to impact the use of NDE methods for current and future platforms from both a initial qualification and a sustainment perspective.
Defect Imaging for Plate-like Structures Using Diffuse Acoustic Wave Generated by Modulated Laser

Takahiro Hayashi and Shogo Nakao, Graduate School of Engineering, Kyoto University, Kyoto, Japan

Flexural vibration is generated by pulse laser irradiation onto a plate-like structure. As energy of the flexural vibration varies with the bending stiffness in the vicinity of the laser spot, scanning the source of elastic wave provides defect images in the plate [1, 2]. The flexural vibration, corresponding to an A0 mode of Lamb waves, is usually used in a short period as a coherent wave in non-destructive inspection. However in a low frequency range or small complex plate-like structures, reflection and reverberation cannot be avoided, and when measuring a long period after the laser irradiation, the wave field becomes diffused and nearly homogeneous in the structure. It was proved that the amplitude of the diffused field is proportional to the generation energy [3, 4]. The diffuse field concept was applied to the defect imaging by the scanning laser source technique in this study. Figure 1 (a) is a distribution of flexural vibration energy when generating narrowband wave by modulating laser output. Due to the large resonance in the plate, diffuse field was not well formed and defect image could not be obtained. In contrast, the use of broadband chirp wave provided diffuse field appropriately and created clear defect images as shown in Figure 1(b).

Acknowledgement:

This work was supported by JSPS KAKENHI Grant Number 17H02052.

(a) Narrowband tone burst wave (b) Broadband chirp wave

Figure 1. Energy distributions for different wave type.

References:

A Non-Contact Ultrasonic Sensor for Pipe-Wall Thinning Inspection of Nuclear Power Plants


Pipe-wall thinning measurements are key to ensure the integrity of piping systems in nuclear power plants. Generally, many ultrasonic thickness measurements are manually performed during the outage of a nuclear power plant. These measurements are time-consuming because a significant quantity of insulation which covers the pipes must be first removed before the inspection. Zhong et al. [1] previously proposed a battery-free, wireless ultrasonic sensor which is based on the principle of inductive coupling. This sensor is considered a good candidate for monitoring pipe-wall thickness and can dramatically reduce the inspection time because the thickness can be measured by the sensor without the need to remove the insulation. Based on this technology, we have proposed the concept of the pipe-wall thinning measurement in the nuclear power plants [2].

In this paper we investigate the validity of this technology for a real plant inspection, first through its ability to survive the environment, and secondly its suitability for multiple measurement locations. In this study, we have investigated the applicability of this concept to the actual plant inspection. In the first part of this paper, we have experimentally tested the sensor durability against thermal cycles and radiation levels commensurate with actual nuclear power plant conditions. The test results confirm that the sensor bonded with a high temperature epoxy has good tolerance against both conditions. Next, we have investigated the applicability of the sensor to straight pipes and elbows of relatively small diameter. From the experiment results, it has been confirmed that the sensors with a rectangular transducer or a curved transducer can measure the thickness of both straight pipes and elbows with sufficient accuracy. Having shown the core technology is suitable, aiming for further reduction of the inspection time, we have developed a multi-transducer system which consists of one coil and multiple transducers driven by a single inspection system. This system enables us to measure the thickness of multiple points simultaneously. We have confirmed the performance of this system in experiments.

References:


(065)

Ranked Set Sampling Applied to Hit-Miss Probability of Detection Data: A Case Study

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Probability of Detection (POD) studies using the hit/miss criteria often suffer from quasiseparation in the data, which leads to a lack of convergence for the maximum likelihood equation, making all results from the logistic regression questionable. Ranked set sampling is a nonparametric statistics approach which mollifies this problem by resampling the data such that separation is no longer an issue. Ranked set sampling is applied multiple times to data from a probability of detection study for finding cracks in fastener heads using eddy current which suffers from quasi-separation. The resulting parameter estimates and POD estimates will be compared and the usefulness of rank set sampling to overcome separation issues demonstrated. The overall goal and motivation for the use of this technique is to be able to accurately predict in post-processing the smallest crack size an inspector could miss with the sensor even in the case of quasi-separated data.

References:


Study of Steel Pipeline Welded Joints with Artificial Aging using Thermoelectric Power Measurements

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In general, the thermoelectric methods are based on the Seebeck effect that is commonly used in thermocouples to measure temperature. The thermoelectric methods monitor the thermoelectric power (TEP) of metallic conductor materials, which is affected by the different types of defects present in the atomic lattice such as atoms in solid solution, precipitates and dislocations. In this research work, the relationship between the TEP and the microstructure will be obtained using the conventional contact TEP technique (hot-tip) and transmission electron microscopy of a welded joint of X60 and X65 micro-alloyed steel artificially aged. It was found that thermoelectric power is very sensitive to the aging process in the two-studied steel pipeline welded joints.

Acknowledgement:

This work was partially supported by CONACYT (Mexico) CB-256013.

Figure 1. Thermoelectric-power measurements of a welded joint in a micro-alloyed steel artificially aged.
Microwave Holographical Imaging of Glass Fiber Reinforced Polymer (GFRP) Reinforcing Bars in Concrete

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In northern climates in the United States, roadway salts are used as a life safety measure to reduce the possibility of ice buildup during winter conditions. Over time, the salt chlorides penetrate into the concrete and attack the steel reinforcing which initiates corrosion. Moreover, substructure elements, near saltwater conditions (seas) are quite susceptible to this type of corrosion [1]. Coating systems have been developed, such as epoxy coated rebars, in an effort to protect the steel from corrosion. However, these coatings often get nicked during construction which leads to pits where corrosion can initiate. Consequently, non-steel reinforcing bars which hold great promise to extend the service life of structures, have been investigated for this purpose. Fiber reinforced polymer (FRP) bars composed of glass, carbon, aramid or basalt are some such examples. However, once embedded in concrete, detecting these reinforcing bars becomes a challenging task. To this end, high-resolution microwave imaging of glass fiber reinforced polymer (GFRP) bars are investigated here. Microwave signals (~300 MHz-30 GHz) readily penetrate dielectric materials, such as concrete, and interact with their inner structures. Using robust holographical (or synthetic aperture radar, SAR) imaging techniques enables rapid, high-resolution and 3D image production of a myriad of complex dielectric and composite structures. These images are produced without the need for contact with the structure, and the irradiating signal frequency and polarization can be effectively used as optimizing measurement parameters to enhance image quality. This type of imaging technique has been successfully demonstrated for detecting corroded steel reinforcing bars in concrete [2]. The difference between the electrical properties of concrete (a dielectric) and steel (a conductor) is quite significant, resulting in detecting steel rebars rather easily, even at low microwave frequencies (i.e., ground penetrating radar, GPR). The relatively low contrast in the electrical properties of concrete and GFRP makes their detection rather difficult, particularly at low microwave frequencies (i.e., GPRs). However, using wideband microwave SAR imaging techniques, where frequency and spatial averaging significantly increase signal-tonoise ratio (S/N) and detection sensitivity, are well-suited for this purpose. In this paper the results of an investigation using wideband microwave SAR imaging technique to detect and produce highresolution images of embedded GFRP reinforcing bars in several concrete specimens are presented. A discussion of the capabilities and limitations of the technique will also be presented.

References:
Microwave Inspection of Wood Bridge Beams and Paved Decks

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Inspection of wooden structural members and beams, used in a variety of applications, is of great interest. Solid sawn timber, structural engineered wood such as glue laminated timbers, or composite wood members have found their utility in a wide range of applications including infrastructure (e.g., bridges) that may be old or newly constructed. To this end, manufacturing technology is used to develop structural members from solid timber, either for structural rehabilitation purposes or new constructions. The 2014 Federal Highway Administration (FHWA) National Bridge Inventory indicates there are over 40,000 wood or timber bridges in the United States [1]. Many of these structures are also exposed to the elements which brings about the potential for rot, void development, moisture permeation (pocket), insect infestation, etc. [2-3]. Consequently, technologies that can provide rapid, accurate, one-sided and portable inspection capabilities, are sought for inspecting wooden structures. In particular technologies that can provide images of the internal state of a wooden structure are desired. Microwave signals (~300 MHz-30 GHz) readily penetrate dielectric materials, such as concrete, and interact with their inner structures. Recent advances in developing high-resolution, 3D and portable microwave imaging systems, using robust synthetic aperture radar techniques, makes the potential for performing such inspections a real possibility. At microwave frequencies inspection of solid or glue laminated wooden structures, presents certain unique challenges due to the significant inhomogeneity, varying moisture content, etc. Consequently, operating frequency becomes an important measurement parameter for this purpose. This paper presents the results of an investigation in using several microwave nondestructive testing (NDT) and imaging techniques, for imaging and inspecting a number of wood specimens (sawn and glue laminated timbers), primarily in the shape and size of beams (i.e., relatively thick), with fabricated internal flaws (i.e., voids and moisture filled cavities), which were unknown to the inspectors. The results show the efficacy of these microwave techniques for detecting such internal flaws.

References:
POD for Automatic Detection of Cracks about Fasteners Without Fastener Removal

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Conventional eddy current inspection of boltholes in aircraft wing structures requires the prior removal of fasteners. This is a time-consuming and tedious procedure, with risk of collateral damage to the structure. Therefore, it is highly desirable to have a technique to detect cracks that does not require fastener removal. Previous work has shown that a pulsed eddy current system performed well on representative samples of lap joints in the P-3 Orion aircraft containing EDM notches in the bottom of the top layer and the top of the second layer, radiating from ferrous fasteners. The approach used a statistical cluster analysis and robust statistics to find outliers, which were assumed to be notches. The robust statistics allowed the process to operate automatically, with calls being made by a computer. This work attempts to establish a POD for the P-3 wing plank application using the MH1823 hit/miss software. One issue in doing this is that, like many NDT samples, the samples are defect rich, while in real life, the structure being inspected is expected to have very few defects. A bootstrap method is used to convert real data, obtained from the test specimens, into data sets more representative of reality. The results highlight the challenges of using a 1 parameter hit/miss (logit) model on real systems. An estimated $a_{90/95}$ of 2.8 mm (82 thou) is obtained for the system under test for a sample size of 80 fasteners. An advantage of this approach is that it provides built in checks on both the adequacy of training and whether or not the technique was carried out correctly in an actual inspection. An additional advantage is that this approach makes it relatively easy to generate large data sets with a sufficient number of repeat observations that it permits examination of the underlying statistical assumptions and can identify sources of variation leading to potential improvements of the inspection system.
Optically Stimulated Electron Emission Analysis of Surface Contamination Levels on Epoxy Composites and Effect on Failure Mode

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Sensitive techniques for monitoring pre-bonding surface conditions are necessary to ascertain surface levels of bond-degrading contaminants such as polydimethylsiloxane (PDMS). PDMS is a common ingredient in mold release agents that are widely used in carbon fiber reinforced polymer (CFRP) composites manufacturing. Even at low concentrations on adherent surfaces, these contaminants have been shown to affect the ability of adhesive bonds to transfer loads across a joint in a composite structure. In this work, optically stimulated electron emission (OSEE) was used to correlate the thickness of deposited PDMS with failure modes of mechanically tested joints. Various concentrations of PDMS were deposited on adherent surfaces in a controlled fashion. A developmental surface preparation technique, laser ablation, was used to remove surface contaminants prior to adhesive bonding. The laser treated CFRP specimens were subsequently adhesively bonded and subjected to double cantilever beam (DCB) testing to assess how the remaining PDMS concentration affected the failure mode. In this study, results are presented on the decrement in bond performance related to PDMS thickness detected with OSEE photocurrent analysis. The photocurrent of PDMS thickness on adherent surfaces prior to adhesive bonding is shown to correlate with failure mode.

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Lamb wave shows a great potential for corrosion detection, due to its long range propagation and sensitivity to defects. The lowest order modes are most commonly used for Lamb wave tomography [1, 2], since pure modes can be easily measured in the excited frequency range. However, the cutoff property of higher order modes is also of importance to determine and describe the corrosion patches. Envelope difference coefficient (EDC) is proposed as a qualitative indicator in this paper to evaluate the effects of corrosion on direct wave packets. Firstly, a toneburst response is extracted from the wideband laser received signal. The center frequency is selected near the cutoff frequency of A1 mode, leading to a preferable resolution for corrosion detection. Subsequently, the extracted signal is compensated for A1 mode to restore the original waveform. The waveform inside a designed window is compared with the reference one, to compute the difference coefficient between their Hilbert envelope curves. Experiments are performed on a corroded aluminum plate. Two cases of the interaction between Lamb waves and corrosion are discussed in detail. Based on our proposed indicator, the probability reconstruction algorithm provides an accurate and robust diagnosis map (see Figure 1).

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Figure 1. Probability reconstruction of EDC of A1 mode as it interacts with the corrosion.
Ultrasonic In-Line Inspection Signal Processing on Long-Distance Oil Pipeline

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The processing for ultrasonic in-line inspection echo signal explaining the corrosion conditions on long-distance oil pipeline to obtain the frequency information so as to determine the high accurate wall thickness information is the key of the ultrasonic in-line inspection technology. An approach for echo signal de-noising of wavelet packet and singular value decomposition (SVD) was advanced in this paper. The echo signals were decomposed with wavelet packet by utilizing the optimal wavelet function. The high frequency noise was removed according to the energy distribution ratio of different frequency band and then the extracted energy distribution band was decomposed by singular value. An adaptive filter was realized eventually after determining the effective echo signal area through singular entropy analysis. Base on Hilbert - Huang transform, forward the frequency information of corrosion conditions on long-distance oil pipeline was obtained hence the pipe higher accurate wall thickness was determined eventually.

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Matching Pursuit with Novel Dispersive Dictionary for Mode Separation in Guided Wave Signals Obtained from Pipes

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Pipes that carry gas into residential buildings are one of the most important infrastructures in cities. These pipes are prone to corrosion after a period of time because of different environmental factors. In order to avoid any pipe rupture that may cause explosion, the integrity of such pipes much be checked on a regular basis. Ultrasonic guided wave is an effective nondestructive testing (NDT) method for structural health monitoring (SHM) of plate like structures and pipes. However, the signals that are obtained from guided waves can be very difficult to interpret due to mode conversion, overlapped modes and low signal to noise ratio. In order to extract meaningful information of guided wave signals, using an advanced signal processing technique is inevitable. Most of the signal processing methods that have been developed so far, neglect the dispersion characteristic of guided waves. Dispersion means that the velocity of the propagating wave is a function of its frequency. As in most guided wave applications for inspecting pipes, we use narrowband tone-burst signal, dispersion causes guided wave signal to spread in time axis as it travels and changes its shape. Matching pursuit is one the greedy algorithm that can be used to approximate signals. This method iteratively approximates a signal by its predefined dictionary. However, the dictionary that usually contains redundant number of fundamental waveforms usually Gaussian signals may not be suitable for guided wave inspection of pipes. In this paper we designed a dictionary based on real guided wave signals by taking finite element method (FEM) approach.

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A method for characterizing defects in multi-layer conductive structures by combining pulsed eddy current signals with PCA components

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Pulsed eddy current (PEC) method has attracted researchers' attention in the detection of multi-layered conductive structures owing to its richer time and frequency domain information. In this paper PEC signal analysis techniques for qualitatively and quantitatively identifying defect parameters in multi-layer rivet structures are studied. After investigating the PEC responses of defects at different deep positions, the valley values of PEC signals are extracted and a fusion feature is presented by combining the valley values with the peak values and cross-zero time data [1]. To deal with the problem of time-domain signals overlapping in cases of small defects in upper layers and larger defects in deeper layers, principal component analysis (PCA) method is studied combining with time domain features [2,3]. To improve the characterizing performance, a random forest (RF) algorithm [4] is introduced to calculate the feature significance and correlate signal features with defect depths. To effectively reduce the data dimension while ensuring the accuracy in depth quantification, the optimal projection direction is studied. By comparing the presented method with a model based on support vector machines (SVM), it is found that random forests algorithm has higher performance during defect localization and parameter identification. The theoretical and experimental research is presented in detail.

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Figure 1. Defect parameter identification by combined features and random forest (RF) model

References:
Multiple Cancelation Through Coded Transmission

Arno Volker, TNO

There are many applications where access is limited to the location where the inspection is needed. One very important is pipe support corrosion. TNO worked on guided wave tomography for mapping wall loss under pipe supports. Due to the nature of this type of corrosion, pitting may occur. Due to the long wavelength of the guided waves used for the tomography, detecting and sizing these small pits is not possible. The idea described in this paper is much simpler and uses high frequency ultrasonic transducers around the 12 o’clock position. If the pipe is liquid filled, echoes are recorded from the opposite position. However these echoes are heavily contaminated with echoes from the upper pipe wall. The idea to be tested here is whether these echoes can be removed by transmitting a specific signal, which is recorded from the pipe wall itself. First a normal pulse-echo measurement is performed. Next the first and second back-wall echoes are windowed out and the second echo is multiplied with “-1”. Then this new signal is transmitted in the pipe wall, which will cancel all multiple reflections because this second echo is perfectly in opposite phase. If the same is repeated for the 2nd and 3rd signal and the this result is subtracted from the previous measurement, then all multiples caused by the returning signal in the top layer are removed. This concept is illustrated using numerical simulations and measurements and can be applied using phased array transducers or simple single element transducers.

Figure 1. Illustration of concept to remove multiple reflections
Intentional weld defect process: from manufacturing by robotic welding machine to inspection using TFM phased array

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Specimens with intentionally embedded weld defects or flaws can be employed for training, development and research into procedures for mechanical property evaluation and structural integrity assessment. It is critical that the artificial defects are a realistic representation of the flaws produced by welding. Cylindrical holes, which are usually machined after welding, are not realistic enough for our purposes as it is known that they are easier to detect than the naturally occurring imperfections and cracks. Furthermore, it is usually impractical to machine a defect in a location similar to where the real weld defects are found. For example, electro-discharge machining can produce a through hole (cylindrical reflector) which neither represents the weld porosity (spherical voids) nor the weld crack (planar thin voids).

In this study, the aim is to embed reflectors inside the weld intentionally, and then locate them using ultrasonic phased array imaging. The specimen is an 8 mm thick 080A15 Bright Drawn Steel plate of length 300 mm. Tungsten rods (ø2.4-3.2 mm & length 20-25 mm) and tungsten carbide balls (ø4 mm) will be used to serve as reflectors simulating defects within the weld itself. This study is aligned to a larger research project investigating multi-layer metal NDE found in many multi-pass welding and wire arc additive manufacturing (WAAM) applications and as such, there is no joint preparation as the first layer is deposited over the plate surface directly and subsequent layers contribute to the specimen build profile, similar to the WAAM samples. A tungsten inert gas welding torch mounted on a KUKA robot is used to deposit four layers for each weld, with our process using 9 passes for the first layer, down to 6 passes for the last layer. During this procedure, the tungsten artificial reflectors are embedded in the weld, between the existing layers. The sample is then inspected by a 10 MHz ultrasonic phased array in direct contact with the sample surface using both conventional and total focused matrix (TFM) imaging techniques. A phased array aperture of 32 elements has been used and the phased array controller is FIToolbox (Diagnostic Sonar, UK). Firstly, a focussed B-scan has been performed with a range of settings for the transmit focal depth. Secondly, a full-aperture TFM method has been processed. All the reflectors of interest were detected successfully using this combination of B-scan and TFM imaging approaches.
Previous passive thermography efforts to monitor the progression of damage during cyclic fatigue testing have focused on the heat generated at the cyclic load frequency. A closer examination of the acquired data has shown that at some locations on a test panel, the passive thermal response has significant content at twice the cyclic frequency. The locations of responses, with the largest harmonic contributions, are typically at the edge of subsurface delaminations based on ultrasonic scans of the panel. A physics-based model is presented that describes how a harmonic signal is expected if there is a friction based heat source. From the model, the expected phase of the heat source is calculated. The source is inserted in one-dimensional and three-dimensional simulations for heat diffusion to calculate the surface response for a subsurface friction source. The phase of the harmonic is found to agree reasonably well with a source at a delamination depth in the same location on the test panel as determined from ultrasonic scans of the damage.
Real time damage detection and characterization during load testing are valuable for understanding composite performance. The early detection and characterization of damage progression are critical for understanding failure modes. When a single stringer panel is subjected to significant quasi-static loading, the deformation of the panel results in damage such as subsurface delaminations. Surface temperature signatures and acoustic emissions enable real time detection of damage formation. Surface temperature signatures are useful for real time imaging of the damage. The time evolution of these signatures is complex. There is an initial, almost instantaneous component with a timing that is independent of the depth of the damage. This timing is based on the arrival of the acoustic emission signal at a rate orders of magnitude faster than the thermal diffusion. This signature decays with time. A second component increases with time, as the heat from damage formation diffuses to the surface. To better characterize the damage, computational simulations of the thermal signatures are performed with multi-dimensional models based on the quadrupole and finite element methods. The simulations are shown to assist in separation of the two components and provide an estimation of the damage depth.
Novel temperature compensation method for guided waves based SHM of pipes

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Torsional guided wave inspection is an established method for corrosion detection in piping systems in a variety of industries. SHM systems based on permanently installed guided wave sensors could theoretically guarantee an increased sensitivity to defect and corrosion when compared to one-off inspection methods. However, the action of changing environmental and operational conditions (EOCs), such as temperature, can severely limit their performance, so hindering the expected improvements. While several temperature compensation procedures for guided waves are available in literature, they usually solely target the effects of temperature on wave propagation speed. A second detrimental effect of changing EOCs on the pipe inspection system is an induced variation of unwanted wave modes (alongside the desired torsional one) generated and sensed by the system itself, which, in turn, results in changed coherent noise affecting the measurements. A method to compensate for this effect has been developed whose goal is to suppress such unwanted modes. Concurrently, it solves a number of other direct or indirect consequences of changing EOCs, such as phenomena related to transducer frequency response, which is often temperature dependent, and to wave attenuation due to viscous coatings, which can also be very temperature dependent. It is shown that the proposed method also compensates for these effects. By using SHM systems in combination with such an improved temperature compensation strategy it is possible to detect defects up to tenfold smaller than when using conventional one-off inspection methods. The method has been validated using data obtained in a blind trial.
Application of the thermoelectric measurements to track aging effects on Inconel 600

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A research was conducted to study the effects of aging on the thermoelectric coefficient of IN600 alloy. Inconel 600 is a solution strengthening nickel-based alloy mostly used in the nuclear industry. The alloy has an austenitic microstructure and if aged at certain temperatures, it can precipitate carbides along grain boundary. Samples from an IN600 alloy plate of 12.7 mm thick were obtained and aged for 0.16, 1, 10, 100, 200, 300 y 500, 1000 and 2000 h at a holding temperature of 700 °C. Vickers microhardness and TEP measurements were performed on unaged and aged samples, respectively. Thermoelectric power gradually increases with increasing holding time from 0.166 h to 100 h. After 100 h, the thermoelectric power starts to rapidly decrease to a minimum value at 500 h. After 500 h, TEP slightly increases at 1000 h and remains unchanged at 2000 hours. Interestingly, microhardness measurements show similar behavior to TEP. These data can provide useful information for future work related to thermoelectric properties of IN600 alloy.

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Friction stir welding (FSW) is a solid state joining process used across a range of industries from shipbuilding to aerospace. However, defects such as kissing bonds or wormholes usually associated with poor control of the rotational and traverse speeds during manufacturing remain difficult to detect using standard nondestructive testing methods. This paper investigates the correlation between the transmission of low-frequency guided waves through a lap joint and the rotational speed used during manufacturing. The aim of the method is therefore to nondestructively assess the manufacturing parameters rather than detect specific defects. Finite element simulations as well as experiments were used to evaluate the potential of method. The experimental setup comprises a 100 kHz shear transducer used for the excitation of $S_0$, six pairs of 3 mm aluminium plates in a friction stir welded lap joint configuration and a 2D laser Doppler vibrometer. The lap joints were manufactured with a rotational speed varying from 600 RPM to 1050 RPM while the traverse speed and the plunge were maintained constant. The experimental results showed that the $S_0$ transmission coefficient was approaching 85% when the rotational speed was 900 RPM whereas it was in the region of 20% at all other rotational speeds.

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Characterization of speckle noise in linear ultrasonic imaging

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Micro-structural or speckle noise in an ultrasonic image is caused by backscattered signals from grain boundaries within the specimen material and is typically the limiting factor in the ability of an inspection to detect a defect. The multi-view total focusing method [1] imaging algorithm can be used to obtain multiple images of the same region of a component by exploiting different reflections and mode conversions. By applying some form of data fusion to the information present in the different views, it is possible to improve defect detection and characterization performance. However, the signal-to-noise ratio for any given defect is dependent on both the view and the position of the defect, and this should be accounted for in a data fusion algorithm. This requires a model of defect scattering to estimate signal amplitude [2] and a technique to characterize speckle noise in each view. The current paper details an efficient procedure for experimentally achieving the latter. Rather than requiring many independent measurements from a defect free component, only a single measurement is required to obtain accurate coherent noise parameters at an imaging level. This is achieved by using a simple model to account for the spatial variation of the noise parameters within each view. A significant complication is the presence (in some views) of imaging artefacts caused by signal responses from other ray paths; these need to be detected and masked before the noise is estimated. This masking process incorporates expected auto-correlation length (ACL) and high amplitude cluster suppression. The expected ACL is determined via a simple ray-based forward model of a single point scatterer. After masking, only material noise information is retained, allowing for accurate quantification of speckle noise throughout the artefact-free region of each view. The technique is applied to direct/half-skip/full skip views of an immersed copper sample. The noise parameters obtained from a single measurement location were found to be within 0.9 dB of values obtained from multiple independent locations.

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Application of recent mathematical results to eddy current problems

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Eddy current inspections are often modelled by a magneto-quasistatic approximation of Maxwell’s equations. There have been recent results in the analysis and approximation of the eddy current approximation to Maxwell’s equations, including the addition of a jump condition to ensure Faraday’s law is satisfied by the eddy current equations. The effect of this condition is discussed in several examples. The difference between numerical approximations of the eddy current equations with and without this jump condition is discussed. Finally, the efficiency of the simulations are compared.

References:
Ultrasonic flaw sizing method in practical applications based on ultrasonic measurement model

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Flaw sizing is one of the fundamental issues in ultrasonic nondestructive evaluation (UNDE) of various materials and structures. The traditional flaw-sizing methods such as distance-amplitude-curve (DAC) and distance-gain-size (DGS) have the following disadvantages: (1) they may lose accuracy in the triple near-field of the used transducer, and (2) the surface condition will affect the flaw sizing results but there is no theoretical method to correct these effects. Therefore, an ultrasonic measurement model (UMM) based flaw sizing curves is developed to address the above inadequacies.

First, the development ultrasonic measurement model using multi-Gaussian beam model is briefly reviewed, and the effects of system gain on the system sensitivity is discussed. Second, the curvatures on the sound beam distributions and the coating and roughness on the sound energy are investigated theoretically and verified experimentally. The predicted flat bottom hole (FBH) flaw signals with and without considerations of the curvature and roughness using the UMM are shown in Fig. 1. Third, the correction methods for curvature, roughness (shown in Fig.2) and coating are introduced into the UMM and a flaw sizing curves for predict the equivalent sizes of flaws are plotted.

When the flaw depth or water distance, curvature, roughness and coating change, the model-based flaw sizing curves can be easily plotted. Experiments are conducted to verify the proposed methods. This work highlights the flaw sizing problem or help to improve the accuracy of flaw sizing problems in practical applications.

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Ultrasonic Characterization of Pores in Ti-6Al-4V Produced by SLM Additive Manufacturing

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Pores are one of the inevitable defects that have detrimental effects on the properties of selective laser melting (SLM) manufacturing material. In this work, an ultrasonic nondestructive method is developed for characterizing pore parameters including porosity, length, width, area, wrinkled degree, number and volume of pores. Firstly, the metallographic images are employed to analyze the statistical relationship between porosity and pore parameters. Secondly, ultrasonic velocity, attenuation and backscattering characteristics are introduced to characterize the porosity. Finally, the total pore parameters can be obtained by using this ultrasonic method. Metallographic and Ultrasonic measurements are performed on Ti-6Al-4V samples with different porosities. The results show that the ultrasonic shear velocity is found to be more sensitive to the porosity than the longitudinal velocity, and the attenuation has an opposite trend with the velocity. Furthermore, compared with the velocity and attenuation, the backscattering measurement is the most sensitive tool for determining the porosity in Ti-6Al-4V alloy produced by SLM.
Detection of Pores in Additive Manufactured Parts by Near Field Response of Laser-Induced Ultrasound

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In-line monitoring of 3D printed parts is vital if quality is to be maintained with this new manufacturing modality. Specifically, the reliable detection of pores in printed parts is vital if the finished products are to have the desired strength characteristics. One reliable method for detecting parts is to use laser-based ultrasound to generate Rayleigh waves on the surface of the part that can then be detected by an interferometer [1]. However, the utilization of Rayleigh waves requires a separation of approximately 1 mm between the ultrasound generating laser spot and the interferometer laser spot. This restricts and resolution of the detection limiting the effectiveness of the technique when smaller printed structures need to be assessed. In this work, we utilize COMSOL(Burlington, MA) to numerically compare a new detection method where the interferometer and laser-generated ultrasound are focused at the same spatial location. The changes in the surface response to defects in the near-field of the induced ultrasound wave are then assessed as a function of defect size and depth. Our numerical results demonstrated that the impact of defects was easier to visualize when quantifying the surface velocity as opposed to surface displacement. Surface velocity can be readily obtained experimentally by using a Sagnac interferometer [2]. The difference between the surface velocity both with and without a defect for the different pore diameters and depths is shown in Figure 1. The amplitude of the difference is comparable to that observed when utilizing scattering of the Rayleigh wave in the detection. However, the new approach does not require a 1 mm separation between the laser-generating ultrasound spot and the interferometer improving the spatial resolution of the detection.

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Figure 1. Difference in surface velocity between sample with and without pores for different pore depths and diameters.

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(088)
Investigation of Nonlinear Ultrasonic Lamb Waves at Low Frequency

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Nonlinear ultrasonic Lamb waves are popular for material characterizations and incipient damage detections in plate-like structures and (S1, s2) mode pair is widely used as they satisfy internal resonant conditions: phase velocity matching and non-zero power transfer. However, this widely used mode pair suffers from two associated complications: inherent dispersive and multimode natures. To overcome these, a new mode pair (S0, s0) at low frequency region is explored because the S0 mode is little dispersive and easy to generate at low frequencies but the mode pair cannot rigorously satisfy the phase velocity matching condition. In this work, theoretical analyses and numerical finite element simulations were carried out to prove that, even though the mode pair cannot satisfy the phase velocity matching condition, the second harmonic mode still exists, and its amplitude increases linearly for significant distance. Experiments were also used to validate the nonlinear features and therefore demonstrate an easy alternative for nonlinear Lamb wave applications.
Weighted Data Fusion of Multi-View Ultrasound Array Measurements for Reliable Weld Inspection

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Multichannel ultrasonic arrays illuminate weld faces from different orientations. The range of illumination angles expands even further if multiply-scattered energy from the back wall is considered. The full matrix captured data processed with the total focusing method (TFM) provides a set of images (multi-views) of the same study area. Each view, being generated using specific ray paths and wave modalities (longitudinal, shear or their combinations), has individual sensitivity to defects of different type, location and orientation. Potential imaging artefacts due to geometry or multiple reverberations are differently distributed within the different views, thus reducing blind zones in the combined interpretation. Data fusion of the observations from different views, taking into account their sensitivities, improves reliability in defect detection and characterization.

In this work we demonstrate the capability of a weighted data fusion approach for detection and characterization of the cracks at the weld face. Synthetic data was simulated for immersion inspection of a metal block with two tilted cracks (70° from horizontal). Multi-view images as well as their sensitivity maps for a set of defect types and orientations were generated for the synthetic dataset. Sensitivity maps (or illumination weights) were predicted with an analytical model taking into account water-metal boundary transmission-reflection coefficients, beam-spread, transmission and reception directivity and the scattering function specific for the defect of the hypothesized type. Hence, for each TFM view the set of sensitivity maps corresponding to the set of hypotheses about the defect type and orientation were obtained.

The amplitudes in the TFM images were converted to p-values (probabilities of no defect) as there are standard statistical procedures established for combining p-values. Multiple views were fused using two different consensus tests: Fisher’s combined probability test [2] and the weighted z-method combined probability test using the sensitivity map values as weights [3].

We found that the weighted z-method provides superior results on defect identification and characterization when the correct hypothesis is used and the weighted z-method is less prone to false alarm than Fisher’s test. The weighted z-method provides robust results that are not much affected by the number of views selected for the fusion, thus making the choice of particular view combinations less critical for the optimal performance of the inspection.

Acknowledgement:

This work was supported by the UK Research Centre in Non-Destructive Evaluation (RCNDE) and EPSRC Grant No EP/N015533/1.
Manipulating Curvature of Plane Wavefront Using Holey Plates

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Ultrasonic inspection is commonly used for Non-Destructive Evaluation. Phased array ultrasonic transducers (PAUT) enable beamforming and beam steering by implementing electronic time delays. By providing appropriate delays in exciting individual elements, PAUTs can generate a curved wavefront. The authors propose a metamaterial device made of Gradient Refractive Index Phononic Crystals (GRIN PCs) [1] to transform curvature of a wavefront generated from single element transducer. The design of holey plate and choice of material is obtained with the aid of transformation elasticity. The manipulation of the wavefront, as it passes through holey region, is simulated using the finite element method (snapshots of wave propagating through the device are shown in Figure 1). Results from experimental studies carried out on a holey plate, designed using this approach, are comparable to simulation results. The authors suggest that add-on devices can be designed for tailoring wave incidence in ultrasonic inspection, using this approach.

Figure 1 Snapshots of Wave Propagation in simulation: (Left to Right) Before Entering, While Passing through, After exiting Holey region in plate.

References:
Application of Signals Processing and Machine Learning Techniques for Segmentation and Spatial Registration of Material Property Data

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Errors introduced into data acquired for nondestructive evaluation due to suboptimal digitization rates, bandwidth and signal processing settings can dominate the perceived noise in acquired data, leading to artifacts and erroneous interpretation. Furthermore, the presence of such errors incurred through the data acquisition process can also inhibit post-processing techniques utilized in multimodal data segmentation and registration efforts. This study illustrates the use of advanced signals processing techniques to limit the effects of quantization errors in normal-incidence ultrasonic inspection data, thereby optimizing the signals for further processing while maintaining the integrity of the data. In conjunction with signals processing methods, neural networks and expectation-maximization algorithms are investigated for applications in automated data segmentation and multimodal spatial registration. Using results from segmented and registered data, techniques in constructing computer aided design (CAD) models are investigated for importing measured material property and flaw information into various modeling software platforms.

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Multifidelity Model-Assisted Probability of Detection via Cokriging

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The concept of probability of detection (POD) [1] was proposed for measuring the reliability of nondestructive testing (NDT) [2] system, incorporating large amount of experimental information. Model-assisted probability of detection (MAPOD) [3] (as shown in Fig. 1) is then developed to reduce the computational cost burden on experiments. However, even with the alleviation on experiments, the computational costs could still be prohibitive due to the uncertainty propagation through high-fidelity physics-based simulation model. In this work, a multifidelity modeling technique [4], in particular the cokriging method [5], is utilized for efficient MAPOD analysis. The proposed approach is demonstrated on an ultrasonic testing simulation benchmark case involving a spherically-void-defect developed by the World Federal Nondestructive Evaluation Center. In this benchmark case, the separation of variable (SOV) and Kirchhoff approximation (KA), are utilized as the high-fidelity and low-fidelity approaches for modeling the scattering process, respectively. The high-fidelity model captures the physics accurately, but is computationally expensive to solve, whereas the low-fidelity model is efficient but is not as accurate. A cokriging metamodel is constructed by fusing the two modeling approaches, and is subsequently used in lieu of the high-fidelity physics-based simulation model within the MAPOD analysis. The results show that the proposed approach can reduce the number of required high-fidelity model evaluations by over one order of magnitude as compared to using the kriging metamodels, while still yielding POD curves of comparable accuracy.

Figure 1: Overview of main elements for MAPOD calculation.
Model-assisted probability of detection (MAPOD) [1, 2] is widely used for measuring reliability of nondestructive testing (NDT) system [3], without requiring large amount of experimental information. Sensitivity analysis (SA) is another important terminology in NDT area for characterizing effects of uncertainty parameters have on model response. Both MAPOD and SA need uncertainty propagation (as shown in Fig. 1), which is traditionally addressed using Monte Carlo sampling (MCS) on physics-based simulation model. However, that could be computationally impractical because of the large amount of model simulations, especially when one simulation is time-consuming. In this work, we propose a type of stochastic expansion, polynomial chaos expansions (PCE), integrated with least angle regression (LARS) technique [4]. The proposed approach is demonstrated on an ultrasonic spherically-void-defect testing case, which was first developed by the World Federal Nondestructive Evaluation Center. Various state-of-the-art metamodels, namely, Kriging deterministic metamodeling, PCE solved by original least squares method, and the proposed LARS PCE, are compared. The results include POD curves, convergence of statistical moments, convergence of sensitivity analysis using Sobol’ indices [5].

Figure 1: Overview of main elements for MAPOD and SA.

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This work is sponsored by the Center for Nondestructive Evaluation (CNDE) Industry/University Cooperative Research Program at Iowa State University.
Casing Eccentering Sensitivity of Pulsed Eddy Current Sensors in Multiple-Casing Corrosion Analysis

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Electromagnetic (EM) multibarrier corrosion inspection can be classified into two categories: continuous wave (CW) and pulsed eddy current (PEC) methods. While advanced processing [1-3] enables quantitative evaluation of multiple nested casings from multi-spacing and multi-frequency CW data, PEC methods [4] rely primarily on time to depth transformation for interpreting individual casing thickness. The CW sensors use remote field eddy currents for total metal loss, while multi-casing evaluation is based on near-field sensors, typically using multiple receivers operating at one or more frequencies, combined with inversion-based processing. The PEC sensors typically have collocated antennas, with the length of the sensor determining the depth of investigation [4, 5]. Sensitivity to casing eccentering is usually not accounted for, although acknowledged as a factor that can affect the interpretation [5] and no sensitivity study has been reported yet.

Comprehensive sensitivity analysis of casing eccentering for PEC sensors of varied lengths is performed based on 3D finite-element modeling. The effect of approaching defects and casing collars for three-casing configuration was also studied. The performance of casing thickness interpretation using PEC time to depth transformation is assessed by comparing the relative difference in responses from the centered noncorroded setting (denoted by $\Delta V_n$). It is found that when approaching heterogeneity or casing eccentering, $\Delta V_n$ is within 3% for shorter sensors ($L < 6$ in.) modeled with and without a magnetic core. Ignoring the core for modeling sensors longer than 10 in., leads to a more than 20% difference from the true $\Delta V_n$ value. Three casing configuration of outer diameters 4.5, 9 5/8 and 13 3/8 in. was used in the study of how individual casing thickness affects the responses for varied sensor length. The presence of 50% or more eccentering in the second casing masks the sensitivity to metal loss in the second and third casings even for long sensors.

Although the collocated PEC sensor design averts double indication of casing heterogeneity shown as ghosts in noncollocated sensors, it does so at the additional cost of increased sensitivity to eccentering and reduced vertical resolution because sensing deeper to evaluate external barriers requires longer sensors. Casing eccentering in realistic settings increases the overall interpretation uncertainty and requires 3D modeling while inversion-based interpretation is needed for quantitative evaluation of multiple nested casings using PEC responses.

References:

Diffuse ultrasonic backscatter measurement with limited data

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Diffuse ultrasonic backscatter techniques have been extensively studied to determine microstructural properties, such as grain size, grain elongation, or material texture. In the past few decades, the Figure-of-Merit and Single-Scattering Response models have been built to extract microstructural parameters in frequency domain and time domain, respectively. However, both of these models require hundreds or thousands of scattering signals in the experiments, and the data-collection processes are usually time-consuming. Besides, the number of collected waveforms is often limited by the geometry of specimen in practical applications.

In this work, the statistics of diffuse ultrasonic scattering from microstructure are investigated under the condition of a limited sample set. The statistical technique of non-stationary random processes in the time domain is introduced within the context of the experimental spatial variance curve. A short time spatial variance curve is obtained by a moving time-window. The present method is applied with the previously developed ultrasonic backscatter model. A stainless steel specimen is used to validate its effectiveness. The results show that the short time spatial variance curve has better convergence performance over the traditional spatial variance curve.

In addition, the applications of the present method are shown. Grain size estimation using limited backscatter data is performed and it is observed that the random error of grain sizing can be well-controlled. The enhanced ultrasonic flaw detection experiment with the time-dependent threshold is also performed using the short time spatial variance curve. The experimental result shows that the present method allows the integration of the nondestructive testing for micro-flaws with sub-wavelength dimensions and the nondestructive evaluation for microstructural property.

In short, the present method improves the practicality of the ultrasonic backscatter method for industry applications because it can greatly reduce the data-collection process, and it may aid the application of ultrasonic arrays for characterization of material microstructure in the near future.
Ultrasonic Beam Model of Leaky Rayleigh Wave Generated by Focused Immersion Transducer

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Abstract:
This work reports a new multi-Gaussian beam model (MGB) for the leaky Rayleigh waves (LRW) generated by focused immersion transducers at oblique incidence. A Green’s function method is used to develop the point source model (PSM) for accurately calculating the LRW beam, and the MGB model is introduced to simplify the algorithm. Simulations show that the LRW beam behavior obtained using MGB model agrees well with that using the PSM, but the MGB model is more efficient. Experiments are conducted to verify the accuracy of the MGB model. Good agreements between the theoretical simulations and experiment measurements for both the on-axis and off-axis fields are shown. This work provides an effective tool for calculating the sound fields and it is therefore significant for the practice of nondestructive testing and evaluation using leaky Rayleigh wave generated by focused immersion transducers.

Acknowledgements:
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References:
In-situ Thermal Inspection of Automated Fiber Placement Manufacturing

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The advent of Automated Fiber Placement (AFP) systems have aided the rapid manufacturing of composite aerospace structures. One of the challenges that AFP systems present is the variability of the deposited prepreg tape layers, which are prone to gaps, overlaps and twists. The current detection method used in industry involves halting fabrication and performing a time consuming visual inspection of each tape layer. Typical AFP systems use a quartz lamp to heat the base layer to make the surface tacky as it deposits another tape layer. The innovation discussed in this paper is to use the preheated base layer as a through transmission heat source and inspect the newly added tape layer in situ using a thermographic camera mounted on to the AFP hardware. Such a system would not only increase manufacturing throughput by reducing inspection times, but would also aid in process development for new structural designs or material systems. To this end, a small thermal camera was mounted onto an AFP robotic research platform at NASA, and thermal data was collected during typical and experimental layup operations. The data was post processed to reveal defects such as tow overlap/gap, wrinkling, and peel-up. Defects that would have been impossible to detect visually were also revealed in the data, such as poor/loss of adhesion between plies and the effects of vacuum debulking. This paper will cover the results of our experiments, and the plans for future versions of this inspection system. We will also present a comparison between this type of inspection and a post-layup laser profilometry inspection.
X-ray transmission through microstructured optical fiber

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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. These fibers are filled with air, helium, and argon and the x-ray transmission spectral characterization of each gas filled fiber is presented. The fiber ends are metal coated to seal the gas filled fibers and the subsequent x-ray transmission spectral characterization is presented. The experimental configuration and results of the x-ray transmission measurements are discussed.

Reference:
Acoustic Measurement Infrastructure To Characterize Nuclear Reactor Operation

James A. Smith, Vivek Agarwal, Measurement Sciences, Idaho National Laboratory, Idaho Falls ID

Research reactors for the development of new nuclear technologies are used to test efficiency and safety of novel advances, such as material or fuel elements under prototypic commercial conditions. Experiments performed in research reactors would ideally have in-situ measurements to monitor the progress and performance of these advanced tests. The reactor core is a particularly severe environment for sensors and instrumentations. The reactor core similarly imposes severe limitations on signal transmission from inside the core to outside of the reactor pressure vessel. This paper will discuss an Acoustic Measurement Infrastructure (AMI) installed at the Advanced Test Reactor (ATR), located at the Idaho National Laboratory. The AMI involves many intrinsic subcomponents since sound travels efficiently through and generated by many reactor components such as ATR in-pile structural components, coolant, piping, coolant pumps, pressure pumps and valves as well as acoustic receivers, data-acquisition system, and signal processing algorithms. Intrinsic and cyclic acoustic signals generated by the operation of the primary coolant pumps are collected using acoustic receivers and processed. The characteristics of the recorded intrinsic signals may identify the process state of the ATR during operation (i.e., real-time measurement).

There are a number of useful features that the signals from the AMI enable by noting signatures in the data. This paper will discuss the AMI results from an Accident Tolerant Fuel Test in the ATR and the unique processing algorithm based on the Short Time Fast Fourier Transform for cyclic or repetitive signals. From the ATR AMI results, it was discovered that there are a number of useful features that can be identified. The pressure pulses caused by the PCP are processed in manner that provides signatures which reveal information about the operational state of the reactor and can potentially identify anomalous conditions.

To try to answer the question, are there PCP states that are beneficial to the experiment as well as to understand what affects the state of the reactor and thus the effects on the experiments, the AMI data will be integrated with (data fusion) the sensors within the experiments and the ATR process sensors. The ability to perform data analytics on this diverse data and understand the history of the reactor states during a test run will provide a mechanism to understand the performance of the specimens, the confounding effects on the experiments and thus enable the separation of those effects.

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Design Of A Laser Shock System For A Remote Nuclear Radiation Environment

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The U.S. National Nuclear Security Administration (NNSA) Material Management and Minimization (M3) program is enabling the transformation of research and test reactors to Low Enriched Uranium (LEU) fuels using reactor safety analysis and new fuel designs. Most of these HEU fueled reactors perform salient technical missions and enable significant volumes for medical isotope production. The M3 program has developed LEU based alternative fuels that will enable reactors to continue their missions while operating safely and cost effectively. In 1996, the NNSA started the development of a high density fuel system appropriate for world’s highest power density research reactors. The Fuel Qualification (FQ) pillar of the M3 program has developed a base fuel design consisting of uranium-10 wt% molybdenum alloy (U-10Mo) in the form of a monolithic foil clad in aluminum alloy 6061 by hot isostatic press. See Figure 1.

**Figure 1**: Base Fuel Design

Because the fuel is a new design, the performance of the fabricating processes and fuel after irradiation is unknown. A salient performance factor of the fuel plate is the bond strength of the fuel foil (including the Zr interlayer) to the Al substrate. The laser shock technique will be used to provide interface strength feedback for the fabrication process development and understand the effects of reactor irradiation. The resulting data will be used in part to qualify new fuels for use in research reactors.

This paper will focus on modifying a laser shock system built for laboratory use that relied on polarizing and polarization splitting free-optics elements in conjunction with optical fiber to deliver and collect signal light for use in a nuclear hot cell. The resulting system designed for installation in a nuclear hot cell system uses only optical fibers without polarization elements as the salient delivery and collection of signal light. The laser shock system based on unpolarized fiber optics is more practical for the rigors and remote operation requirements in a nuclear hot cell. The paper will also discuss the fiber feedthrough and the use of sacrificial fiber when the fiber becomes highly attenuative to light due to radiation damage. The bond strength results obtained in the laboratory using the laser shock method from the polarized and non-polarized systems will be compared.

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This work was supported by the U.S. Department of Energy, Office of Material Management and Minimization, National Nuclear Security Administration, under DOE-NE Idaho Operations Office Contract DE-AC07-05ID14517
Eddy current measurements of flaws in titanium are corrupted by spatially correlated grain noise, which is generated due to local changes in the conductivity of the material. This makes inversion of eddy current data to characterize flaws detected in titanium particularly challenging. Specifically, failing to account for the correlation structure of the grain noise may lead to inaccurate estimates of the flaw geometry. As has been demonstrated in [1], the grain noise can be modeled as a Gaussian process, using spectral mixture kernels to represent the covariance function. Incorporating this model for the grain noise into the forward model results in improved estimates of the flaw geometry. In [1] the authors found a representative covariance function using eddy current measurements from a set of unflawed titanium specimens; however, the statistical behavior of the grain noise can differ greatly between samples of the same material, meaning it is difficult to find a single representative covariance function to describe the grain noise. To ensure that we correctly capture the behavior of the grain noise in the damaged specimen data, we estimate the covariance function using eddy current measurements from an unflawed portion of the damaged specimen. In addition, we formulate a criterion to determine if the estimated covariance function is an appropriate fit for the damaged portion of the specimen. Confidence intervals for the flaw parameters are computed by sampling from the likelihood distribution which incorporates the grain noise Gaussian process model. A series of test problems addressing varying grain noise and a mix of simulated and real discontinuities will be used to study inversion sizing accuracy with confidence intervals and the noise fit criterion.

Acknowledgements:

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References:
Applicability of Statistical Methods to a Mixed Experimental and Simulated Study for Optimizing Ultrasonic Characterization Approach for Impact Damage in Composites

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An ultrasonic characterization approach can be studied qualitatively, by visualizing the direct output of an inspection in the form of the gated image of a two-dimensional C-scan. However, evaluation of a single inspection does not provide information regarding the variability inherent in the technique or the interdependence of repeat measurements and varying conditions between subsequent inspections. One way to provide a quantitative assessment of the measurement variability and effectiveness of the approach is to conduct a formal design of experiments (DOE). In practice, a formal DOE can be cost prohibitive due to the time and expense of conducting a large experimental test matrix. By conducting a limited DOE augmented with simulation results, the NDE technique optimization process is greatly improved by addressing a wider range of test conditions that are difficult to consider using empirical and model-based studies alone. This paper will discuss the results of a DOE performed using experimental and simulated data, and the effect of metric choice on the results of the optimization study.

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A Damage Localization and Quantification Algorithm for Indirect Structural Health Monitoring of Bridges Using Multi-Task Learning

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Indirect structural health monitoring of bridges has become popular since it is a low-cost and low-maintenance approach in which sensors on the vehicle are used to detect bridge damage. Over the past decade, a number of researchers have provided methods for extracting modal parameter-based features to detect and localize damage. Notably, signal processing and machine learning based approaches have been shown to perform well in achieving higher-level structural health monitoring objectives, such as damage quantification [1]. However, these methods not only lack robustness to measurement noise, but also require more physical insights. As a step towards improving this situation, we propose a multi-task learning (MTL) approach for estimating both the location and magnitude of damage occurring on an experimental bridge using acceleration signals collected from a passing vehicle. The damage is represented by a mass with a gradually changing magnitude (ranging from 60 to 200 grams) attached at different positions (0.61 m, 1.22 m and 1.83 m away from the support) on the bridge. Guided by a theoretical formulation of a simple vehicle-bridge interaction system, our approach preserves the nonlinearity of the trend of the acceleration signals as severity changes, and simultaneously localizes and quantifies the damage for minimizing uncertainties propagating from the location estimation. We evaluate our model on an experimental dataset, and the results (Figure 1) show that it outperforms a two-step baseline model and can estimate locations of the damage with an average error of 0.08 m and changes in severity level with an average error of 17.81 grams.

Acknowledgement:

The authors gratefully acknowledge the support of the National University Transportation Center for Improving Mobility (Mobility21) at Carnegie Mellon University.

Figure 1. Damage location and severity prediction results using a two-step method and MTL.

References:

Pulse-echo Nonlinearity Measurement of Solid Samples Using a Dual Element Transducer

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A pulse-echo method for measuring the acoustic nonlinearity parameter $\beta$ of isotropic solids is presented. The method is based on the use of a dual element transducer for enhanced second harmonic generation resulting from the partially constructive interaction of two reflecting components from the stress-free surface. The received fundamental and second harmonic fields are corrected for the total effects of diffraction, absorption and boundary reflection.

The uncorrected $\beta'$ was presented in Fig. 1. It is very small and underestimated considerably compared to the through-transmission (TT) results of $\beta$ [1]. These results are attributed to the low second harmonic amplitude generated from the stress-free boundary. The effects of making attenuation correction (AC) and diffraction correction (DC) are investigated separately. The $\beta_{AC}$ in Fig. 1 denotes the nonlinearity parameter after AC and it is slightly increased from the $\beta'$, meaning the attenuation effects are not significant. However, the $\beta_{DC}$, the diffraction-corrected nonlinearity parameter, is substantially raised from the $\beta'$. The final $\beta$ after making the total correction is also presented. The $\beta$ of the 2 cm thick sample is very large compared to the $\beta$ of other thicknesses. This is attributed to the second harmonic amplitude lower than the noise floor. All other samples produce the mean $\beta$ of $5.49 \pm 0.24$, which agrees very well with the TT mode [1]. These results demonstrate that the proposed P-E approach provides reasonably accurate $\beta$ values for relatively thick samples.

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References:

Ultrasonic Phase-coherent Multiple Signal Classification Imaging for Non-Destructive Evaluation

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Xiongbing Li, School of Traffic and Transportation Engineering, Central South University, Changsha, PR China

In this paper, phase-coherent multiple signal classification (PC-MUSIC), the phase-coherent form of time-reversal with multiple signal classification (TR-MUSIC), is introduced in the area of ultrasonic non-destructive evaluation (NDE) to detect and image the defects in solids. The method is tested with experimental ultrasonic array data acquired by full matrix capture process. It is shown that PC-MUSIC can overcome the elongated point spread function that appears in TR-MUSIC images, and hence provided enhanced axial resolution. However, PC-MUSIC fails to locate the targets correctly. For accurate localization, a phase factor is calculated based on the positions of targets, which can be estimated from the TR-MUSIC or total focusing method (TFM) image depending on the situation. And then the phase factor is compensated in the PC-MUSIC imaging function, termed PC-MUSIC with phase compensation (PC-MUSIC with PC). It is shown that the PC-MUSIC with PC can diminish the axial elongation shown in TR-MUSIC images, as well as locate the targets accurately.

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Figure 1. Comparison of point spread function for PC-MUSIC and PC-MUSIC with PC.
Comprehensive Diagnosis the Fault of On-line Bearing

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Bearing is one universal mechanical component to make up the rotating equipment. Its running state directly affects the performance of the entire mechanical system. During the process of rotation, bearing with defects will generate seasonal impulses. Well, the method to detect those impulses is bearing fault diagnosis. Recently the general detection technology is envelope analysis. In this method the filtering technique is applied. However, selection for filter parameters is critical for analysis results[1]. In accordance with the defects of traditional envelope analysis to specify the filter parameters, some scholars introduced kurtosis-optimization wavelet denoising[2] and empirical mode decomposition (EMD)[3]. In this paper, the three methods proposed by predecessors are analyzed and discussed based on bearing vibration data under different rotational velocity. The results show three methods have their advantages and disadvantages. But the two or three above methods can be combined to come true comprehensive fault diagnosis.

Figure 1. Envelope Analysis

Figure 2. Envelop spectrum by Wavelet Kurtosis Optimization

Figure 3. EMD

Acknowledgement:

Thank Chengdu Tiean Technology Co., Ltd., for providing support.

References:
The Application of a Battery-Less Torsional Vibration Sensor with Magnetostrictive Patches to a Large Rotating Ship Propulsion Shaft

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For torsional vibration monitoring of rotating ship shafts, a strain gauge system with a telemetry unit is generally used in fields. Unfortunately, it is not suitable for the permanent use because this system is powered by batteries, which should periodically be replaced by stopping rotating shafts. Therefore, this work is concerned with a first attempt to measure in real-time the torsional vibration of a large rotating ship propulsion shaft using a sensor without a battery and a telemetry unit. To this end, the use of a magnetostrictive patch sensor is proposed to overcome the limitation of a conventional battery-based strain gauge system. The proposed sensor consists of very thin magnetostrictive patches and small permanent magnets tightly bonded onto a shaft. Instead of a telemetry unit, a solenoid coil is then placed on the patches and magnets for the noncontact transduction of vibration signals in the form of voltage output. For the feasibility test, experimental and numerical studies with the proposed sensor were performed first using relatively small stationary solid shafts in our laboratory. After confirming the feasibility of using the proposed sensor, the proposed sensor was used to measure torsional vibrations of a rotating propulsion shaft in an LPG carrier ship. For this application, the proposed sensor was properly sized and redesigned to accommodate the large-sized shaft. The measured signals by the proposed sensor were then compared with the strain gauge signals. After some calibration of the proposed sensor, it was observed that the measured signals by the proposed sensor were sufficiently close to the strain gauge signals. This study suggests that the proposed sensor can be used as an alternative means for real-time battery-less monitoring of rotating shafts if a refined calibration technique is further established.

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References:
Finite element modeling of elastic wave generated by crack growth

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This presentation discusses the finite element modeling of cracks growth and elastic wave propagation. Three common methods of crack growth modeling including Cohesive element method, Virtual crack closure technique and Extended finite element method are discussed. Two mostly used crack source model of elastic wave propagation including point source, extended source are discussed. The main goal of this research is to find out a method to combine the crack source model with fracture mechanism and use it in the simulating of acoustic emission monitoring of concrete ASR expansion based on the mesoscopic constitutive law[1,2], the AE experimental monitoring system of ASR is shown in figure 1. The efforts to reach this numerical research goal include using crack source model based on virtual crack closure technique, using crack source model based on extended finite element method.

Acknowledgement:

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Figure 1. Experimental acoustic emission system of concrete ASR expansion

References:
Elastic Wave Scattering by a new Computationally-Advantaged Formalism

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Boundary integral equations (BIE) methods are inherently advantageous for infinite medium problems such as elastic wave scattering for ultrasonic NDE. The reduction in dimensionality of the problem (e.g., volume to surface) leads to computational advantages versus finite element or finite difference methods for homogeneous material models. Low or high frequency, or weak scattering assumptions are not required. BIE methods inherently allow scatterers of any shape, may include irregular surface features, and multiple scatterer interaction is automatically included without modifying the algorithms. However, numerical integration of the strongly singular \(1/r^2\) traditional direct BIE formalism has been a challenge to implementation - although successful functioning codes have long existed. Still, methods to incrementally minimize this difficulty have been the subject of research for three decades. A new, but equally unrestricted method which is computationally less burdensome for scatterers with stress-free boundary conditions (such as voids, open cracks, and nearby free surfaces) is presented. This formalism utilizes Betti reciprocity, superposition, and an analytical representation of the incident stress field (normally known for plane waves and ultrasonic beam models) to eliminate integration of the strongly singular Stokes’ gradient tensor kernel. An associated weakly singular \(1/r\) BIE problem is readily solved numerically instead. Computational advantage comes from needing fewer Gauss-Legendre integration points and not needing to employ elaborate regularizing transformations. Additional numerical efficiency arises from the relative simplicity of the Stokes tensor (Green’s function) versus evaluating its surface gradient. Finally, the fictitious eigenfrequency difficulty of exterior-domain conventional BIE formulations is also easily avoided. Cases validating the method for scattering amplitude determination by a time-harmonic formulation are presented.
Nonlinear Resonant Ultrasound Spectroscopy for Nondestructive Evaluation of Thermally Aged Small Pressed Pellets

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As pressed granular pellets of high explosives age, their microstructure changes in the form of microcracks and crystal coarsening, which can affect their explosive performance. However, current methods to interrogate the microstructure can be time consuming, hard to perform in situ, or do not necessarily produce meaningful information. Nonlinear wave propagation in consolidated granular material, such as sandstones, concrete or in this case, pressed pellets, is a function of the microstructure and can be influenced by poor sintering of the grains, micro cracks and grain distribution [1]. Nonlinear Resonant Ultrasound Spectroscopy (NRUS) is a tool that is able to measure the bulk hysteretic nonlinearity by resonating a sample at different amplitudes and observing the shift in resonant frequency. Typically, NRUS has been used on larger samples [2, 3], but in this work, we use the technique to probe small pressed granular pellets that have a diameter of 7.6 mm and a thickness of 1.2 mm that are artificially aged by placing in an oven for a period of time. The samples are resonated by adhering a small piezo-transducer and measured with a laser vibrometer. The nonlinear measurements are compared to explosive performance metrics.

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A sparse-TFM imaging method based on sparse array optimization and new edge-directed interpolation

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Ultrasonic phased array total focusing method (TFM) has the advantages of full-range dynamic focusing and high imaging resolution, but the problem of long imaging time limits its practically industrial application. To reduce the imaging calculation of TFM, the location of active array elements in the sparse array is optimized by combining almost difference sets with genetic algorithm (ADSGA), and corrected based on the consistency of the effective aperture with the equivalent point diffusion function. At the same time, to further increase imaging efficiency, the sparse-TFM image with lower resolution is obtained by reducing the focus points and then interpolated by the new edge-directed interpolation algorithm (NEDI) to obtain the high quality sparse-TFM image. Experimental results show that the quantitative accuracy of the proposed method is only decreased by 1.09% in comparison with TFM when the sparse transmitting elements number reaches 8 for a 32-element transducer, while the imaging speed is improved by about 16 times with the same final pixel resolution.

Figure 1. The results with different imaging methods (a) ADSGA Sparse-TFM, (b) ADSGA-NEDI Sparse-TFM, (c) TFM.

References:
Carbon fiber reinforced plastics (CFRP) are so light and highly rigid that they have been used for aircrafts and other structures[1]. In order to apply these materials to structures, the need for techniques of adhesive bonding or integrated molding has been increased. Also, the structural integrity of joint parts between these materials is a crucial concern. Nowadays, ultrasonic guided waves are expected to be used for inspection of these parts because of their advantages that they can monitor structural health and inspect inaccessible parts[2]. However, the propagation behavior of guided waves through joint parts has not yet been elucidated sufficiently. So in order to use guided waves to monitor the condition of the joint parts, we attempted to investigate the way of guided wave propagation in CFRP panels with joint parts analytically. When joint parts are inspected by using guided waves, the waves must propagate from non-joint area to the other non-joint area through the joint area, as shown in Figure 1. However, when guided waves propagate at geometric and material discontinuities or waveguide transitions, mode conversion can occur[2]. So it is necessary to occur appropriate mode conversion between the non-joint and the joint areas. In order to predict mode conversion, we derived phase velocity dispersion curves to compare phase velocities of these areas, and compute correlation coefficients of displacement profiles to estimate the match of wave structures. An example of correlation coefficients superimposed on dispersion curves for a joint area between the propagation modes in the joint area and one propagation mode in non-joint area is shown in Figure 2. In Figure 2, the solid line indicates the dispersion curve of the propagation mode in non-joint area. From these analysis, we showed effects of various conditions such as the stacking sequence of CFRP plates and the adhesive thickness on the behavior of guided wave propagation through joint parts.

References:
Feasibility of Structural Health Monitoring in a Composite Plate using Omnidirectional SH₀ Transduction

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Structural health monitoring (SHM) is attracting interest from the scientific community to ensure the integrity of safety-critical components by continuously monitoring the host structure. Ultrasonic guided waves are a prominent candidate for SHM because of their ability to propagate over long distances with minimal attenuation. The fundamental shear horizontal (SH₀) ultrasonic guided wave mode is very promising for SHM because of its non-dispersive nature and its through thickness mode shape [1]. Moreover, SH waves do not convert to other guided wave modes when interacting with a boundary or defect parallel to the direction of polarization. In SHM of large panels omnidirectional transduction is preferred so as to maximize the inspection coverage. This paper aims to assess the capability of omnidirectional SH₀ SHM for the detection and imaging of several flaws in a CFRP composite plate with properties relevant to the aerospace industry. Experiments were conducted using three omnidirectional piezoceramic transducers with a centre frequency of 150 kHz [2]. The results show that the non-dispersive nature of SH₀ associated with broadband omnidirectional transducers lead to high resolution images when compared with other fundamental guided wave mode SHM methods.

References:


Expected Phase Suppression for Anomaly Detection in Synchronous Magnetic Imaging NDI

David Gray, Sam Zerwekh and Melissa Natwick. Prime Photonics

The ability to detect non-surface breaking features, including fatigue cracks, poses significant challenge in many non-destructive inspection techniques. The relatively small feature size precludes detection in many amplitude-based measurement techniques. However, for single-tone wave-type techniques - such as single frequency pitch-catch ultrasound, or Synchronous Magnetic Imaging – information about anomalous energies can be retrieved from careful inspection of the phase of the propagation energy. Prime Photonics proposes a data processing algorithm that enables detection of small perturbations in propagating waves by removing the expected phase from wavefield-type measurements. An example of a phase-cancelled waveform is shown in the right of Figure 1, where the response of a back-side EDM notch in a Ti 6-4 plate is apparent in a Synchronous Magnetic Imagining scan, though the signature is not obvious in a raw amplitude presentation of the data. Compared to straightforward amplitude-based processing techniques, phase cancellation enables detection of very small anomalies arising from surface or subsurface cracks, voids, or defects, as well as more distributed effects that arise from changes in specimen stiffness (e.g. delaminations in composites) or local changes in microstructural texturing.

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Figure 1. Longitudinal mode suppressed residual phase in an undamaged Ti flat plate (a.) and a Ti flat plate with a sub-surface EDM notch (b.)
Investigation of the acoustic nonlinear parameter using higher harmonic generation

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Acoustic nonlinear parameters are frequently employed in harmonic generation measurements as a quantitative indicator for material nonlinearity and microstructural features. The determination of the second-order nonlinear parameter ($\beta$) is well established both theoretically and experimentally. With respect to the third harmonic generation, the third harmonic amplitude generally depends on both $\beta^2$ and $\gamma$ (the third-order nonlinear parameter). For most biological fluids and crystalline solids, the experimentally measured third harmonic amplitude is dominated by $\beta^2$, not $\gamma$. Thus, some care should be taken when attempting to measure nonlinear parameters using the third harmonic amplitude. This paper investigates the determination of $\beta^2$ using the third harmonic beam fields in water. In order to improve the measurement accuracy, the diffraction effects are corrected using the quasilinear solutions of the Westervelt equation, and attenuation corrections are made by extracting the attenuation coefficients. The $\beta$ from the second harmonic amplitude is simultaneously measured for comparison. The measured $\beta^2$ in the range of 0.05 to 0.2 m agrees well with the second harmonic measurement, revealing that the third harmonic amplitude is closely related to $\beta^2$. A necessary input voltage is checked for reliable generation of the third harmonic, and the effects of nonlinear parameters on the third harmonic amplitude are discussed.

Acknowledgements:

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Research on the Boundary Reflection Characteristics of Complex Defects in Pipeline

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Quantitative evaluation of complex defects is crucial to understanding the interaction between ultrasonic guided waves and corrosion defects. The majority of researches currently mainly focus on simple and regular pipeline defects[1] and characterization of defects is mainly based on the overall defect reflection signal[2]. Therefore, it cannot realize the three-dimensional quantitative characterization of defects. The complex pipeline defects with the surface profile of Gaussian thickness distribution is modeled with the aid of superposition technique, and we propose an evaluation strategy based on boundary reflection of defects that involves the decomposition of primary reflection signals from defect reflection signal and the analysis of the relationship between the boundary reflection and radial depth change of defects with using identified boundary reflection signals to enable an accurate and quantitative characterization of pipeline defects. An experimental verification of pipeline corrosion is conducted to support the FE simulation results. The strategy reduces the complexity of the concerned defect reflection problem because the combined effect of defect three-dimensional parameters that govern the reflection of guided waves can be therefore decoupled and the interference among reflection components can be efficiently removed, thereby considerably enhancing the reliability and accuracy of quantitative characterization for different pipeline defects.

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References:
Increasing Defect Mapping Accuracy for Robotic Pipe Inspection

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In NDE, robotic inspection systems are becoming common practice in the industry to mitigate impact on health and safety as well as the efficiency of determining the health of a structure. One of the issues with robotics to establish a precise position for an inspection measurement. For NDE this is a challenge for both defect mapping and defect monitoring. If generated defect maps are inaccurate, it becomes difficult to find the correct location to repair or to monitor.

Methods for obtaining position and orientation of a robot on a pipe involve external sensors and systems, such as GPS, or relying on a known start point and encoders. External sensors are expensive, take extra time to calibrate and requires set up, while encoders have error which accumulate with time.

Advances in Micro-Electrical-Mechanical Systems (MEMS) have made localizing sensors smaller and feasible to implement into mobile robotics. One cost-effective device is an Inertial Measurement Unit (IMU) which can measure acceleration with 3 degrees of freedom.

One NDE area which can benefit from robotics is pipe inspection. An algorithm has been developed which calculates the clock face angle (ω) and orientation angle (α) (shown in Figure 1) using only the gravity vector. This approach offers a quick method of obtaining accurate position and orientation information using an internal sensor, which has applications not only for robotics, but for manual scanners as well.

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Figure 1: Problem Schematic for ω and α Angles
Induction Infrared Thermography for Non-Destructive Evaluation of Alloy Sensitization

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Matthew Roberts and Kevin Wang, Virginia Polytechnic Institute and State University, Blacksburg, Virginia

This talk presents a combined experimental and computational study on the efficacy of using induction infrared thermography (IIRT) to detect sensitization in chromium steel. Sensitization refers to the precipitation of certain compounds — Cr$_2$C$_6$ in chromium-steel — at grain boundaries due to cyclic temperature variations, which makes the alloy susceptible to corrosion, environmentally assisted cracking (EAC), and broader failure. Current methods for sensitization detection (e.g. ASTM A262-15 for austenitic stainless steels) require destructive tests in a laboratory environment. The idea of using IIRT as a non-destructive, in situ method is based on the hypothesis that, because the sensitized grain boundaries have a much higher electrical resistivity than the original, non-sensitized grain structure, materials of various degrees of sensitization will produce different heat signatures under induction heating which can be captured using infrared thermography. In particular, it is expected that an IRT camera could detect the local increase in temperature in sensitized regions without explicitly resolving the grain boundaries. In this talk, we first present an experimental study to demonstrate the feasibility of the method. We introduce various degrees of sensitization to chromium-steel specimens through welding and conduct IIRT testing using a customized inductor wand and a FLIR SC8203 infrared camera. Next, we present a computational study to test the aforementioned hypothesis and compare with the experimental results. Specifically, we present a thermo-electro-magnetic model including Fourier’s law of heat conduction and Maxwell’s equations for predicting the electromagnetic field caused by a sinusoidal excitation current through the inductor coil. We also introduce an empirical model to relate the density and thickness of sensitized grain boundaries with the local increase in eddy current density which are solved using a combination of COMSOL and in-house codes. Finally, we compare the experimental and computational results and discuss the capability of the proposed IIRT method for detecting different degrees of sensitization.

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Research on detection and imaging method for corrosion defects of plate structures

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Corrosion, as a common damage to the plate structure, is easy to form defects of various shapes and sizes, and can easily lead to rapid failure of the plate structure. Accurate and effective detection can avoid catastrophic accidents. In practice, recovering useful information about a defect directly from the scattered field is very challenging[1]. Aiming at the corrosion defects in the plate structure, this paper develops a guided wave quantitative identification method for corrosion defects. By calculating the finite element model of the defect geometry as an input parameter, the characteristics of the defect scattering field under different defect geometries are obtained. Using the Markov chain Monte Carlo algorithm, the simulated scattered field is matched with the measured value. Finally, statistics on the nature of the defect (such as depth, shape, size, etc.) are obtained. The simulation results show that this method can effectively invert the defect shape and size information.

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References:
Feasibility of using a fully 3D laser-based transduction system for monitoring the integrity of I-Beams using Rayleigh waves

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This paper presents the investigations using Rayleigh waves to monitor the structural integrity of an I-Beam. Unlike the conventional contact-type of sensors, such as the piezoelectric transducers and magnetostrictive sensors, a fully 3D type of laser-based transduction system was used in the present study to generate and receive the propagating Rayleigh waves. This laser-based transduction system is a new and attractive inspection technique because it can be used where contactable sensors cannot be applied directly to the target structure, such as those with high temperature surface, have limited access for mounting the sensors and are operating in a hazardous environment. In this study, a high power and pulsed Nd:YAG laser was used to emit the required Rayleigh waves. The emission and sensing were performed simultaneously and the wave propagation data was recorded by scanning the surface of the I-beam sequentially. The 3D laser scanner measured the out-of-plane velocities across a user-defined grid. Note that less research effort had been focused on specimens like I-Beam due its structural complexity and complex wave propagation phenomena. Interpretation of wave propagation in such specimens is still a challenge. The research presented here is an attempt to fill these gaps and solve these problems. As a first step, simulations were carried out in order to localize the defect and reveal the characteristics of wave propagating in the tested I-beam. Second step was to conduct experiments to verify the effectiveness in detecting the defect. Within this inspection range, an artificial defect was created on the web part of the I-beam. The responses were recorded using the 3D laser-based transduction system before and after creating the defect. The excitation was in broadband, due to which filtering of the signal was carried out in the frequency-wavenumber domain in order to interpret the responses. Additionally, as the data recorded by 3D laser-based transduction system is less sensitive to environmental disturbances, the data at healthy and defective state can directly be compared. The presented results thereby confirm the robustness of the non-contact generation and measurement setup for the structural health monitoring of I-Beams. The capability of using such totally laser-based transduction system to reveal the characteristics of the propagating Rayleigh waves and its interaction with defects are substantial.

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Baseline-Free Damage Detection of Composite Laminates By Using Time Reversal of Lamb Waves

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A structural health monitoring (SHM) system is developed for damage detection in composite laminates. Most lamb wave-based SHM techniques are rely on reference signal, which are significantly influenced by the environmental and operation conditions. Time reversal (TR) is a baseline-free method, which is widely used for Lamb wave-based SHM system. According to the principle of TR, an input signal can be reconstructed at the actuator location if a response signal captured by a sensor is re-emitted back to the actuator after being reversed in the time domain. Damage diagnosis based on Lamb wave TR relies on the fact that the time reversibility will be broken down when a certain type of defect exists along a wave propagation path. Hence, damage can be diagnosed by comparing the waveform of the reconstructed signal with that of the original input signal. However, the time interval of the response signal components for re-emitted and reconstructed signal components for comparison, which are difficult to determine, have great influence on the accuracy of TR. To simplify the extraction of these two signal components, a time-frequency based method is proposed. The short-time Fourier transform (STFT) and an effective local maximum method are used to filter out the desired mode components from broadband Lamb wave signal. Subsequently, the desired narrow-band response and reconstructed signal can be easily calculated without determining the starting and ending time of the extract time interval. The effectiveness of the time-frequency based TR algorithm and its application are verified by experiments. The results show that the accuracy of the time reversal method (TRM) are significantly enhanced.

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Figure 1. The excitation signal (a) and the extracted waveforms from the broadband response signal (b)
Non-Destructive Testing of Nuclear Structures behind Screen using Leaky Lamb Waves

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The technology of Sodium cooled Fast Reactor has been chosen for the French 4th generation of nuclear power plants. Facing harsh liquid sodium conditions, ultrasonic solutions are studied to perform non-destructive testing (NDT) with a transducer outside of the liquid sodium. The aim is to control the main vessel and other structures behind it immersed within liquid sodium with guided waves (Figure 1.a).

When propagating in a immersed plate, leaky Lamb waves are re-emitting bulk waves in the fluid on each side of the plate, inducing a huge damping [1]. However these bulk waves can be used to generate a new leaky Lamb wave in a second parallel plate, opening the way to the NDT of the second plate [2]. An energy based model (EBM) is proposed here to compute the amplitude of the reflected waves that travel from a default located in the second plate, back to the same outside transducer (Figure 1.b). The first plate acts like a screen to be going through. The EBM is validated by finite element modeling (FEM) and is in good agreement with in water experimentation.

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References:


Evaluating the grain size and orientation of austenitic steel using ultrasonic phased array with through-transmission technique

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Structural noise affects the precision of small defect detection. Aiming to study the influence of grain size and orientation of metal material on ultrasonic wave propagation, austenitic steel blocks with different grain sizes were prepared. The finite element model of the blocks was built with the stiffness matrix of material and the grain information obtained by electron back-scattered diffraction method. According to the constraints between the wave speed and the infinitesimals representing the grains, the ultrasonic beam between each pair of elements was simulated by wave tracing algorithm. A precision through-transmission scanning device based on ultrasonic phased array was designed and built to conduct the experiment, and the received signal of each element is weighted and reconstructed to evaluate the grain size and orientation according to the aforementioned wave path propagation model. By adding the dimension of tilt angle to collect the scattering and diffraction signals at each sampling point, the developed method has obvious advantage of evaluation sensitivity over traditional method. Also the spatial distribution information of the microstructure was obtained by scanning, thus the error induced by the average effect in the traditional ultrasonic evaluation method of discrete sampling was suppressed.

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References:
Laser generation of narrowband lamb waves for in-situ inspection of additively manufactured metal components

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Recent developments in metal additive manufacturing (AM) has created a lot of interest in sectors including automotive, aerospace and biomedical engineering. It is imperative that the components manufactured additively be inspected for flaws, mechanical properties and dimensional accuracy. Several non-destructive testing (NDT) techniques such as X-ray computed tomography and conventional ultrasonic testing have been implemented to evaluate the quality of these components [1]. Recently, research has been focused on techniques that can perform non-contact testing and carry out an online inspection layer by layer while the component is being fabricated [2]. Laser based ultrasonic technique has been found to be a promising method owing to its non-contact nature and ability to operate in harsh environments [3]. In our study, narrow band lamb waves were generated using a pulsed Nd-YAG laser system consisting of a spatial array illumination source. The generated wave modes were detected using a two-wave mixing based laser interferometer. The wavelength-matched method enabled generation of specific lamb wave modes for in-situ inspection of additively manufactured components.

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References:
Trailing Waves for Nondestructive Testing of Thick Plates

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Traditionally, Lamb waves and bulk waves are two main means of ultrasonic-based damage detection for plates [1, 2]. Trailing waves are the transition state of Lamb waves and bulk waves and generated by elastic waves propagating in plates at large frequency thickness product. They perform like a list of longitudinal waves with constant time delay. The phase relationship and amplitude distribution of pulses in trailing waves are discussed. Trailing waves have unique advantages of high resolution and high efficiency for the detection of thick plates. However, the split of waves complicate the interpretation of signals. We propose a compression method to purify the pulse train. The accurate time delay of defects are obtained. It proves that trailing waves can complete the detection efficiently and effectively.

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References:
The interaction between SH\(_0\) guided waves and vertical notches or cracks is already well understood and documented. However, many defects such as stress corrosion cracking generated in high pH environments are much more complex and cannot be modelled under the assumption that the defect is vertical. In order to move towards a practical characterisation method, a finite element model is developed for simulating the ultrasonic response from a tilted, surface-breaking crack, investigating the effect of both the tilt and depth of the defect. The incident wave interacts with the tilted crack to generate a transmitted wave, a reflected wave and a wave trapped below the crack. It is shown that the direction of the tilt of the crack relative to the incident wave direction does not affect the reflection and transmission behaviour. Additionally, for all crack depths a tilt angle can be determined at which zero transmission is obtained, due to destructive interference between the reverberating signals. The importance of the value of the frequency-thickness product is highlighted, showing that transmission nulls only appear for frequency values below the SH\(_1\) cut-off frequency. The critical angle leading to unity reflection depends on the inspection frequency, suggesting that testing below the SH\(_1\) cut-off using a broadband input and exploiting the transmission null will enable the detection and characterisation of tilted defects. Experimental validations of the key results are also presented.

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Fundamental Experiments of Eddy Current Testing for Additive Manufacturing Metallic Material toward In-Process Inspection

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We confirmed detectability of the eddy current testing (ECT) for the inner defects of the additive manufacturing (AM) metallic specimens by performing the fundamental experiments. AM technologies generally called 3D printing are expected to become widely used because the technologies have high added value which is to manufacture complex shaped objects monolithically. A scope of AM technologies is extended to metallic materials in recent years. On the other hand, defect detections in early stage of AM processes and stable qualities of AM products are required since defects may be generated within the objects at the time of manufacturing. Inspection areas of structures made by welding as a conventional manufacturing method are mainly welded parts and heat affected zones except base metal parts. It is assumed that those of monolithic objects made by AM are total area. This expansion of inspection areas makes difficult to set inspection devices such as sensors on complex shaped surfaces of monolithic objects. For that reason, we started investigating applicability of an ECT to an in-process inspection while an AM metallic material is being manufactured. We conducted inner defect detection tests by an ECT from as-built surfaces of metallic specimens manufactured by a powder bed fusion AM process using an electron beam or a laser. From the experimental results, we evaluated that the ECT was able to detect the inner defect of 0.5 mm in diameter which was at 0.5mm in depth from the surface of the specimen in signal-to-noise ratio of 2 or more. We also confirmed that the ECT had the potential to separate inner defect signals from noises caused by the surface shape using the difference in the phase angle between signals and noises.
Optimized Manycore Ultrasonic Simulation Code with Sequential Monte-Carlo Based Parameter Estimation

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Simulation tools can enable optimized nondestructive evaluation (NDE) techniques and a cost-effective path to assess the capabilities and limitations of structural health monitoring (SHM) systems. The utility of NDE modeling and simulation tools is increased by rapid simulation runtimes, for both forward models and inverse solutions. This presentation discusses the implementation of a custom, optimized ultrasonic elastodynamic compute kernel for isotropic materials and its integration into a parallelized sequential Monte-Carlo (SMC) parameter estimation method. The code is optimized to run efficiently on the Intel Xeon Phi Knights Landing manycore compute hardware and uses Message Passing Interface (MPI) and OpenMP threading for parallelization. The scheme exploits multiple levels of parallelism. The compute kernel exploits threading across all physical cores on the compute node, with in-core vectorized instructions, with a cache optimized memory model. SMC then spawns multiple compute ‘particles’ and farms compute work out to a compute cluster with different simulation cases to be executed. The SMC is used to estimate a crack’s location, depth, width, length, and orientation (6 parameters in total) in a thin plate. Setup and computational aspects of that study will be presented here, with detailed results presented in a separate presentation. The goal of this work is to demonstrate a physics-based forward model that runs quickly enough to serve directly as the model kernel for an inverse solution. These optimizations enable movement toward model assisted defect characterization.

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Diagram of the data layout in computer memory related to the simulated plate. The data are laid out in stacks of 2D tiles of data, enabling each thread to perform operations on its local data, reducing contention with neighboring threads for memory accesses. Where the page is set to a width of one or a width of the plate results in “Naïve” (directly mapped/sequenced) memory layouts.
Ultrasound Forward Model Validation of Normal and Angle Beam Inspection of a Quasi-Isotropic Composite Layup with Embedded Damage

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The cost to sustain the United States Air Force fleet is rapidly mounting due to the growing complexity of material systems, aging of structural components, and ever greater demands on performance. These costs can be partially offset by improvements to the nondestructive evaluation techniques used to detect and characterize damage. For composites, the primary sensing method is ultrasound. Ultrasonic characterization of damage can be accomplished via model-based inversion of the response from the damaged region. Therefore, validated forward models of realistic composite materials and inspection configurations are critical for characterization. As the combination of normal incidence longitudinal wave and angle beam shear wave inspection has been proposed to enable characterization of composite damage features, a study validating the forward model for both testing configurations is presented in this work. For this study, a custom immersion ultrasound system (MaPSSII) is used to provide normal incidence longitudinal wave and angle beam shear wave C-scans of a quasi-isotropic IM7/977-3 [-45°/90°/45°/0°]\textsuperscript{3s} composite panel with ultrathin Teflon inserts acting as delamination surrogates. PZFlex is used to simulate B-scans of an inspection in both undamaged and damaged regions of the panel for each probe configuration. B-scans are extracted from the experimental data for comparison to the model outputs. Registration techniques are applied to align the experimental data with simulation results to support a quantitative comparison. Results will be presented for the time-of-flight of the diffracted responses from the Teflon edges and the amplitude of those responses relative to the front wall signal comparing the model and experimental data.

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A Comparison of the Performance of Imaging Strategies for the Total Focus Method (TFM) Beamformer

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The TFM beamformer applied in conjunction with the Full Matrix Capture (FMC) data acquisition method represents a major evolution in ultrasonic inspection capability. Application of these technologies holds the potential to address components with irregular and/or varying surfaces. Materials and components exhibiting directionally anisotropic properties may similarly be addressed via modelling of the material structure during the beamforming stage. Taken together these new capabilities can greatly expand the range of potential application of ultrasonic testing.

The TFM beamformer may be realized applying any one of several representations of the ultrasonic signal. Such possible representations include: the time domain signal, the analytical representation of the time domain signal, and a representation of the signal envelope. Under ideal circumstances where all parameters are known, and error sources have been eliminated, the result of the signal summation should be identical with respect to coherence at the point of focus. However, as error and parameter variation are manifested during the data acquisition process the results of the TFM beamformer diverge with respect to the signal representation employed. This paper explores the effects of error and parameter uncertainty expressed as timing variation on the TFM process when applying a range of representations of the ultrasonic signal.
Multi-Aperture Beamforming for Automated Large Structure Inspection using Ultrasonic Phased Arrays

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The inspection quality and speed are essential in manufacturing applications, especially
for large structures (e.g. the quality inspection of modern aircrafts). Traditional ultrasonic
manual scanning can be comprehensive, but lacks repeatability and is time-consuming. It has
been demonstrated that robotically manipulated ultrasonic phased array (PA) probes can
speed up the inspection of large parts with complex geometries [1], since PA probes have a
wider active area than single element probes. The current bottleneck is given by the time
required to electrically fire all elements of the PA probes, which limits the maximum
scanning speed of the automated manipulators. A paintbrush firing method could increase the
inspection speed, however the simultaneous firing of all elements at once produces unfocused
ultrasonic beams and poor scanning resolution.

This paper discusses the development of a multi-aperture beamforming method to focus
the beam with multiple focusing points at a single firing. The multi-aperture beamforming
scan can run up to six times faster than the traditional linear beamforming. We report herein
on the influence of different sub aperture excitations to evaluate crosstalk in this approach.
Experimental validation uses a 5MHz 64-element phased array (RollerFORM, Olympus) on a
KUKA robot and the FIToolbox (Diagnostic Sonar Ltd) phased array controller. A 50m fiber
optic cable is used to stream the ultrasonic data to a server computer at a rate of up to
1.6GB/s. Figure 1 presents a comparison of the ultrasound datasets acquired on a section of
composite wing using linear and multi-aperture beamforming.

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Autonomous Inspection for Manufacturing and Remanufacturing (AIMaReM) project.

Figure 1. Linear beamforming ultrasound data and Multi-Aperture ultrasound data
acquired on a section of plane wing sample
Simulation Assisted Guided Wave Structural Health Monitoring of Aerospace Structures

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This work describes the comparison of laboratory guided wave (GW) structural health monitoring (SHM) data and simulated data for an aluminum fuselage section undergoing testing at the FAA. The test set up consists of 12 piezoelectric transducers (PZT) which are each actuated individually. Data is then collected from each unactuated sensor. The structure tested was a fuselage panel and the structure simulated was two bays of that panel. The simulations were completed using a custom code implementing the elastodynamic finite integration technique to model GW SHM of metals. The goal of modelling and simulation is not only to provide a deeper understanding of real-world phenomena, but also to enable a cost-effective and feasible route to studying a larger number of defect detection scenarios. Modelling the physics of GW SHM systems provides a path for understanding system dependencies, capabilities and limitations for different damage detection scenarios. This work describes the method for simulating the data and the method for collecting data in the laboratory setting. We also describe progress towards comparing the data sets (experimental and simulation) and the resulting conclusions about defect detectability and the use of simulations to add knowledge to SHM testing and its potential in assisting in the model assisted probability of detection (MAPOD) process.

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Z velocity plotted for a center slice of the simulated panel.
Fast simulation approach dedicated to infrared thermographic inspection of delaminated planar pieces

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Infrared thermography is a popular Non-Destructive Testing (NDT) technique that is typically used to detect delamination and volumetric flaws in composite materials, or to detect small cracks affecting metallic part near the piece surface. Simulation tools provide in this context a great help for designing experimental setups, interpret measurements and characterize inhomogeneities.

In the present work, we propose a fast semi-analytical model based on Truncated Region Eigenfunction Expansion (TREE) method, historically introduced to solve low frequency electromagnetic problems [1]. The problem is thus solved in Laplace domain with respect to time and the temperature distribution is approximated by its expansion on a tensor product modal basis. This approach, limited to canonical pieces geometry, yields very fast and accurate results in this domain of application. Configurations addressed by this model are inspections of stratified planar pieces containing thin delamination patches, as shown in Figure 1. Sources considered in this work are lamps providing an excitation at the surface of the inspected piece. The flaws are modelled as thin air gaps between the piece layers, which consist in an additional resistance to heat flow if the laminate is thermally stimulated. Hence, they are integrated in the modal approach and do not require additional discretization. This work complements a previous work aiming at treating 2D configurations involving induction coils as thermal sources [2]. The principle of the theoretical approach will be exposed and quantitative comparisons with reference data [3] from the literature will be presented.

![Image](image-url)

**Figure 1.** Case of study: inspection of a layered slab affected by delamination flaws using a lamp sources (Left). Modelling thin flaws as imperfect contact between layers (Right).

**References:**

Modelling of guided wave propagation in multilayer, anisotropic and viscoelastic media for the inspection of composite structures.

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Use of adhesives in large composite structures is very common in aerospace industry. As the need for inspection of adhesive bonds increases, the study of ultrasonic guided wave propagation in such large structures becomes important. Composites are usually stacking of plies made of fibers embedded in polymer-based matrices, thus the medium of propagation is heterogeneous, anisotropic and often viscoelastic. There are two possible approaches for the numerical predictions of guided wave modes in plates: a multilayer model considering mechanical properties, mass density, thickness and angular orientation of each ply, or a single-layer model using equivalent properties representing the plate as one homogenous medium. The latter is often preferred because it is much faster and easier to use. However, careful attention should be paid to confirm its validity regarding the structure to be inspected (e.g. thickness and number of plies in the composite), waves to be used (e.g. Lamb modes, SH modes), the frequencies, wavelengths etc. In this study, we look at the effectiveness of equivalent properties in the prediction of guided wave propagation and their interaction with adhesive joints between [0/45/90/-45]_{3S} composite plates, that should be further inspected. Numerical simulations were carried out to study Lamb modes as well as shear horizontal (SH) guided modes in the composite structure. Using the well-known Semi-Analytical Finite Element (SAFE) method, dispersion curves and mode shapes from model using equivalent properties are compared with those from multilayer model. Numerical predictions of reflection and transmission coefficients of the joint are also made using both the concepts mentioned above. Experimental results are used to reinforce the findings from the numerical studies.

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Mobile Efficient Modified Linear Delta Robotic Non-Destructive Examination Platform

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Commercial NDE scanning platforms that are capable of high precision and speed currently lack mobility. Adding mobility to such scanning systems is vital because new technologies in both sensors and components subject to examination will become less effective in terms of performance and cost if they are restricted to the conventional stationary scanning cell paradigm. Unlike conventional serial gantry-type scanning systems, which are often large, bulky, and relatively immobile, the innovative implementation and modification of the linear delta robot configuration proposed here promises to enable the target mobility. This project has developed the design and complex mathematical control of the 3-D scanning (including abstract 3-D paths) platform and demonstrated its application implementing the NDE vibro-acoustic imaging method. The proto-type configuration is also enabled with components possessing precision and speed comparable to stationary and in-field systems while employing components and a configuration with a very centralized center of mass and relatively low moment of inertia optimizing it for mobility and energy efficiency. In addition to single location scanning, the mobility, in combination with the modified linear delta configuration, enables the ability to scan multiple sections of a larger component, resulting in images that can then be stitched together to achieve a complete component representation. The system has shown apt performance when compared to a conventional serial Cartesian robotic system. Kinematic workspace, tolerance, and path planning calculations, essential for design and cost optimization, has been performed using the MATLAB and LabVIEW software, with which graphical outputs will be employed to visualize and communicate computations. CAD software has been used to validate that the available components are compatible and the system is devoid of potential motion interferences when coupled with kinematic simulations. The system has applicability to nearly any NDE method employing scanning methods including ultrasound. This paper will present several applied and potential applications including graphite block scanning and a concept to couple the system with an INL probe plunging mechanism to measure channel gaps between irradiated fuel plates submerged in INL's Advanced Test Reactor. The mobile platform promises to have major impact on many in-field NDE applications (e.g., evaluating pipeline welds, mounted airplane turbine blades, mounted in-service train wheels, in-service nuclear reactor components, and in-canal nuclear fuel [pre- and post-irradiation], etc. As component technologies continue to push the performance envelope in terms of optimized size and new applications, the need for nondestructive in-field health evaluations becomes more imperative. The system also has potential benefit in the 3-D additive manufacturing arena for evolving the current practice of stationary single component development to in-field multiple component integration and repair.

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Comparison of laser triangulation, phase-shift triangulation and swept source optical coherence tomography for non-destructive inspection of objects with micrometric accuracy

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We compare the performance of three optical 3D imaging techniques for the purpose of quantitative non-destructive inspection. Two of these techniques, laser triangulation and phasesshift triangulation, are based on active triangulation [1]; the third, swept source optical coherence tomography (SSOCT), uses interferometry [2]. Phase-shift triangulation is a full-field 3D measurement technique, while laser triangulation and SSOCT usually require point by point (or line by line) scanning. Measurement uncertainties of these techniques can be reduced to a few tens of micrometers or less, making it possible to locate and geometrically characterize defects at the micrometric scale.

In the first part of this work, we compare the three techniques for surface inspection. Although herein we focus on surface defects having a geometrical signature, the results obtained are valid for other cases of surface inspection including for example the monitoring of surface deformation during a manufacturing process. The three techniques are used to inspect surfaces with different optical properties. For opaque surfaces (metallic, ceramic, composite material etc.), the three techniques provide very similar results. For semi-transparent and transparent surfaces (plastic material, marble, glass, etc.), the performance of active triangulation techniques depends on various elements including the hardware features (sensitivity of the camera sensor, integration time, etc.) and the positioning of the system in relation to the surface. For these surfaces, the accuracy achieved by SSOCT relies on the capability of detecting, selecting and classifying the peaks in each axial scan (A-scan).

In the second part of this work, we explore the possibility to combine SSOCT and phase-shift triangulation for the quantitative (surface and internal) inspection and the internal geometrical characterization of semi-transparent and transparent objects. For that, we contemplate various scenarios by taking advantage of two facts. First, SSOCT provides a direct overview of the internal geometric structure of semi-transparent and transparent objects; this is of high value in characterizing complex defects. Second, phase-shift triangulation can perform a full-field (dense) 3D reconstruction of a large area very quickly; this is of high value for real time inspections.

References:
An Inversion Methodology for Ultrasonic Characterization of Titanium Alloys with Microstructures

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Titanium alloys are widely used in the aerospace industry. However, it is known that due to microtexture in those alloys cold dwell fatigue may significantly reduce the part life compared to cyclic fatigue [1]. Microtexture results from regional material anomalies characterized by orientation clustering of thousands of alpha crystallites with preferable crystallographic orientation. To satisfy the practical need for nondestructive microtexture characterization, an inverse ultrasonic methodology is proposed to quantify mean parameters of microtexture regions (MTRs) having ellipsoidal shapes. Although model-based ultrasonic inversion for characterizing MTR sizes and morphology has been reported [2-4], one limitation is that single crystal elastic constants, which are not always available for engineering alloys, are required. The inversion methodology reported in this study overcomes this constraint by adopting the far field attenuation model [5] and the backscattering model for duplex microstructures [3]. The inversion is a two-step process: in the first step, MTR sizes are determined from the directional backscattering ratios and the attenuation-to-backscattering ratios; in the second step, the elastic scattering factors are reconstructed, and those factors are dependent on the effective elastic properties of the MTRs. In this approach, all necessary averaged MTR characteristics are obtained solely from directional ultrasonic measurements (backscattering, attenuation and velocity) without a priori knowledge of material microstructures or elastic properties of different material phases. As illustration of the inversion methodology the mean MTR sizes, morphology and elastic scattering factors were determined from the ultrasonic experimental data collected from a Ti-6242 alloy sample. The inversion results are compared with prior inversion methods and destructive electron backscatter diffraction (EBSD) analysis. It is found that agreement is reasonable.

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References:
A novel Hall-based probe for measuring mechanical properties of structural steels

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In the study, we proposed a novel Hall-based eddy current probe with compact configuration and high sensitivity characteristics for measuring the mechanical properties of structural steels. In addition, the effects of heat treatment on microstructures and mechanical properties of structural steels after quenching and tempering were investigated. The different tempering temperatures led to the differences in the microstructures of samples[1-2]. Optical analysis results indicated that the microstructures of samples mainly consisted of tempered sorbate, tempered troostite and tempered martensite. A high-resolution probe was developed and finite element modelling was carried out to optimize the excitation magnetic circuit for the purpose of improving the spatial resolution. The results of numerical modelling showed that the outer radii of the excitation coil significantly affected the spatial resolution. The Hall sensor was considered as signal receiving device to accept the synthetic magnetic field. A real-time measurement system composed of a data acquisition system and a motion control system was established. A prototype Hall-based eddy current probe with the optimized coil and Hall sensor was developed and the samples with different mechanical properties were tested. The experimental results showed that Hall-based eddy current probe could distinguish the mechanical properties based on the amplitude and phase angle of the ratios, $\eta$. The spatial distribution measurement results of the probe revealed that the spatial resolution of the probe reached 2 mm.

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References:


It is well known that microcracks generate higher harmonics in propagating monochromatic waves. There is a large amount of literature on modeling this phenomenon, but most of these existing papers only describe one specific mechanism. For example, Zhao et al. [1] assumes that the crack faces are either open under tension or closed under compression, and in the latter case they may slide against each other. On the other hand, the Nazarov and Sutin [2] model assumes microcracks as an elastic contact of two rough surfaces, which are never completely separated by an external load. All these mechanisms depend on the level of excitation. In this research, we develop a micromechanical model for the acoustic nonlinearity generation of microcracks by combining the opening-closing model and the rough surface contact model to describe the excitation-dependent nonlinear behavior of distributed microcracks. It is shown that the first and second harmonic amplitudes have the relationship: $A_2 = A_1^n$, with $n$ dependent on the amplitude of excitation, and $2 \geq n \geq 1$ for non-adhesive crack surfaces.

Nanostructured ferritic alloys (NFA) [3] are considered as an example. These materials are characterized by outstanding high-temperature properties, irradiation tolerance and thermal stability, making them a leading candidate for advanced fission and fusion applications. One characteristic property of mechanically processed NFAs is their layer-like structure, with a large number of microcracks aligned in a specific direction. Linear (phase velocity and attenuation) and nonlinear (acoustic nonlinearity, $\beta$) ultrasound measurements with bulk waves are used to characterize this material. The results show that these measurement techniques are sensitive to the orientation of the cracks. The model developed in this research is then used to interpret these experimental measurements and used to characterize the microcracks in a NFA specimen.

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References:


Thickness Determination for Wet Coatings on Composite Materials Using Terahertz wave Technology

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In the industrial field, coatings are employed for various intentions, such as environmental barrier coatings (EBC) and thermal barrier coatings (TBC). These coatings are seriously required their thickness controls because the durability of the components and/or products have been strongly influence by coatings. Electromagnetic and ultrasonic methods are typically applied to thickness determination of coatings. In recent years, composite materials that are employed in various fields have high electrical resistance and it is thus difficult to determine the coating thicknesses by the electromagnetic method. In addition, ultrasonic method has not been applicable to the thickness determination when the coatings are thin (e.g. several tens of microns) due to the weight reduction.

In this study, we developed the determination technique of thickness for thin coatings on the composite materials using terahertz wave technology. Since terahertz waves are transmitted through the coating and reflected boundary between the coating and the substrate, the coating thickness can be predicted from the time-of-flight of the terahertz pulses and refractive index of the coatings [1] [2]. Figure 1 shows the results of coating thickness measurement during drying from after painting. As a fundamental study, aluminum was used for the substrate in order to compare with conventional techniques. Terahertz technique has the equivalent coating thickness measurement result as electromagnetic thickness meter and micrometer gauge, and a decrease in coating thickness during drying was also observed. It is considered that the terahertz waves are able to determine the wet coating thickness nondestructively with contactless, and are applicable to the monitoring under the dry condition of the coatings as well. Measurement results using the composite material as the substrate and multilayer coatings will be presented.

![Figure 1. Determination result of coating thickness during drying from after painting.](image_url)
Characterization and Nondestructive Inspection of Additively Manufactured Materials

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Additively manufactured (AM) components often exhibit significant discontinuities and indications without a clear understanding of how they might affect the mechanical properties of a part during qualification and service. This uncertainty is unacceptable for the design and manufacturing of most aerospace components. Current research in both mechanical testing and nondestructive evaluation involves developing methods for characterizing and inspecting AM components as the use of such materials continues to rise. Although several AM manufacturing methods have been developed in recent decades, this paper focuses on AM production-ready processes for a direct metal laser sintering (DMLS) powder bed fusion machine and will provide background on Sandia National Laboratories’ research efforts in this area. Tensile bar samples manufactured using the DMLS powder bed fusion method were inspected in this study, and the results of ultrasonic spectroscopy for assessing internal flaws will be presented. A combination of modeling, material property evaluation, microstructural characterization, and nondestructive inspection techniques will also be described. The results obtained from these material evaluation methods assist in determining inspection limits and methods for qualifying AM materials.

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Development of a railway inspection unit using phased-array ultrasonic transducers

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Rail transport has been one of the most widely-used transportation types. Because of its economic advantages, the length of railway and train speed have been increasing in Korea, and, in addition, the transit tonnage by rail transport have also been increasing due to the growing number of trains. However, these circumstances also contribute to accelerating the occurrence and progress of defects in rail, and a possibility of serious accidents grows in the rail transport. Therefore, the railway inspection becomes more significant than before, and Korea Railroad Corporation started a research project about development of railway inspection systems at 2015. In this paper, we will introduce the project in the QNDE conference and share the results about the development of a rail inspection unit for detecting defects in rails. Phased-array ultrasonic transducers are equipped for the unit, which make it possible to cover wide range of scan angles and to readily visualize the results. Comparison between the current inspection unit and the unit we developed for Korean railway will be presented.

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Enhanced Phased Array Imaging Through Reverberating Interfaces

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A key challenge to achieve non-invasive process analysis is the transmission of information through the vessel wall. Typical non-invasive technologies, such as Raman spectroscopy, require an optically transparent ‘window’ into the process to acquire the process data. In this work, ultrasonic arrays are used to image a dynamic process through planar steel vessel walls into a fluid load. Due to the acoustic impedance mismatch, only a small fraction of the excitation energy comes back to the receiver in the form of useful echoes from the dynamic process. Also, the ultrasonic energy that is not transmitted across the steel/fluid interface reverberates within the vessel wall, masking signals that are reflected from within the process. Here, the ultrasonic array was deployed using Full Matrix Capture (FMC) followed by the Total Focusing Method (TFM) [1] that focusses the ultrasonic beam at every pixel in the image. The TFM algorithm assumes that all reflectors are point-like in nature, and maps this assumption onto pixels of the image. This assumption can lead to pixel aliasing where signals from two different points in space can incorrectly combine, contributing to the value of a pixel where no real reflector exists. As a result, planar surfaces are rendered as poorly defined clouds, which for reverberating structures creates interference throughout the desired image region. To extract the signals corresponding to the process fluid, a method has been developed called the Reverberation Pattern Gain Correction Method (RP-GCM). Firstly, the algorithm uses ray-tracing to predict the path length of reverberations from the steel interface. The signals in the FMC data set corresponding to these reverberations are then windowed and a gain filter applied, prior to application of the regular TFM process. The RP-GCM has been applied to a simulated FMC data set, developed in PZFlex (PZFlex, LLC). Initial results, shown in Figure 1, demonstrate the effectiveness of this method to separate the vessel reverberations from the ultrasonic echoes of interest relating to the process.

![Figure 1](image_url)

**Figure 1**: A. Overview of PZFlex simulation model. B. Standard TFM image of process region. C. TFM of process region after application of RP-GCM.

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**References:**

Smart Numerical Tools for Fast and Easy Modelling of the Ultrasonic Testing on Curved Composite Structures

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Modelling high-frequency wave propagation is a major asset in numerous advanced industrial fields. Providing a numerical solution to these problems requires complex and expensive calculation procedures, sometimes even hardly parameterized with a generic finite element software whose interface is not dedicated to the targeted control configuration. This is especially true in the presence of a curved carbon fiber reinforced composite structure. In this context, traditional homogenization procedures lead to stratified anisotropic material properties, whose anisotropic orientations depend on the geometric deformation of the specimen (e.g. from flat to curved media). Indeed we must be able to associate the desired local orientation with each point inside the mesh and ensure a discretization sufficiently fine to account for the stack in the curvature. For these practical reasons an over-refined mesh, for which the local orientation is considered constant in each (small) cell of the mesh, is often favored. It results in a drastically limitation of the computational performance, thus making it difficult to access any parametric study based on modelling.

For few years now CEA LIST propose a numerical computation strategy based on a specific use of high order spectral-like finite elements [1]. The overall computation performances are enhanced by considering block-structured subdomains, enabled by a domain decomposition approach. Here we extend this strategy to ultrasonic inspections of carbon fiber reinforced composite structures by considering two coordinate systems representing the specimen prior to and after its deformation. Passing from one system to another enables efficient on-the-fly reconstruction of local fiber orientation. In this talk we will present the advances of the integration of these specific tools into the CIVA software platform.

Figure 1. Guided (left) and bulk (right) wave propagation in curved stratified composites.

References:

Calibration of Ultrasonic Hardware for Enhanced TFM Performance

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In Non-Destructive Evaluation (NDE), phased array calibration typically pertains to its beam steering and focussing ability. This paper demonstrates a robust methodology for ultrasonic hardware calibration that aims to investigate hardware integrity rather than beam integrity. To achieve this, information is extracted from the Full Matrix Capture [1] of the reflection from a planar interface. Using a 128 element linear phased array coupled to two different Phased Array Controllers (PACs), multiple FMC datasets are acquired under identical experimental conditions. The purpose of this work was to increase the reliability of measured ultrasonic data by providing an understanding of the variation between FMC datasets, individual array elements and PACs. The FMC diagonal matrix, corresponding to signals with the highest degree of scattering certainty, were used to infer the bandwidth, pulse length, sensitivity and peak time for each element. Following this, using the measured peak time and the empirical time-of-flight (TOF) to the back wall, a relative Delay Factor (DF) was established for each element. The DF was incorporated into the Total Focussing Method (TFM) [1] to offset the TOF estimated for each image pixel. The DF was applied to a typical steel NDE calibration block, shown in Figure 1, where the Array Performance Indicator [1] has been enhanced by 56 %. In addition to this improved TFM image performance, a key finding of this work was that the DF matrix was different depending purely on the PAC used to drive the array. Therefore, a conclusion of this work is the recommendation that calibration of ultrasonic hardware should always pertain to the coupled array-PAC system.

Figure 1: A. Standard TFM. B. Delay Factor applied to TFM.

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Investigation of higher-order guided ultrasonic waves in a welded plate

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Guided ultrasonic waves with strong mode confinement in the feature area of plate-like structures, i.e. feature guided waves (FGW), have manifested their NDT and SHM capabilities, in term of enhanced interrogation of structural features and increased propagation distances. In the earlier work, two fundamental FGW modes, of either shear or compressional nature, have been reported to exist in weld joints, and their interaction with different types of defects located in the Heat Affected Zone (HAZ) has been investigated. In this study, we explore the feasibility of exploiting higher-order weld-guided waves for long-range screening of welded joints, towards inspection of more specific hotspots in the weld and higher defect resolution.

Modal studies of the waveguide are performed by using the Semi-Analytical Finite Element (SAFE) modelling approach, combined with the Perfectly Matched Layer (PML) techniques. Multiple families of weld-guided modes are identified, with wave energy highly concentrated in different portions of the weld joint, such as in the weld cap, the central region of the weld, as well as in the HAZ adjacent to the weld. The physics underlying such FGW phenomena is discussed, and proper mode-frequency combinations are suggested for NDT applications due to their potential of screening long welds for rapid detection of localized damage. Modal properties of these higher-order modes are cross-verified by the 3D Finite Element (FE) simulation. Preliminary experiments are carried out as well to validate the modelling results.
Uncertainty sensitivity analysis of damage tolerance evaluation with ultrasonic data

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The study presents a method for sensitivity analysis of damage tolerance evaluation with ultrasonic NDE data. The model-assisted probability of detection (MAPOD) is employed to model the uncertainty of ultrasonic flaw sizing. A global sensitivity analysis method is proposed to investigate the influence of uncertainties from flaw sizing, material properties, and fatigue life model parameters. The uncertainty sensitivity modeling in this study deals with parametric distributions. For any given function $g(x)$ with an uncertain parameter vector $\theta$ under the PDF of $f(x; \theta)$, the expected value and variance of $g(x)$ are

$$g_{\theta} = \int g(x)f(x; \theta)dx = E_{\theta}[g(x)],$$

and

$$\text{Var}_{\theta}(g) = \int [g(x) - g_{\theta}]^2 f(x; \theta)dx = E_{\theta}[g^2(\theta)] - g^2_{\theta},$$

respectively. The partial derivative of the expected value of the response function with respect to the distribution parameter $\theta$ writes

$$\frac{\partial g_{\theta}}{\partial \theta} = E_{\theta}[g(x) \frac{\partial \ln f(x; \theta)}{\partial \theta}].$$

It is noted that the uncertainty is quantified as the derivatives of the response function with respect to the distribution parameters instead of uncertain variable themselves; therefore, it is considered as a global sensitivity measure. By utilizing this sensitivity measure, the global uncertainty contributions of different uncertain sources can be quantified. For damage tolerance analysis with inspection data, the fatigue crack propagation life and probability of failure are of interest. The time-dependent uncertainty sensitivities of sizing uncertainty and fatigue model parameters can be evaluated. Figure 1(a) presents the probability density function (PDF) of the true flaw size using MAPOD modeling and a given equivalent reflector size (ERS) of 2.1mm from ultrasonic inspection. Figure 1(b) presents the time-dependent probability of failure (PoF) of a steam rotor burst event when the rotor operates with the flaw. The corresponding time-dependent uncertainty contributions of ultrasonic flaw sizing, $\ln$(TFS), and the crack growth model parameter, $\ln$(c), are evaluated and shown in Figure 1(c). It can be seen that the sizing uncertainty plays a significant role in the overall uncertainty of PoF assessment. Based on the sensitivity results, a guide for uncertainty reduction for fatigue life extension can be suggested. For example, the overall uncertainty in fatigue life prediction and PoF evaluation can be reduced if more accurate and reliable sizing can be achieved through more advanced inspection or data interpretation methods.

Figure 1. (a) The probability distribution of a true flaw size obtained using MAPOD and an equivalent reflector size (ERS) of 2.1mm from ultrasonic inspection, (b) probability of Failure (PoF) evaluation of a steam turbine rotor, and (c) the corresponding time-dependent uncertainty sensitivity results in terms of uncertainty contributions from flaw sizing and material properties.

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Model uncertainty quantification and assessment for probability of detection (POD)

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The study presents a method of uncertainty quantification and assessment for probability of detection models. The method considers model itself as an uncertain variable, and a hierarchical uncertainty modeling framework is established based on Bayes probability theory. The overall flowchart of the method is shown in Figure 1, where each model is a suitable POD model for the sizing data. To evaluate the probability of models and its parameters efficiently, the reversible jump Markov chain Monte Carlo is employed to estimate the distribution of model parameters and the probability of each models simultaneously[1]. The basic idea is to recast the target densities by adding additional random variables to match the dimensions between two model parameter spaces. By transferring the sample from one parameter space to another via coordinate transformations, the chain can move across models with different dimensions, as illustrated in Figure 2. Two sets of realistic ultrasonic sizing data are used to demonstrate the effectiveness of the overall method.

![Figure 1 Bayesian POD model assessment framework](image1)

![Figure 2 Illustration of a Markov chain in the general state space](image2)

Acknowledgement:

This work was performed with support from the Science Challenge Project of Chinese Academy of Engineering Physics, No.TZ2018007.

References:

Laser lock-in thermography on dental inspection

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Detection of the defects in teeth and the evaluation of a dental restoration in a non-invasive way is of paramount importance in clinical practice. Common dental X-rays diagnose is precise but causes a lot of concerns due to its ionizing radiation nature, not-so-comfortable patient experiences, as well as used-in-caution for women in pregnancy, etc. The advanced works on dental inspection using laser lock-in thermography has proven to be effective with good sensitivity and resolution. Using low laser power without causing damage to the dental pulp, the minimum detectable open crack at the cavity-restorative materials interface has an average width of 1 µm, which is close to the diffraction limit of the IR camera [1]. The defect information is further extracted with better resolution using phase versus amplitude image signals [2]. Lock-in thermography showed the most promising results in detecting both marginal and internal defects. Consequently, clinical use of a thermographic camera in assessing the marginal integrity of a restoration becomes feasible. The results support the use of an IR camera in dentistry, for the diagnosis of micro-gaps at bio-interfaces. The aim of this study is to compare the detection efficiency using different laser wavelength, power, as well as laser modulation frequency.

![DC Image](image1) ![Amplitude Image](image2) ![Phase Image](image3)

Figure 1. DC and lock-in IR amplitude and phase images of sample.

References:
Austenitic weld stiffness map inversion powered by GPU-accelerated finite element simulations

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Austenitic stainless steel welds pose a well known challenge to ultrasonic inspection. The solidification process, including epitaxial growth, yields microstructures, in which the orientation of columnar grains and their size vary significantly across the weld. Consequently, ultrasonic beams take rather complex paths and are affected by scattering, attenuation and dispersion. One way to allow insightful inspection of such structures is to construct a map depicting the variation of the elastic tensor inside the weld. The synthesis of such a map can be done based on ultrasonic array measurements and an inversion process, usually powered by a model. To date, inversions based on a ray tracing model have been reported [1]. The main advantage of that model is its execution speed, at a cost of neglecting grain scattering effects. In this paper, we investigate stiffness map inversions based on finite element simulations, which allow for defining both grain orientation variation and grain size distribution. The aim of this work is to assess the effect of the granular structure on the inversion process and establish guidelines for the experimental investigation. Weld map inversion based on finite elements became possible thanks to fast, GPU-accelerated simulations [2]. Consequently, our approach enables the generality of the weld configuration to be retained without incurring unbearable computational costs.

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References:


Efficient Calculation of the Eddy-Current Crack Response around Conducting Fasteners

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The eddy-current testing (ECT) of fasteners is an important task for the structural health assessment of the aircraft fuselage. The reason is that this particular part of the aircraft structure is prone to the appearance of fatigue cracks due to the stress concentration around the fastener hole.

Due to the complexity of the fastener geometry in combination with the weakness of the crack signature (crack signals are small perturbations to the base geometry signals) the accurate simulation of ECT in those regions is a challenging task. The perturbative nature of the problem makes the use of integral equation approaches a suitable choice for this type of problems [1]. Nonetheless, the application of the integral equation method (VIM) requires the explicit expression for the Green dyad corresponding to the geometry of the flawless medium. Although the Green operator has been constructed for the simplified case of a cylindrical fastener hole [1], we still lack an expression for the Green dyad for the typical hole geometries (e.g. holes with conical parts). Things become even more complicated when the fastener is present since it introduces an additional perturbation to the total signal.

These issues can be partially addressed if we include all deviations from the nominal cylindrical hole geometry in the integral formalism [2], which however increases the size of the problem we need to address. An alternative approach consists in calculating the primary field (field in the absence of the flaw) for the exact problem geometry using a numerical technique and superposing thereupon the flaw signature calculated by the VIM using an approximate Greens operator. This technique has been successfully applied in the past for the calculation of flaw responses in steam generator tubes under or near support plates [3].

In this work, the latter hybrid approach will be considered in order to address the problem of the crack inspection in the vicinity of conducting fasteners binding multilayered structures. For the calculation of the primary field, a mixed numerical modal approach will be considered, which allows the exploitation of the rotational symmetry of the structure [4].

**References:**

3-Dimensional Forward Ultrasonic Models for Aerospace Applications

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The development and use of forward sensing models in NDE applications is becoming more common as computer hardware and software advances have occurred within the past decade. In this effort, the development of 3-dimensional sensing models is of interest, where the time-evolving nature of ultrasonic waves propagating within complex material systems is being studied for aerospace applications. Previous research [1-3] has shown the value of utilizing computational tools and forward ultrasonic models in the understanding of damage scattering processes [1] and material heterogeneity effects on the propagating waves [2,3], but in most instances the ultrasonic models have been limited to 2-dimensional studies [1,2] or small 3-dimensional volumes and idealized pressure wave studies [3]. In the present effort, two advances in 3-dimensional sensing models are reported including: 1) the collection of piezoelectric signal information in addition to the wave propagation and scattering information, and 2) the extension of 3D models to macro-scale sensing applications, both of which are needed for practical sensing studies in aerospace materials. Examples are provided for immersion and contract transducer applications involving polycrystalline aerospace material systems.

Figure 1. Example of 3-dimensional wedge transducer model and surface wave generation.

References:
Coherent Ultrasonic Backscatter within a Textured Titanium Alloy

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The ultrasonic scattering from macro-texture regions (MTRs) within a Ti-6Al-4V titanium alloy are analyzed for mode-converted shear wave interactions. Crystallographic orientation information gathered from electron backscatter diffraction (EBSD) measurements are used to guide the analysis, where critical orientations of the MTR crystallites were identified and analyzed with respect to misorientation states, grain feature sizes, and shear wave propagation directions. The analysis suggests that macrotexture regions (MTRs) within the titanium alloys can efficiently scatter and reflect the ultrasonic energy in a coherent manner when MTR size, misorientation states, and grazing-incidence conditions are met for the shear-wave fields [1,2]. Analysis results are provided for reflection and refraction from a representative macrotexture feature in a realistic material system supported by EBSD measurements and analysis. The results are expected to be important for NDE polycrystalline material inspections and characterization in aerospace applications.

![Focused beam launched at 16° of incident angle](image)

**Figure 1.** Coherent reflection from macrotexture feature in titanium.

**References:**
Characterization of the linear-acoustic material behavior of fiber-reinforced composites using Lamb waves

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Although ultrasonic measurement techniques are widely used in non-destructive detection of material defects, the material parameters are still mostly determined destructively, which is considerable problematic in the determination of Poisson’s ratios. One non-destructive method is the evaluation of guided ultrasonic waves, which application on fiber-reinforced composites is also challenging due to their high acoustic absorption and anisotropy. In this contribution Laserinduced Lamb waves are used in the acoustic characterization of plate-shaped specimens. However, pure Lamb modes are independent of the third spatial dimension, so this approach does not yield a complete description of material behavior by evaluation of Lamb waves only. While for some special cases, e.g. isotropy, a complete set of parameters can be derived, this cannot be directly applied to composite materials. Therefore, multiple measurements are performed for different rotations of the sample plate, so that the entire 6x6 elasticity matrix can be determined by combining the individual measurement results. [1] The procedure is exemplarily applied onto fiber-reinforced polymer plates with different fiber weave patterns (plain weave and twill). Although neither mode conversion is considered in the forward model nor shear horizontal modes are evaluated and despite high absorption the complete elasticity matrix containing both Young’s and shear moduli and Poisson’s ratios can be determined. The resulting values for Young’s modulus (in-plane) and Poisson’s ratio are shown in Figure 1, which coincide with the ones predicted by laminate theory [2] and micromechanic simulation approaches [3].

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Figure 1: Resulting Young’s moduli and Poisson’s ratios for plain weaved and a twilled composite plate (left, middle) with a 50:50 fiber distribution ratio and Young’s moduli of a twilled composite plate with 80:20 fiber distribution ratio (right).

References:
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 nonlinear ultrasonic measurements of stainless steel specimens thermally aged to produce grain boundary precipitates to measure the veracity of said model.

Acknowledgement

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![Normalized β for increasing heat treatment at 675° C for annealed stainless steel 304 and 304L.](image)

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

References:

Using zero-group-velocity Lamb waves to determine thickness and bulk sound velocities of isotropic plates

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We present an ultrasound method to simultaneously determine the thickness of a plate together with the longitudinal and shear elastic wave velocities of its material. The method works without assumptions or a priori knowledge of the plate thickness or the sound velocities usually required in order to obtain the other quantity from time of flight measurements. The method is based on the measurement of the frequencies of two zero-group velocity (ZGV) Lamb modes and one respective wavenumber (see Fig. 1). ZGV Lamb waves are resonant waves which appear at multiple defined angular frequencies $\omega$ and wavenumbers $k$ in the Rayleigh-Lamb dispersion spectrum of plates, where the group velocity $c_G = \frac{d\omega}{dk}$ becomes zero [1,2,3]. We use this relation, which depends on the elastic properties, the mass density and the thickness of the plate in an inverse problem to obtain the properties of the plate. Experimentally, the frequencies of ZGV points can be obtained at high precision by measuring the elastic response spectrum of a plate, using laser-ultrasound techniques. By shaping the excitation laser spot with a spatial light modulator, we extend this to enable measurements of the corresponding wavenumber. The introduced method is demonstrated for a tungsten and an aluminium plate.

The research was supported by the strategic economic- and research program "Innovative Upper Austria 2020" of the province of Upper Austria and the Austrian Science Fund (FWF), project number P 26162-N20.

Figure 1 A: Measured elastic response spectrum of a 127µm thick tungsten plate to focused laser excitation, results in $f_{ZGV1}$ and $f_{ZGV2}$; B: Elastic response of a plate at $f_{ZGV1}$ to annular excitation laser spot with radius $R_0$, results in $k_{ZGV1}(R_{ZGV1})$; C: Measurement principle for annular excitation

References:
High Speed Hollow Axle Inspection with a new designed Cone Type Phased Array

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Hollow axle inspection can be performed without demounting the axes and without dismantling the wheels and the brake discs by using the drilling for the scan. To increase inspection reliability and inspection speed the application of phased array systems instead of conventional probes is a good choice. For solid shaft inspection phased array setups became standard in the recent years. But for hollow axle inspection typically a number of conventional probes rotating through the axles drilling are applied.

The new approach uses an electronically rotating sound field for the circumferential scan realized by a cone shaped phased array which operates in immersion technique. That allows a significant increase in inspection speed and a reduction of the mechanical effort of the inspection system. The inspection can be carried out by a linear movement of the probe setup along the axis drilling. Applying additional focal laws allows exact inclination and focussing of the sound beam in the plane vertical to the specimen axis to concentrate the sound in the zones close to the external surface. An additional focus in the plane of incidence increases overall resolution and sensitivity.

The cone type phased array probe has been optimized to detect transversal flaws in and close to the outer surface of the hollow axle with orientation in the radial-radial plane. The prototype probe system, sound field simulations and measurement results will be presented.

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Figure 1. Cone type Phased Array for electronic beam rotation
Reflection study of Shear Horizontal Guided Wave Modes with Plates Edge at Different Incident Angles

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This study investigates the reflection behavior of SH guided wave modes from a flat plate edge. Different SH modes viz. SH0, SH1 and SH2 are generated using Periodic Permanent MagnetElectromagnetic Acoustic Transducers (PPM-EMAT) of constant wavelength (\(\lambda\)). Reflection characteristics of these modes were studied by varying the angle of incidence from 0\(^\circ\) to 70\(^\circ\). The probes are positioned in such a way that incident and reflected angles are equal. The response of different SH modes at the various angle of incidents was explored in terms of amplitude variation and frequency shift. 3D finite element models were developed to further investigate reflection characteristics of different modes. The exact configuration of the PPM-EMAT has been simulated using a two-stage modelling approach. The spatially varying Lorentz force was calculated in the electrodynamic module and then applied to the elastodynamic module and the resulting elastic disturbances are compared with experimental results.
The Dispersion Curves and Wave Structures of Lamb Waves in Functionally Graded Plate: Theoretical and Simulation Analysis

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Functionally graded materials (FGM) have received extensive research and attention in recent years for their excellent structural properties. Ultrasonic guided waves (such as Lamb waves) propagated in FGM plates possess obviously dispersion characteristics. Therefore, it is of great academic value to extract the relationship between the dispersion curves of ultrasound guided waves and the material properties in FGM plates. In this research, the theoretical process of calculating the propagation characteristics of Lamb waves in FGM plates is deduced by combining the FGM volume fraction curve (shown in fig.1)[1] and Legendre polynomial series expansion method[2]. In this proposed method, it avoids slicing the FGM plate into multiple layer. A Mathematica program for numerical calculations was developed, then the Lamb wave dispersion curves were solved, shown in fig.2. For comparison, the Lamb wave dispersion curve of sliced layer model of a FGM plate is drawn in Disperse software, the results verify the validity of the numerical calculations. Meanwhile, in PZFlex software, the FGM plates was subjected to finite element simulation, also based on the layered plates model. The acoustic characteristics detection experiment (also know as $V(f,z)$ measurement) was performed in the PZFlex simulation, thus the Lamb wave dispersion curves were extracted. The influence of the change of the gradient function on Lamb wave dispersion curves was discussed.

Acknowledgement:
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References:
Simulation analysis of a micro-strip antenna strain sensor based on RFID

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In order to realize the wireless detection of strain, a micro-strip antenna strain sensor based on RFID (Radio Frequency Identification), using ultra high frequency through electromagnetic wave interaction is proposed and analyzed [1]. The micro-strip antenna sensor, as a tag antenna, receives the RFID signal, which also can activate the chip in RFID tag. The background noise can be eliminated by the signal modulation. Then, the effective signal will return to the antenna, and the deviation of the resonant frequency will inform the reader to realize the wireless passive strain detection. In engineering, the lowest echo loss $S_{11}$ is considered as the resonant frequency of the antenna [2]. Through the analysis of solid mechanics coupled with electromagnetics by FEM using COMSOL, the sensor’s structure and strain’s response are obtained and shown in figure. 1 and 2. The resonant frequency decreases with the increase of strain. A linear relationship between the resonant frequency deviation and the strain is extracted, which shows proportionally $K=0.880\text{kHz}/\mu\varepsilon$, as shown in figure 3. In addition, due to that each RFID chip possesses a unique identification code, as a result, the RFID reader can read multiple chip at the same time. The micro-strip antenna strain sensor based on RFID system provides a new wireless tool for high-end equipment structural strain monitoring.

![Figure 1: Structure of sensor](image1)

![Figure 2: Strain response of sensor](image2)

![Figure 3: Resonant frequency and strain relation of sensor](image3)

(a) Return loss $S_{11}$ curve under different strain actions, (b) The fitting curve of resonant frequency and strain relation.

Acknowledgement:

This work was performed with support from the NDT&E center of Beijing University of Technology.

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1. MO L F. UHF RFID tag anti metal [D]. Hangzhou : Research Department of control science and engineering Zhejiang University, 2009
Multi-Gaussian Beam Effects on Pitch/Catch Diffuse Ultrasonic Backscatter

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Microstructural information of polycrystalline media can be extracted from the effective ultrasonic grain scattering. Recently, longitudinal-to-transverse (L-T) and transverse-to-transverse (T-T) scattering models were developed for estimating the diffuse ultrasonic backscattering of the corresponding experimental pitch/catch configurations. As with previous longitudinal-to-longitudinal (L-L) scattering models, both L-T and T-T models were used successfully to determine the material correlation length L by using the model to fit experimental results. However, research on the T-T model has shown better agreement at low frequencies suggesting insufficiencies in the theoretical model. In this presentation, a multi-Gaussian beam (MGB) is used in place of the single-Gaussian beam (SGB) that has been used extensively for the L-T and T-T models of pitch/catch configurations. The effects of the focal length, center frequency, and the incident angle on the Wigner transform amplitude based on the MGB are investigated in the numerical calculations. Furthermore, comparisons between SGB-LT/TT scattering response and MGB-LT/TT model scattering response are examined using both numerical analyses and experimental measurements. The proposed models are anticipated to extend the range of pitch/catch ultrasonic scattering model, especially in terms of higher detection frequencies.

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Detection of second harmonic guided waves using electromagnetic acoustic transducers

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The nonlinear guided wave method is a nondestructive inspection method having both merits of guided waves and nonlinear ultrasonics. By detecting harmonics excited from fundamental waves by nonlinear resonance, this method can efficiently measure changes in nonlinear material constants that may be caused by plastic strain and so on.

In studies with the nonlinear guided wave method, analysis using a perturbation method has been usually carried out [1]. In the analysis using the perturbation method, the amplitude of the second harmonic wave generated from the fundamental wave by the nonlinear resonance is said to increase in proportion to the propagation distance. However, in order to solve some problem found in using perturbation methods, analysis using the method of multiple scales (MMS) has been conducted very recently [2]. MMS analysis shows that the amplitude of the second harmonic increases with the propagation distance, but that it is not proportional.

In this study, a second harmonic nonlinear guided wave was detected using electromagnetic acoustic transducers (EMATs) [3]. Whereas piezoelectric elements can only adjust the input frequency, EMATs can also adjust the input wavenumber when transmitting waves. Therefore EMATs are suitable for transmission of guided waves by targeting a specific propagation mode. Further, it is also possible to excite ultrasonic waves without contact, so that nonlinearity due to contact has no effect. Obtained results are similar to the results predicted by MMS.

Acknowledgement:

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References:

Eddy Current Inspection System for Fatigue Crack Detection in Welded Joints of Clad Pipelines

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The potential for fatigue cracks to occur in pipeline structures due to cycling loads inherent of offshore oil production, such as, tide variation, waves, etc., makes necessary have an inspection tool to carry out periodic NDT. The most critical point of pipeline structures is the circumferential weld and demands special attention during inspection. Figure 1A presents a section of clad pipeline with a base material of carbon steel API X65 coated with Inconel 625 and highlighted the inspection region with the crack position. This scenario, detection of fatigue crack in Inconel, encouraged the development of an eddy current (EC) system with the goal to inner inspection of clad pipelines. The main challenges are the circumferential weld geometry and the fact that the inspection tool must operate high speed condition. An orthogonal eddy current transducer was applied to detect the crack in the weld bead root. An electronic hardware was built to drive the transducer and evaluate the testing coils electrical impedance by the means of Goertzel algorithm [1]. Figure 1B presents the inspection results with the notch besides the weld bead. One can observe that the defect indication was clearly separated with a SNR of 14 dB.

Figure 1. A: Clad pipe with the inspection region highlighted, and B: inspection result of the clad sample with the circumferential weld bead.

References
Monocrystalline silicon wafers are employed in the photovoltaic industry for the manufacture of solar panels with high conversion efficiency. Micro-cracks can be induced in the thin wafer surface during the cutting process. High frequency guided waves are considered for the testing of the wafers and the nondestructive characterization of the micro-cracks. The material anisotropy of the monocrystalline silicon leads to variations of the guided ultrasonic wave characteristics depending on the propagation direction relative to the monocrystalline silicon orientation. In non-principal direction of the crystal, wave beam skewing occurs due to material anisotropy.

Experimentally selective excitation of the fundamental Lamb wave modes was achieved using a custom-made angle beam transducer and holder to achieve a controlled contact pressure. The out-of-plane component of the guided wave propagation was measured using a noncontact laser interferometer, scanned parallel to the specimen using a positioning system.

Artificial defects were introduced in the wafers using a micro indenter with varying force. The defects were characterized from microscopy images to measure the indent depth and combined crack length. The scattering of the A₀ Lamb wave mode was measured experimentally and the characteristics of the scattered wave field were correlated to the defect size. The detection sensitivity is discussed.
Eddy Current System for Complex Geometry Inspection in High Speed Application

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The application of clad material to subsea pipelines is gaining ground in deep water oil exploration. Its bimetallic configuration presents an attractive combination of mechanical strength and corrosion resistance, ensuring the safety and integrity of pipelines that connect the reservoir to oil rig. The clad material for oil exploration consists of a base material, usually carbon steel, inner coated with a thin layer of corrosion resistance alloy (CRA), turning into an attractive economical solution for deep water exploration since only a small portion of the noble anti-corrosive and expensive alloy is required. The potential for fatigue cracks to occur in pipeline structures due to cycling loads inherent of offshore oil production, makes necessary have an inspection tool to carry out periodic non destructive inspection in the inner pipe surface. The most critical point of pipeline structures is the transition point between the inner clad surface and the circumferential weld root, figure 1A, and demands special attention during inspection. The results achieved with the inspection system, hardware and sensors, developed in the current work, demonstrate the feasibility to apply eddy current technology to detect fatigue cracks in welded joints of clad pipes in a speed range of 0.5 m/s, figure 1B.

Acknowledgement:

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Figure 1. A: Clad weld bead macro with an EDM notch representing the fatigue crack. B: inspection result of the clad weld joint with the EDM notch indication.
Passive thermography is used for real time damage detection during quasi-static load testing of a composite single stringer hat stiffened panel. When significant subsurface damage is detected the composite panel is unloaded to enable a more precise determination of damage extent by X-ray CT or ultrasound inspections. This enables characterization of damage growth through-the-thickness and provides critical information to validate structural designs and damage progression models. A significant advantage of passive thermography is precise, real time location and imaging of damage. Passive thermography data were processed to enhance defect contrast for comparison to other NDE techniques. In particular, passive thermography data have shown good correlation between the real time thermal indications and acoustic emission. The relationship between the measured transient thermal signatures is compared to the acoustic emission event time to estimate damage depth. The thermally detected damage size is also compared to the acoustic event energy. Lastly, estimations of the flaw size, as determined from passive thermography, are compared to ultrasonic through-the-thickness measurements.
Topological Imaging of Tubular Structures using Ultrasonic Guided waves

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Tubular structures are widely used in a variety of industries such as Aerospace, Oil and Gas, Nuclear, etc. Non Destructive Evaluation of these structures plays a crucial part during its life cycle. In order to test large structures with limited accessibility, Guided wave testing was developed as a viable solution. The aim of this work is to obtain the 3D topological image of multilayer isotropic tubular structures. This work follows from the work on topological imaging in plates and looks to extend the solution to cylindrical structures. The method of imaging consists of performing a correlation between the direct and adjoint wave fields for defect localization. The wave equation is expressed as a function of the spatial variables $\theta$ (angular position) and $z$ (axial position), and temporal variable $t$ (time) for each radial position ($r$) of the cylinder in the real domain. Using Fourier and Laplace transforms, this equation is converted to an ordinary differential equation with respect to $r$. There is no general solution for this analytical equation. However, a solution exists for the transversely isotropic case in the form of 6 partial waves which can be expressed as combination of the modified Bessel’s function of the first ($I_n$) and second kind ($K_n$) with normalized amplitudes. The layers are assembled using continuity equations to obtain the complete field in the structure and inverse Fourier and Laplace transforms are performed to obtain the real wave field. Using the aforementioned technique, a quick robust semi-analytical algorithm is employed to obtain accurate topological images.

Figure 1: Topological Image of Defect

Acknowledgement:

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Influence of magnetostrictive strip size in the generation of L(0,2) and T(0,1) wave mode using MPT

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Magnetostrictive patch transducer (MPT) is widely used to generate ultrasonic guided waves in non-ferromagnetic materials. MPT majorly consist a solenoid, biasing magnet and magnetostrictive strip material. The objective is to investigate the influence of magnetostrictive strip size in the generation of L(0,2) and T(0,1) wave mode at a low-frequency regime using finite element and experimental study. To understand the physics of wave characteristics, a 3-D finite element model was developed. For simulating the effect of magnetostrictive strip size, a displacement field was applied in an area (transduction region) whose dimension is equal to the strip size. The effect was analysed by varying the length and width of the transduction region. For experimental study, a 3.6-meter 3-inch aluminium pipe with a notch and hole defect is used, and the size of the strip varied along the axial and circumferential direction of the pipe. The effect of strip size in the acquired signal is characterised based on the signal strength, SNR and the wave modes generated. This study leads to the efficient optimisation of magnetostrictive patch transducer in the generation of L(0,2) and T(0,1) wave modes for long-range inspection.
Detection of disbonds in multi-layered aluminum plates by local wavenumber estimation of guided ultrasonic waves

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Adhesively bonded multi-layered structures are commonly used in aerospace industry due to their favorable structural properties. Nondestructive evaluation of bond integrity in such structures is both very important and difficult to perform efficiently. Detection of disbonds can be performed using a typical ultrasonic through-transmission C-Scan system. Detection in this case can be performed successfully but the process is time-consuming when applied for large surface areas and cannot be applied in operating conditions as access from both sides of the structure is required. The use of guided ultrasonic waves and Local Wavenumber Estimation (LWE) technique provides a potential solution to this problem. It takes advantage of the dispersive properties of guided ultrasonic waves (Fig. 1), which can propagate over long distances and make the inspection of large surface areas possible. We present an example of the practical application of the LWE method to localize disbonds in multi-layered adhesively bonded aluminum plates. The method is based on the processing of time histories of surface vibrations, resulting from transient ultrasonic excitation, over a grid of points in the area of interest. Surface bonded piezoceramic transducers are used to excite the plates and Scanning Laser Doppler Vibrometer (SLDV) is used to acquire vibration responses. We demonstrate that it is feasible to use the proposed approach to identify disbonds in the analyzed plates. The approach reduces the examination time and it is suitable for practical engineering applications.

![Fig. 1. Experimentally measured dispersion curves on an adhesively bonded multilayered aluminum plate.](image)

Acknowledgement:

This work was performed within the scope of project no. LIDER/2/0117/L-7/15/2016, financed by the National Centre for Research and Development in Poland.
Probability of Detection Curves for Dissimilar Metal Welds as Input to Probabilistic Fracture Mechanics Code

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The U.S. Nuclear Regulatory Commission (NRC) in cooperation with the nuclear industry has developed a probabilistic fracture mechanics code called xLPR (extremely Low Probability of Rupture). xLPR is a modular-based probabilistic assessment tool for determining probability of leakage and rupture for pressure boundary piping. One of the modules in xLPR is the In-Service Inspection (ISI) module which models the probability of detection (POD) and sizing performance of NDE performed during in-service inspection to account for and predict the influence of periodic inspections on the probability of component leakage and rupture. The accuracy of the ISI module in xLPR is dependent on the quality of the estimates of detection and sizing performance that are input to the module. Multiple efforts have been attempted to quantify the detection and sizing performance of NDE in the nuclear industry. These efforts include an analysis of inspection data collected as part of the industry’s Performance Demonstration Initiative (PDI) [1] and data collected from NRC sponsored round robin studies such as PINC–Program for the Inspection of Nickel Alloy Components [2] and PARENT- Program to Assess the Reliability of Emerging Nondestructive Techniques [3]. Usage of a given data set in the xLPR ISI module requires understanding of which set of data is most representative for the specific scenario under consideration. A comparative analysis of detection performance data from PDI, PINC, and PARENT is provided in this paper in an effort to elucidate for users of xLPR types of applications the above mentioned data sets may be most appropriate for.

References:
Iterative numerical 2D-modeling for quantification of material defects by pulsed thermography

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Pulsed thermography is a well-known non-destructive testing technique and has proven to be a valuable tool for examination of material defects. Typically, analytical 1D models are used to determine the defect depth of flat-bottom holes (FBH), grooves or delamination [1, 2]. However, these models cannot take into account lateral heat flows, or only to a limited extent [3]. They are therefore limited by the FBHs aspect ratio (diameter to remaining wall thickness) [4], to ensure that the heat flow above the defect can still be described one-dimensionally. Here, we present an approach for quantitative determination of the geometry for FBH or grooves. For this purpose, the results of a numerical 2D model are fitted to experimental data, e.g., to determine simultaneously the defect depth of a groove or FBH and its diameter of width. The model takes lateral heat flows into account as well as thermal losses. Figure 1 shows the temperature increase of a pulsed thermography measurement at three different locations on the sample. The numerical model is fitted to the experimental data (red lines) to quantify the groove. The numerical simulation matches the experimental data well.

Figure 1: Temperature transients of a pulse heated steel sample with a groove, recorded in reflection configuration of three different positions of the sample (see inset). The grey dots are the experimental data. The measurement point (a) are located directly above the groove, data point (b) is located directly above the groove edge and (c) 5 mm from the edge of the groove. The red lines show the fitted transient temperatures of the model at the corresponding positions.

References:
Millimeter Wave Inspection of Additive Manufactured Non-Conductive Materials

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Additive manufacturing or 3D printing methods are playing a significant role in current and future manufacturing processes. These methods have drastically shortened the product development time from computer-aided design (CAD) stage to making a physical part. Furthermore, they allow for building parts with complex shapes that are not possible with traditional subtractive manufacturing methods, which leads to manufacturing parts that are lighter and stronger. Lately, additive manufacturing is being used to manufacture functional parts in many safety-critical industries such as aerospace, space, and biomedical. The use of additive manufacturing for functional parts is growing rapidly and is expected to continue in the near future. Therefore, the inspection of such parts for manufacturing defects such as porosity, lack of proper bond or correct internal manufactured geometries becomes critical from expected strength and performance points of views. Millimeter wave nondestructive testing (NDT) methods, utilizing electromagnetic waves in the frequency range of 30 – 300 GHz, are well-suited for inspection of dielectric (non-conductive) materials. This is due to the low-loss nature of the polymers and ceramics used in 3D printed parts, which allow for ample signal penetration into the parts. Millimeter wave synthetic aperture radar (SAR)-based 3D imaging techniques, in particular, have demonstrated great potential for the detecting and characterization of porosity and layer delamination in polymers and composites. This is mostly due to the fact that SAR 3D imaging technique relies on constructively combining reflected signal data from many measurement points within the synthetic aperture (i.e., a multi-view technique) which greatly enhances the image quality. Additionally, SAR 3D imaging techniques can be implemented using imaging arrays that yield imaging results in real-time [1-2]. Here, we present the utility of millimeter wave SAR high-resolution imaging for inspecting 3D printed materials for several common manufacturing defects. Several electromagnetic-simulated and measurements results on 3D printed parts will also be presented.

References:


[2]. https://youtu.be/RE-PPXmtTeA
Microwave signals span the frequency range of ~300 MHz to 30 GHz, corresponding to a wavelength range of 1 m to 10 mm. Signals at these frequencies can easily penetrate inside dielectric materials and composites and interact with their inner structures. The relatively small wavelengths (particularly at higher frequencies) and wide bandwidths associated with these signals enable the production of high spatial-resolution images of materials and structures. Incorporating imaging techniques such as synthetic aperture focusing (holographical) methods based on robust back-propagation algorithms coupled with more advanced and unique imaging systems designs have brought upon a flurry of activities in this area and in particular for nondestructive evaluation (NDE) applications. Here, we demonstrate a prototype portable microwave camera, operating in the 20-30 GHz frequency range, capable of producing high-resolution, 3D and real-time images of interior of objects [1-2]. Figure 1 shows a picture of this camera (all-inclusive size of ~ 10” x 9” x 7”) and a 3D image of a panel with nine small embedded objects dispersed in different locations within the panel.

Figure 1: (a) Picture of the portable, high-resolution, 3D real-time prototype microwave camera imaging a low-density sample with embedded objects and (b) 3D image of embedded objects.

References:
[2]. https://youtu.be/RE-PPXmtTeA
Application of Active Microwave Thermography to Inspection of CFRP Structures with Radar Absorbing Material Coatings

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Radio-frequency (RF) absorbing materials (RAM) are widely used to reduce electromagnetic interference and scattering from reflective (i.e., conductive) surfaces such as those utilized in aerospace and military applications. In particular for aerospace and military applications, structures of interest are often constructed of multiple layers of carbon-fiber reinforced polymer (CFRP) laminates. These structures can sustain impact damage (causing delaminations in the CFRP) that may not be readily visible through the RAM coating. Thus, it is important to nondestructively assess such structures for their structural health (i.e., defect detection). To this end, active microwave thermography (AMT) is considered as a viable solution. AMT is based on microwave and thermographic nondestructive testing (NDT) principles, and utilizes a microwave-based thermal excitation. The resulting surface thermal profile of the structure or material under inspection is measured with a thermal camera. Defects present in the structure may affect the heat diffusion and present as indications in the resulting thermal image. As it relates to CFRP structures with a RF/microwave absorbing surface (such as radar absorbing material, or RAM), when RAMs are illuminated by microwave energy, this energy is absorbed. Therefore, the RAM can serve as a thermographic heat source to the underlying structure. In this way, subsurface defects can be detected and evaluated. The utility of this approach has been demonstrated in [1], where a thin RAM was placed on the surface of a layered structure containing a CFRP laminate placed atop a cement-based substructure. A delamination was present at the interface of the CFRP laminate and substructure. It has been shown that the presence of the defect was easily detected when the RAM was present. This work will extend this proof-of-concept work by investigating the potential for AMT to inspect for the presence of damage and delaminations in thick CFRP structures. The effect of RAM thickness, thickness of the CFRP structure, microwave frequency, and illumination angle will be investigated, along with delamination location and dimensions.

Acknowledgements:

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References:

Ensuring the integrity of oil and gas cased-wellbores is of crucial importance to operators around the world to maintain safe production and environmental compliance. Casings and cement are two critical elements that must be assessed and verified over the life of a well, from construction phase, through production, to final plug-and-abandonment. Sonic and ultrasonics have been well-known, powerful tools for nondestructive evaluation and on-line structural health monitoring. They provide great advantage for well integrity and cement evaluation through the deployment in the industry of many acoustic tools with a focus, however, on single string evaluation. Evaluating the cement condition of subsequent casings in a multiple pipe-string configuration has not been addressed due to the limited sensitivity of the current ultrasonic tools to the first cement layer and extreme complexity in the sonic tool responses. One major challenge is the lack of an effective modeling approach to understand the interaction between cement damage or disbond and complex higher order waves.

In this talk, we present a theoretical study aiming at understanding the interactions between the many pipe acoustic modes and cement imperfections, such as weak bonding / debonding, fluid channeling, and cement degradation. We introduce a Semi-analytical Finite Element (SAFE) method to investigate the dispersions and modal shapes of the acoustic wave fields in double strings with geometric and material complexities. The SAFE provides for a flexible framework to study the modal sensitivities in a multi-string system with arbitrary eccentricity, azimuthal heterogeneities, and partial bonded interfaces. The acoustic features such as reflection amplitude, slowness dispersions and attenuation can then be used to accurately characterize the dimension, position and severity of the wellbore damage. Experimental corroboration of the modeling results are presented in a companion abstract, Experimental investigation of acoustic features associated with cement damage in double cased-wellbores, which indicate that the modeling method is capable of accurately predicting the interactions between borehole guided modes and various types of cement imperfections.

Acknowledgement:
The authors thank Larry McGowan, David Ramsdell, Ting Lei, Bikash Sinha and David Linton Johnson from Schlumberger for many contributions to this study.

References:
Cement evaluation in cased oil and gas wells is conducted by lowering an ultrasonic tool that implements imaging through steel casing based on the casing (quasi-Lamb) modes – a thicknessmode-dominated measurement through a pulse-echo modality and a flexural-mode-dominated measurement through a pitch-catch modality [1,2]. The service is important to ascertain well integrity before proceeding to putting the well on production. The measurement data is processed to extract information about the properties of the annular fill behind casing: either cement, mud, mud-contaminated cement, or gas. The pulse-echo resonance data is inverted for a measure of the annular impedance, while the dispersive flexural mode data yields a modal attenuation of the casing-propagating signal across two receivers. Both measurements are combined and interpreted in terms of a solid versus liquid or gas annular fill. When the annular fill is comprised of a solid with a compressional wave velocity that intersects the dispersive flexural mode phase velocity curve within the signal frequency bandwidth, phase matching to a headwave in the annulus occurs and we observe an additional contribution that follows closely the arrival from within the casing: a feature we refer to as a clinging P. We use this occurrence on the raw waveforms to our advantage, as a basis for a quantitative diagnosis of the solid behind the casing. To leverage this effect in a non-assisted robust (online) diagnosis, we use a machine learning (ML) based workflow that automates the detection of clinging P arrivals in the flexural wave data. In the first step of our proposed workflow, we perform feature extraction on time frequency energy maps that are labelled, and train a support vector machine algorithm to detect candidates for clinging P. In the second step, we address the possibility of confounding the clinging P detection with an actual specular reflection from, say, a closely-located reflector beyond the casing outer interface. For the latter, we exploit the fortuitous appearance of a processing artifact called galaxy pattern in the inverted impedance map from the pulse-echo resonance [3]. To detect these occurrences, we use and train a convolutional neural network applied to labelled acoustic impedance maps. The combination of the two supervised ML schemes yields an automated workflow that highlights axial and azimuthal regions, where the annular fill behind casing is confirmed to be a solid with additionally a tight range for its compressional wave velocity – therefore rendering the diagnosis of the tool measurement more quantitative and more autonomous than delivered with existing inversion schemes. In this presentation, we will briefly review the physics of the measurement and then share the characteristics of the ML approaches.

References:


Adapting Robot Paths for Automated NDT of Complex Structures using Ultrasonic Alignment

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Automated inspection systems using industrial robots have been available for a number of years. The IntACom robot inspection system has been recently developed at TWI Wales and utilises phased array ultrasonic probes to inspect complex geometries, in particular aerospace composite components. To increase inspection speed and accuracy, off-line path planning is employed to define a series of robotic movements aligned to the surface of a component. To minimise influences of refraction at the component interface and effects of anisotropy, the ultrasonic probe must be kept perpendicular to the surface throughout the inspection. Deviations between the actual component and computer model used for path-planning result in suboptimal alignment and a subsequent reduction in the fidelity of the ultrasonic echo signal.

In this work we demonstrate methods for using the ultrasonic echo signals to adapt the robotic path to achieve a minimal variation in the reflected surface echo. The component surface is imaged using phased array probes to calculate a sparse 3D point cloud with estimated normal directions. This is done through a preliminary alignment path covering approximately 10% of the total surface to minimise the impact on overall inspection time. The data is then compared to the expected geometry and deviations are minimised using least-squares optimisation. Compared to manual alignment techniques, this method shows a reduction in surface amplitude variation of up to 33%, indicating that the robot is following the surface of the component more accurately, as shown in Figure 1.

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Figure 1. Variation in amplitude of the surface reflection between using manual methods and the new method presented in this paper.
Quantitative ultrasound (QUS) has shown a great potential in the assessment of bone
characteristics in the recent research. However, wave propagation in bones is very challenging
due to the nature of multi-layer, anisotropic, and viscoelastic behaviors. Our knowledge of wave
interaction with bone structures is, therefore, far from complete and the resulting wave modes
have not been fully explained. The aim of the current study is to develop a model for propagation
of ultrasonic guided waves in a soft-tissue layer over a cortical bone layer. The amplitudes of
wave modes generated by time-harmonic loads in the two-layer model are theoretically
computed by reciprocity consideration. A semi-analytical finite element scheme (SFES) is also
developed to simulate the propagation of guided waves in the bone plate coupled with the soft-
tissue layer. The comparison between analytical and numerical calculations shows reasonable
agreement.

Acknowledgement:

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Comparative Study of Residual Stresses in API X65 Steel by X-Ray Diffraction and Ultrasonic Technique

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API 5L X65 steel is used in the construction of pipeline for oil and gas transportation. Residual stresses are intrinsic to all manufacturing processes and, under an external action, residual and applied stresses can be added linearly even in elastic regime, causing an unexpected and premature failure of the component. The study of nature, magnitude and directions of residual stresses is relevant to ensure the safety of structures and components, especially those working in extreme conditions. Therefore, offer alternative techniques that provide the quantification of these stresses is a very important task [1]. The aim of the present work is to compare the residual stresses measured by X-ray diffraction using the sin²ψ method and by ultrasound, using the TOFD technique, aiming to contribute to the ultrasonic technique establishment. API X65 steel samples, fabricated using the same manufacturing process and shot peening treatment, with different residual stresses surface field were studied. In figure 1 obtained in four samples using both techniques showed that TOFD produced wave flight times consistent with the nature of the residual stresses that were measured by X-ray diffraction. The frequency spectrum provided better visualization of the ultrasonic signal produced.

Acknowledgement:

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Figure 1. Residual stresses measured by X-Ray diffraction and Time of Flight, in four samples labeled A, B, C and D.

References:
Cryoultrasonic NDE

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The inspection of complex-shaped parts, which may contain multiple internal vanes and present highly curved surfaces, poses a major challenge to conventional NDE techniques. In current industrial practice, these parts are inspected using x-ray CT (XCT) for internal volumetric defects and liquid penetrant inspections (LPI) for surface breaking cracks. However, the sensitivity of XCT rapidly decreases with part size and material mass density, while LPI is ineffective on internal surfaces or in the presence of high surface roughness. Cryoultrasonic NDE is a new technique that could address these limitations by combining the versatility of ultrasonic testing (UT) with the remarkable properties of ice [1]. The high ultrasonic velocity of ice (~4000 m/s), its excellent adhesion properties to metals, and its low ultrasonic attenuation, provide an effective coupling medium that significantly reduces the signal degradation otherwise observed with immersion UT. The underpinning hypothesis of Cryoultrasonics is that a complex-shape part can be transformed into a simple-shaped solid by immersing the part in water and subsequently freezing it. Damage detection can then be performed by analyzing cross-sectional images of the ice-encapsulated part obtained by applying migration methods to the ultrasonic signals measured by an array of transducers. This paper provides an introduction to Cryoultrasonic NDE and presents new experimental methods that include unidirectional freezing to produce crystal clear ice as in the example of Fig. 1. The paper also outlines a number of ongoing research efforts aimed at engineering ice composites with increased ultrasonic impedance and advanced imaging methods that can correctly account for the complex wave interactions occurring at the ice-metal interfaces.

Figure 1. Example of a 3D printed Ti 6Al-4V impeller entirely encased in an ice cylinder. Clear ice, free from bubbles and cracks is obtained by controlling the propagation of the freeze front.

References:
Guided Wave based SHM (GW-SHM) relies on the use of elastic guided waves to interrogate plates or unidirectional structure for defects and has received considerable attention from the literature in the past few years. Despite a large number of in-lab setup and some mature prototypes, there is a growing need to develop new tools to improve the maturity of existing in-lab GW-SHM applications and transfer them to the industry. Indeed, the complexity of the GW propagation phenomena inhibits the demonstration of reliability of GW-SHM. In other words, in order to ensure the efficiency of GW-SHM system on real-life situations with varying environmental conditions and exploitation constraints, a huge number of experiments are to be conducted. In order to quantify the robustness and efficiency of the GW-SHM systems, dedicated simulations tools have been developed and will be released in a future version of the CIVA software. These tools rely on a spectral finite element and a dedicated meshing strategy to ensure fast but reliable computation. The computational efficiency and the user interface are such that a non-expert can create and run large simulations on a regular desktop computer and enable the creation of large simulated databases in reasonable computational times.

This communication presents the validation of such tools in a GW-SHM configuration. First the simulation tools are tested with respect to a comprehensive and recent benchmark [1]. Secondly, simulated signals are compared to experimental ones for both isotropic and anisotropic panels. Finally, results of guided wave imaging algorithms are compared between simulated and experimental datasets.

References:

Automatic defect localization and characterization through machine learning based inversion for guided wave imaging in SHM

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Guided Wave (GW) based Structural Health Monitoring (SHM) relies on the permanent integration of sensors on a structure to measure propagated guided waves and deduce information regarding its current structural health. GW imaging takes advantage of the GW measurements to establish a cartography of the health of the inspected structure, leading to the detection and the localization of the possibly present defects. Characterization of the defects from the obtained maps is often no directly possible, as the size and magnitude of the defect indication depends on a substantial number of parameters beyond the defect size, such as the wavelength of interrogation or the reflectivity of the flaw. So far, characterization of defect size through guided wave imaging in an SHM context has therefore only been achieved in controlled environments for well-known flaws.

This communication presents the use the GW-SHM simulation models developed at CEA-LIST to build a large database of GW imaging results and train a machine learning based inversion algorithm on it. Firstly, a training set accounting for various inspection parameters, e.g., frequency, flaw position and size is generated. Secondly, imaging algorithms are applied to each database sample and these images are used, in the so-called training phase, to build an inverse model with a supervised machine learning algorithm. In practice, this corresponds to fit a regressor (e.g., kernel ridge regressor, support vector regressor, Gaussian process regressor, etc.) on the set of signals/parameters pairs. To assess the performance of the inversion strategy, (i.e., the capability to retrieve flaw positions and/or dimensions), the inverse model is evaluated on new datasets (usually called test sets), which were generated independently from the training phase. The inversion results are analyzed with respect to accuracy and CPU time efficiency.
Digitization is steadily gaining growing impact on production processes and the related chains of economic value-added. Generation, evaluation and exploitation of information in the form of data describing quality features and material properties are of essential significance. NDE has thus to deliver and enhance appropriate technologies for nondestructive monitoring aiming at the characterization of materials, components and products. In this attempt, NDE has to increase communication and cooperation with scientists, engineers and technicians addressing process issues in the various phases of the value chain. The objective is to optimally acquire, interpret and use the sensor data recorded via NDE techniques. A near-at-hand example is the utilization of data acquired along a manufacturing process for regularization and optimization. Nevertheless, NDE will still be inevitable in view of reliable quality assurance in the conventional sense, particularly in safety relevant domains, where the development of new and the enhancement of existing techniques helps to meet and – moreover – improve existing quality standards. Here, methods of smart and efficient data handling and processing – a must to satisfy the demands of Industry 4.0 – will also lead to enhanced NDE capabilities.

In this presentation, we will report on Fraunhofer IZFP’s current activities to address these various aspects. We will present selected examples of respective NDE applications in industrial environments as well as research activities on the enhancement of data processing based e.g. on Machine-Learning algorithms. In short, we further report on a new Committee of Experts within the German Society of Nondestructive Testing DGZfP which addresses NDT 4.0 issues such as interfaces and man-machine-interaction.
Further investigation on Profiling Defect Depth in Composite Materials Using Thermal Imaging NDE

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Sonic Infrared (SIR) NDE is a relatively new NDE technology; it has been demonstrated as a reliable and sensitive method to detect defects in wide range of materials including metals, metal alloys, ceramics and composites. Defect characterization is of a great importance for NDE practitioners as it provides the information that aids to make proper maintenance decisions. In last conference, we presented an analytical model that describes heat diffusion from subsurface defects in composite structures. The major factors that affect the temperature curve are: thermal properties of the material, defect depth, defect size, and the duration of ultrasonic excitation. In this paper, we will present our continued work on the defect depth profiling by using the temporal information of IR images, and our study on the effect of defect size as well as the duration of the ultrasonic excitation. In addition, we will address the limitations of the current analytical model.
Theoretical and Experimental Results on Rayleigh-Wave Harmonic Generation in Materials with Depth-Dependent Non-Linear Properties

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In the last decades, non-linear acoustics has been shown to be sensitive to monitor fatigue or microstructural variations in elastic media. While sound velocities or other ultrasonic quantities associated to linear properties only change by a few tenths of percent with internal stresses and micro-dislocations, harmonic generation is known to provide relative variations tens to hundred times higher. Non-linear Rayleigh waves have hence been proposed to track the state of surface-treated materials. In some applications such as shot-peening, the near-surface region of a solid is modified through plastic deformation in order to induce compressive residual stresses to increase the lifetime. Such changes also affect the microstructure and lead to variations of the non-linear properties. Because the changes are localized near the surface and because the energy of a Rayleigh wave is contained in a region that depends on the wavelength, a frequency dependence characteristic to the depth-profile can be expected.

In this contribution, we report on results of a theoretical study as well as on first experimental results obtained in this context. Our theoretical investigations focus on materials having inhomogeneous third order and homogeneous second order elastic properties. Compared to the complete homogeneous case, the constants coupling the harmonics turn out to depend on frequency. We present numerical examples for depth profiles characteristic of dislocation densities in shot-peened metals. The predicted low-frequency scales are consistent with observations recently reported. We also report on preliminary experimental investigations, which we have performed on shot-peened as well as on untreated Titanium specimens.
Characterization of Adhesive Shear Modulus in Bonded Stiffeners using Ultrasonic Guided Waves

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Adhesively bonded stiffeners are widely used in aerospace structures. Nondestructive evaluation of the curing state of the adhesive offers the potential to reduce assembly time as well as ensure both strength and stiffness of airframes. The feasibility of using feature-guided waves for the inspection of adhesive bond lines in difficult-to-access regions has already been investigated in the literature. However, due to the complexity of the guide wave phenomena in the bond line region, an inverse method to identify the curing state from the measurements remains an open issue. This work introduces a multi-mode and multi-frequency inverse method for the characterization of stiffeners bond lines using Semi-Analytical Finite Element (SAFE). Experiments were conducted on a T-shaped stiffener bonded to an aluminium plate. The feature-guided wave modes were excited using a piezoelectric shear transducer and measured using a laser interferometer at several times during a period of four days. The experimental dispersion curves were computed from the measured data and then systematically compared to the simulated solutions obtained with the SAFE model. At each measurement, the shear modulus of the adhesive material could be estimated by iteratively minimizing the error between experimental and numerical data. The results showed an abrupt step in the shear modulus from the first to the second day, suggesting that the end of the curing processes was achieved. In general, the inverse scheme presented in this work was shown to be able to distinguish differences of 5% in the shear modulus.
Active Thermography by Inductive Excitation in Anisotropic Carbon Fiber Composites

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Induction thermography is an active thermographic technique, where eddy currents are generated in an electrically conducting material. In metals, heat is released due to resistive losses, which can be detected by an infrared camera. At cracks close to the material surface, the induced currents will have to circumvent the crack and areas with increased or decreased current densities are generated. The corresponding thermal contrasts indicate defect locations, show the defect orientation and the time dependence of the contrasts provides some information on defect depth. The technique found successful applications for surface crack detection in several industrial branches, with the general aim of searching for alternatives to magnetic particle or liquid penetrant testing.

Although most of the present investigations are devoted to metallic materials, carbon fiber reinforced polymers (CFRP) are electrically weakly conducting and suitable for application of induction thermography. Several mechanism of heating are known: resistive heating of the fibers, resistive heating of the contact points between crossing fibers and dielectric heating of the matrix close to crossing points between fibers [1]. In earlier work, induction thermography was used to detect manufacturing defects and impact damage in CFRP [2, 3]. In the present work, we focused on some phenomena caused by anisotropy usually not occurring in metals. Uniaxial, biaxial as well as woven fabric CFRP were studied. The uniaxial material was investigated as a function of the fiber orientation angle and showed heating far away from the inductor and heating patterns with local minima. The occurrence of minima was explained by induction current cancellation effects. The experimentally measured thermal contrast patterns were confirmed by the results of numerical simulations. Cracking from impact damage is detected with better contrast than by homogeneous optical excitation. Reference measurements using x-ray CT proved the existence of cracking and showed inner delaminations as known to be generated by impacts.

References:
Characterization of microtexture regions in titanium alloys using eddy current probes

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Microtexture region (MTR) formation in engine components made from titanium alloys has been shown to significantly reduce the dwell fatigue life of the components. Specifically, when the MTR is large enough and the c-axis is oriented in a specific direction relative to the loading axis, cracks in MTR’s can grow much more rapidly than predicted by traditional fracture mechanics. It has been shown that eddy current methods are sensitive to MTR formation on a bulk scale, but no study has been done to assess the fundamental limitations of eddy current methods for detecting specific MTR’s. In this work, the sensitivity of eddy current sensors to MTR’s at specific orientations with respect to the surface area and the volumetric depths was analyzed in a modeling and simulation framework. One MTR in a host of otherwise randomly oriented single crystals was simulated, varying the size and orientation parameters. The eddy current signals were predicted using a previously developed approximation based model as well as a commercially available simulation tool. Both reflection differential as well as absolute coils were analyzed in this work. The model responses were verified using an alternate FEM model. The simulation data was calibrated against the simulated response from a calibration notch, and the signals were analyzed using the liftoff/gain calibration procedures common in eddy current.
Acoustic steering and vibration isolation in traditional engineering components is of significant interest for protection of sensitive equipment as well as sound reduction in noisy environments, such as helicopters or airplanes. While active techniques have shown promise for these applications, passive techniques are easier to implement and offer excellent damping ratios over a specific range of frequencies. The use of shunted piezoelectric patches has been widely explored for such an application. One embodiment of such a system distributes piezoelectric elements across the surface of a structure, and each one is then connected to a shunt circuit consisting of a combination of a resistance and inductance. The resonance of the circuit is tuned such that within a certain frequency band, a large portion of the mechanical energy is converted to electrical energy which is then dissipated, thus greatly reducing the amplitude of those components in the mechanical wave traversing the piezo augmented region.

Testing and characterization of these structures often involves measuring the displacements/velocity of the mechanical wave propagating in the component on which the patches are placed. This effectively verifies the performance of the piezoelectric elements in situ. However, measurements of the resonance properties of the individual elements can have a critical role in the design and analysis of these materials. Furthermore, a model of the element can be used to analyze the behavior, and determine the optimal geometry for a certain frequency range, as well as harmonics where the patch will operate. In this work, a piezoelectric element was modeled using the finite element method, incorporating the physics of the electric fields generated due to the piezoelectric effect as well as the circuit elements attached to the element. Multiple circuit conditions were evaluated to determine the mode shapes and resonances of the individual crystal. The crystal was modeled using the measured geometry of a sample, and the elastic properties of the materials were determined using traditional resonance ultrasound spectroscopy. The sample was then analyzed using resonance measurements as well as laser vibrometry mode shape imaging, and several aspects of the behavior of the shunted piezo crystal (such as mode separation and negative effective properties) were verified experimentally.
Is phased array the future in modern ultrasonic rail inspection?

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Compared to standard ultrasonic testing methods the application of phased arrays offers advantages and flexibility by the electronic steering possibilities to control the transmitted and received sound fields as well as the image based evaluation of the recorded scans. For more than one decade phased array systems have been introduced and used in the railway sector for the inspection of wheelsets in the workshops. Up to the present field applications of phased array systems in rail inspection are rather rare. On the other hand a lot of scientific work on rail testing using phased arrays has been carried out in the recent past.

Mechanized ultrasonic rail inspection poses strong challenges e.g. due to the harsh environment, complex flaw types and high inspection speeds. Different tasks have to be carried out by non-destructive testing ranging from manufacturing inspection of thermite welds to in-service inspection for operational induced flaws in the rail head, rail web and rail foot as well as rolling contact fatigue. This work will give an overview and categorization of different present approaches for rail testing using phased array.

Phased array systems typically offer digital image based inspection results. This make these systems become the perfect candidates to feed inspection data into a modern big data based workflow, using e.g. cloud computing, signal processing and data fusion for recording, positioning and tracking of flaws and artefacts in rails and to gain additional benefit.

Evaluation of promising innovative approaches and solutions for phased array based ultrasonic rail inspection in the frame of “Industry 4.0” will be discussed.
Nonlinear Ultrasonic Techniques for the Quantification of Dislocations and Residual Stress Fields in Additive Materials

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This research applies nonlinear ultrasonic (NLU) techniques for the quantitative characterization of additively manufactured (AM) materials. The characterization focuses on identifying the dislocation density and residual stresses produced during the additive construction process. AM materials are subject to variations in print rate, bulk material properties, and cooling rates, leading to uncertainties in their life cycles. The nondestructive evaluation (NDE) of AM parts could be used to compare different prints of the same piece and help in the decision-making process to accept or reject a printed part.

Second harmonic generation (SHG) techniques based on the transmission of Rayleigh surface waves are used to measure the ultrasonic nonlinearity parameter, β. This ultrasonic nonlinearity parameter is sensitive to microstructural changes and has previously been used to characterize fatigue and thermal damage [1,2]. Experimental and theoretical work has proven that β is a quantitative indicator of dislocations and residual stresses [3,4]. The first task in this research is to compare β and acoustic attenuation between four metal specimens: 316L Wrought, 316L Powder Bed, 304L Wrought, 304L LENS. Laser Engineered NetShaping (LENS) is an AM technique that applies focused thermal energy during the deposition of material; Powder Bed Fusion methods apply thermal energy to an already deposited layer of powdered stock material [5]. This task is an evaluation of β as it changes with respect to the manufacturing process as well as its change between stainless steel variations. The second task of this work is to measure β after a heat treatment process; heat treatment is used to isolate the effects of dislocations in a specimen [6]. By heating the specimen at a gradual rate, the residual stresses that are formed during the quick temperature changes from the additive manufactured process are removed, allowing for an isolated measurement of the nonlinearity produced by dislocations. This measurement provides new insight into β’s response to changes in dislocation densities. The β parameter is found to be more sensitive to differences in the manufacturing technique used than the slight differences in chemical composition that separates 304L and 316L stainless steels.

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References:

Heat transfer tube as a nuclear power plant nuclear island part of the first and second loop of the border, plays a very important barrier role. At this stage, eddy current array (ECA) only serves as a qualitative inspection method of the transition of the expansion tube part of the heat transfer tube. However, with improvement of the dimensional requirements to understand defects information located at heat transfer tubes for nuclear power plants (NPP), qualitative inspection can no longer meet the requirements. In this paper, comparison of the signal amplitude between the peak and the trough of 360 degree sense area of X-probe coils, the accuracy of unilateral signal amplitude of crack located at free segment of the tube is studied and the quantitative error distribution was given when the ECA probe inserted into the tube at random position.
Preliminary Study on Detection Technology for L-type Cladding Weld of Spent Fuel Storage Pool

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As the first barrier of the Spent fuel storage pool, the steel cladding using different sizes (length×width) of 304L stainless steel 3 ~ 6mm thick plate argon arc welded together which is direct contacted with boric acid water. Environmental humidity between the back of steel cladding and concrete, makes phosphate, chloride ion overflowed from the concrete that corroded on the weld zone with different mechanism. Part of corrosion defects can be penetrated leaded to leakage of boric acid water accelerated crack propagation. Since the steel cladding is welded by different sizes of steel plates, there will be different weld structures, and L-shaped weld is one of the most important weld structures, mainly appearing in the bottom of the pool.

L-shaped weld is made by butt welding of two bent L-shaped plates. Stress concentration and weld quality problems at the inflection point of the bend make this critical position easily leak. Therefore, the detection of this location is the focus of attention in current research. In this paper, Eddy current (EC) and ACFM are both used for weld inspection, the former adopted copy-shaped array probe, while the latter used pen array probe. The detection sensitivity of the two methods is verified by designing a series of different scales of defect test samples, which provides an empirical reference for the actual engineering inspection.
Adaptive Array Processing for Enhanced Ultrasonic Non-Destructive Evaluation (NDE) and Imaging

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Robust and reliable flaw detection in the presence of grain noise is a challenging yet essential problem in ultrasonic non-destructive evaluation (NDE), which has attracted significant attention from the NDE community in recent decades. A variety of coarse-grained materials like alloy and austenitic stainless steel offer attractive properties like high-temperature strength or excellent resistance to corrosive environment, and thus are widely used to build components like ducting, combustion cans, and transition liners in a range of key industrial sectors such as energy, oil and gas, nuclear, and aerospace. However, when these materials and structures are inspected using ultrasound, the flaw echoes are usually contaminated by high level grain noise originating from the material microstructures, furthermore, the grain noise is time-invariant, demonstrating similar spectral characteristics, and correlated with the flaw echoes. A wide variety of techniques have been investigated to suppress grain noise and enhance flaw detection through exploiting the key differences between defect echoes and grain noise. The defect echo typically has a coherent structure with energy mainly scattered from a single spatial point, while the grain noise is spatially distributed throughout the insonified resolution cell. The difference has motivated spatial diversity and array processing techniques, such as adaptive beamforming [1] and coherence factoring [2]. In this paper, a novel method is investigated to distinguish flaw echoes from grain noise through evaluating if the impinged signal is reflected from the array focal point or from the distributed reflectors like grain boundaries. Different from beamforming and coherence factoring techniques, this method explicitly addresses the model of spatial noise across the array aperture and the correlation between the target signal and the interfering echoes scattered from numerous distributed reflectors, and estimates the likelihood that the echo is reflected and originated from the focal point of the transducer array. The likelihood is then normalized and subsequently used as a factor to correct and weight the image created with the total focusing method (TFM). The technique is validated with experiments on austenitic stainless steel samples with a 128-element 5MHz transducer array. It has been observed that the echoes from cracks and back-wall of the specimen demonstrate the likelihood much higher than that of grain noise, and the TFM images are improved by more than 20dB when the amplitudes are weighted using the normalized likelihood as a factor.

Reference:
Advances in Modelling the Eddy Current Inspection of Steam Generator Tubes

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Simulation tools for steam generator tubes inspection with eddy current testing is very useful to interpret measured signals, design new probes and assess the performance of existing industrial procedures. It allows in particular to separately quantify effects due to influential parameters, like the probe trajectory and lift-off, the presence of external objects, like deposits or support plates, or tube deformations consecutive to a bending process or wears under antivibration bars. This communication aims to present advances of modelling tools developed at CEA LIST enabling to take account of such effects, that are already available or that will be soon integrated in the CIVA [1] software.

The functionalities associated with the probe evolve on the basis of the process presented in [2], by hybridization between numerical and analytical models. A simplified access to pre-parameterized industrial probes will facilitate the setup of parametric studies to study complex effect like 3D orientation of probes equipped with shielding and ferrite cores. Regarding the tube, a dedicated modal approach will consider a 360° external deposit or a thick cylindrical support plate, as shown in Figure 1. In parallel to these improvements that should be available in the next commercial release of CIVA, a specific module dedicated to non-canonical configurations of inspection is currently developed. Based on a 3D numerical computation engine, this tool will focus on complex 3D geometries effects: bending with deformation of the tube section, presence of quatrefoil support plate or antivibration bar(s), and modelling of realistic friction wear defects.

Acknowledgement:

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Figure 1. Simulation of a support plate effect (left), modelling of a wear defect under a quatrefoil support plate (right).

References:
1. [http://www.extende.com](http://www.extende.com)
Error Analysis and Alignment for a Structured Light Probe System Designed for Internal Pipework Inspection

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The interior visual inspection of pipework is critical to maintain and characterize the deterioration of infrastructure over time. A probe system consisting of a laser profiler and omni-directional camera has been developed to inspect 3-6 inch diameter pipes. The system is shown in Figure 1 alongside an example laser profile image and a scan of three flat bottom holes. In order to identify the nature and spatial extent of imaged defects within the pipework, the system sequentially takes an image of the projected laser line which provides dimensional information, followed by an image of the pipe illuminated by LEDs providing texture and colour information. These are post processed into a 3D textured map of the interior surface of the pipe. The dimensional accuracy of the result therefore depends upon the systematic and sampling errors of the laser profiler. In this paper the technique to quantify and calibrate the systematic error due to the misalignment of the laser and image plane is described.

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Figure 1. Laser profiler and omni directional camera and example laser profile of flat bottom holes
High-resolution defect imaging in laminate composites and honeycomb structures using sparse piezo-electric transducers network for guided waves excitation and sensing

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The carbon fiber reinforced polymer (CFRP) plates and honeycomb composite sandwich structures (HCSS) are extensively used in the aerospace industry due to their excellent strength-to-weight ratio, stiffness, and corrosion resistance. Nevertheless, these structures are susceptible to hidden damage defects such as face sheet delamination or core-sheet debonding that may appear due to impact forces or thermo-mechanical aging and can decrease these properties.

The GW based structural heal monitoring (SHM) system is referred as a promising solution for such structures inspection. It has been proven, that GWs can explore large areas while being sensitive to the present flaws.

This paper reports on the guided waves imaging for CFRP plates and HCSS in order to localize and characterize defect. High-resolution cartography of the structure of interest is obtained by means of the base-line demanding defect-imaging algorithm. It computes and assigns a damage index value to each pixel of the cartography. A damage index value is obtained by correlating experimental to the theoretical signals. While a sparse grid of piezo-electric transducers is used for GW actuation and sensing, the theoretical signals are computed by two-dimensional semi-analytical finite element (SAFE) modeling.

The major advantage of this methodology is the capability to localize and to characterize defects with a high degree of accuracy.
Nonlinear ultrasound for nondestructive evaluation of adhesive joints

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Structural adhesion can be used to replace rivets, it leads to lighter structural weight, better stress repartition and can be used to assemble different materials such as composite. Adhesive bonding technology has therefore gained much attention in many industries, specifically aeronautic. However, to be used for structural joining and critical application, high reliability is needed. Thus, efficient non-destructive control strategy should be proposed to evaluate the nominal bonding quality but also possible progressive in-service degradations.

While linear ultrasound is efficient to detect decohesion or voids in a structure, it is barely sensitive to bond strength, or constraining hypotheses are formulated to retrieve the mechanical properties from measured ultrasound signals [1]. The present research presents a method to generate high amplitude plane wave, which may produce nonlinear phenomenon able to reveal kissing bonds or other types of adhesion defects. In this purpose a chaotic cavity transducer [2] has been designed, it acts as a two-dimensional virtual array and can be used to generate high energy plane wave. Numerical simulations and experimental measurements were made to optimize the device in order to obtain sufficient energy to solicit the structure. Then the method is applied and evaluated on metallic bonds with bonding defects. Combined with the pulse inversion technique, nonlinear phenomenon can be measured in the form of harmonic generation in the defect zone. We use this method to image defects created by different means: PTFE spray, finger trace etc. on one adherent before bonding. Mechanical destructive tests have been performed to validate the nondestructive measurements.

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References:


Mutual interactions of guided waves in plate: finite element studies

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Nonlinear ultrasonics provide the capability to nondestructively detect changes in the microstructure of a material that affect its strength and durability. Nonlinear guided waves enable this same capability to be extended to applications where accessibility is limited and where dimensions preclude the use of bulk waves. Use of nonlinear features of wave propagation provides early detection and/or sensitivity not available from linear ultrasonics. Here, we consider second order harmonics generated by mutual interactions of guided waves in a plate. It is now well-known that phase velocity matching is an important condition for strong internal resonances that generate sufficient nonlinearity to be detectible by sensors [1]. Recently, Hasanian and Lissenden showed the wave vector involvement in the resonance condition in order to consider directional guided wave mixing with different angles [2]. The aim of this work is to conduct finite element simulations of some of the more interesting primary guided wave modes in order to assess their potential for laboratory or field use. For example, nonlinear mixing of Shear Horizontal (SH) guided waves yields primary and secondary wave fields having completely different polarizations, which is extremely beneficial for separating material nonlinearity from instrumentation nonlinearity. To show that noncollinear guided wave mixing has utility, the noncollinear SH guided wave mixing illustrated in Fig. 1 is simulated. SH₀ waves at 1.5 and 0.78 MHz have been mixed in a 1 mm aluminum plate resulting in generation of S₀ waves at 2.28 MHz.

Figure 1. Orthogonal SH wave mixing. Right: Out of plane displacement field associated with generated nonlinear guided wave (color bar in m)

References:
Wave mixing technique for nondestructive assessment of Alkali-silica reaction damage in concrete prism samples

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Alkali-silica reaction (ASR) is a deterioration mechanism in concrete that degrades the concrete’s strength over time [1,2]. In a humid environment, concrete may absorb moisture from the surrounding environment. As the absorbed moisture diffuses through the concrete, the ASR gel expands its volume and such volumetric expansion of the ASR gel produces large internal pressure, which may then cause microcracking of the concrete. In this study, we proposed a collinear wave mixing technique with two longitudinal waves to nondestructively evaluate (NDE) the damage induced by ASR in concrete. Next, linear and nonlinear ultrasonic techniques were conducted on concrete prism samples that contained reactive aggregates and were subjected to different ASR conditioning. Destructive tests were also carried out for the benchmark data of the proposed technique. The result shows that although ASR damage does cause changes in the linear parameters of the concrete, these changes are not sufficient or sensitive enough to be effective for quantitative NDE purposes. The acoustic nonlinearity parameter, on the other hand, shows much greater sensitivity to ASR damage and correlates well with the degradation of compressive strength, and thus can be used as a measure of ASR damage for NDE purposes. In addition, we also found that in order to measure the acoustic nonlinearity parameter accurately, the attenuation in the sample must be measured. In other words, both linear and nonlinear measurements will need to be carried out for the NDE of ASR damage in concrete.

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Additive manufacturing (AM) is promising for replacing conventional manufacturing processes since it is capable of fabricating complex geometries, enables compact design for multi-component integration, and has potential to accelerate deployment schedules. However, degraded mechanical properties and inconsistent microstructures between printed parts has thus far severely limited the application of AM. For example, microstructural features such as dislocation density, grain size and anisotropy, level of recrystallization, and porosity can be influenced with different printing process parameters such as laser speed and heat treatment. These different microstructures can greatly affect the mechanical properties and behavior of the printed component. Developing a non-destructive evaluation method to qualify the microstructure of AM components is thus critical for the successful deployment of this manufacturing technology. In this work, linear and nonlinear ultrasonic NDE are used to interrogate mechanical and microstructural properties of additively manufactured 316L stainless steel produced by laser powder bed fusion (L-PBF). Different microstructures were obtained by varying the heat treatment schedule of AM L-PBF samples. While ultrasonic velocity is directly related to material moduli and can be sensitive to changes in porosity, changes in the ultrasonic nonlinearity parameter $\beta$ are sensitive to changes in microstructural features such as dislocations and precipitates. Ultrasonic velocity measurements were made along different orientations with respect to printing direction in a through-transmission setup. Nonlinear ultrasonic measurements of $\beta$ were made using second harmonic generation techniques with longitudinal waves. Experimental ultrasonic results and initial material characterizations show that both linear and nonlinear ultrasonic measurements are sensitive to differences in the additively manufactured material properties and microstructures.

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Performance Comparison of Analytical Reverse Time Migration and Synthetic Aperture Focusing Technique in Nondestructive Evaluation of Concrete Structures

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Synthetic aperture focusing technique (SAFT) is a well-established imaging method in ultrasonic nondestructive testing of the members of concrete structures. SAFT is a very efficient imaging technique that has been used extensively to measure thickness and to detect rebar, delamination, and damage [1-2]. However, it suffers from some shortcomings. For instance, it comes short in locating steep boundaries (Fig. 1b), and bottom boundaries of tendon ducts. Recently, reverse time migration technique (RTM) has gained attention in ultrasonic nondestructive testing of concrete members. In contrast to SAFT, which converts multiple reflections to artifacts, RTM takes advantage of multiple reflections to locate interfaces and boundaries with a steep slope (Fig. 1c) and bottom boundary of inclusions and defects. On the other hand, RTM is computationally costly and it needs a massive memory. Asadollahi and Khazanovich [3] invented an analytical technique to overcome the limitations of RTM and could make it comparable to SAFT in terms of efficiency. In this study, we use synthetic and real data to compare the performance of SAFT with that of the analytical RTM.

Figure 1. (a) A bottom-up crack in a synthetic concrete slab imaged by (b) SAFT and (c) RTM.

References:

The Eddy Current Pulsed Thermography Detection of Fatigue Crack Closure

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This paper describes a induced thermography method for the detection of crack closure in the railway wheel tread. The crack closure, which is result of corrosion or some kinds of third medium, is studied with a finite element model. Some key parameters of the crack closure, such as the shape, size and electromagnetic property are analyzed with two aspects including the perturbation of both the electromagnetic field and temperature field. Finally, a testing block with artificial crack closure defect is inspected. Some features are extracted and studied also to quantify the crack closure in term of the eddy current pulsed thermography. The proposed method greatly enhances the capability for cracks detection and evaluation.

Keywords: Eddy current pulsed thermography, crack closure, corrosion, railway

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Reference:


Direct Printing of Graphene Sensors for Health Monitoring of Additively Manufactured Structures

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Graphene, the first discovered and most studied two-dimensional material, has gained increasing interest in the research community due to a combination of unique optical, electronic transport, and structural properties. Single layer graphene is transparent, conductive, strong and flexible. In this work the flexibility, conductivity, and solution processing of the material are coupled resulting in direct printing of reduced graphene oxide (RGO) strain sensors using 3-D printer platforms. Monolayer flakes of commercially available graphene oxide dispersed in water are ink-jet printed and then reduced to form the sensors. The chemical reduction process using ascorbic acid is performed at temperatures compatible with additively manufactured thermoplastics, enabling direct sensor printing during part fabrication. The temperature dependence and piezo-resistance of the sensors are characterized and presented in terms of the variable range hopping model. Experimental results from coupon testing through full-scale flight tests are discussed.
2D Phased Arrays for Improved Defect Detection and Characterisation in 3D Geometries

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One of the current methods used to inspect complex 3D geometries involves the use of a single element transducer to transmit and receive ultrasonic signals. The received signals are then processed to form an image of the interior of the component under inspection. This process has been used in inspections for years. However, the limitations of single element probes include the inability to focus at multiple depths, a restricted number of fixed directions available to observe the defect from and the consequent potential for missing defects that are in unexpected positions or orientations. A possible solution to this problem involves the use of 2D phased arrays. Using a 2D phased array can not only drastically reduce inspection time as it involves more elements, but it also allows the data-acquisition process called full matrix capture (FMC) to be implemented. Defect image resolution can also be improved by exploiting the unique ability of immersion-coupled 2D arrays to focus through doubly-curved surfaces such as those found in pipework nozzles and pressure vessel nozzle cases. Using a 2D phased array also guarantees complete coverage of the imaging area by steering and focusing the ultrasound beam throughout a 3D volume without moving the array, thus allowing a more detailed inspection. Additionally, when using a single element probe the orientation of the defect to the incident beam is crucial to detecting defects. In most inspections, the orientation of potential defects can be predicted but in some cases the defect orientation cannot be anticipated and so multiple inspections at different orientations must be carried out. Data sets taken using 2D phased arrays excludes the need to align the incident beam to the defect as every point in the imaging region can be probed from any angle in post-processing. The benefits of using ultrasonic phased arrays in FMC mode are well-established in several industrial sectors, where a number of FMC-based inspections using 1D arrays have been qualified. As using 2D phased arrays for 3D inspection of components is almost never utilised in industry, this work paves the way to introduce a novel method of FMC-based ultrasonic inspections.

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Correlation Between Signals of Eddy Current Obtained with EDM notch and Fatigue Cracks

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Artificial defects are commonly used to calibrate eddy current testing because of easily manufacturing and simple geometric parameters control. However, this defects even with a best control and caution during the manufacturing process, there are different geometric characteristics than real situation defects [1]. To ensure reliable calibration results is necessary to analyze the correlation between the signals from artificial defects and real defects. This paper shows a detailed study that interconnects eddy current inspection results from electrical discharge machining (EDM) notches and fatigue cracks. In this work, two eddy current conventional probes were used, an absolute pencil probe and a differential form operation with orthogonal configuration for inspection of welded joints. In acquired results, as shown in Figure 1, it can be noted that there is a difference among signals from EDM notch and from fatigue cracks, however, using right correlation is possible to work with EDM notch to reliably represent a fatigue crack.

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Figure 1. Signal amplitude as a function of the opening of discontinuities.

References:
Multiple Scattering Filtering For Volumetric And Plane Defects

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The coarse grain structure of polycrystalline media significantly degrades the performance of ultrasound inspections. In order to circumvent these difficulties, a combination of strategies is applied, starting with a careful choice of transducer configurations to limit the volume of material actually contributing to multiple scattering, in order to obtain an acquisition with the best signal to noise ratio to begin with.

An additional gain in signal to noise ratio can be obtained by exploiting the random characteristics of multiple scattering to reduce their contribution. This approach, referred to as MSF-DORT (multiple scattering filtering – decomposition of the time reversal operator), has been successfully applied for volumetric defects, and uses the singular value’s statistics of the medium response matrix to separate single and multiple scattering contributions.

However, it can be shown that the method fails to produce the same gain for planar defects. In conventional UT inspections, planar defects are detected using angle beam transducers with wedges, exploiting the corner effect, rather than using the much weaker tip diffraction echo that would be produced in normal incidence. Using angle beam probes, however, violates the paraxial approximation necessary for the MSD-DORT method.

An alternative method for plane defects was recently derived from optical coherence tomography. The method is based on the acquisition of a time gated reflection matrix of the scattering sample, considering each observation point in each of the focal planes of the observation zone as a virtual transmitter/receiver. By considering only elements on the diagonal of the resulting matrix, the method naturally degrades to the total focusing matters. Taking aberration into account, single scatters are located in close vicinity to the diagonal, while contributions of multiple scatterers are located further away, and can thus be filtered easily.

In a second step, the filtered matrix is interpreted just as in the MSF-DORT method by an Eigenvalue decomposition, leading to an ordered list of reflectors with decreasing amplitude. In practice, the number of Eigenvalues above a certain threshold (which is still subject to discussion) will be limited to one or two at most. Back propagation of the Eigenvalues/vectors then leads to the final image.

We present promising preliminary results, as well as a discussion of the perspective of the method for parallelization and integration into acquisition systems.
The Digital Twin paradigm is an idea that, by creating a faithful virtual counterpart of a real component, its serviceable life and performance can be better predicted and monitored, leading to improvements in end-product safety and cost [1]. Such a model requires accurate inputs for the initial material state of the part as well as for in-service loads and damage states throughout its service life. The resonance frequencies of a part correlate to a part’s material state and damage state. Similarly, changes in resonance frequencies correlate to changes in the part’s material state resulting from in-service loads and damage. Process Compensated Resonance Testing (PCRT) leverages these physical relationships to perform nondestructive evaluation (NDE) and material characterization using the measured resonance frequencies of a component [2,3]. Prior work established techniques for modeling the effects of material properties, crystal orientation, and damage states on resonance, as well as quantifying uncertainty propagation from model inputs to outputs [4]. This study examines the use of PCRT model inversion to obtain material properties and calibrate digital twins of real components. Digital twin instances were first created for a population of single crystal Ni-based superalloy samples using dimension and mass measurements. Then, after collecting resonance spectra from the physical counterparts, model inversion techniques were employed to estimate elastic properties and crystal orientation for each part. The digital twins were then calibrated with these additional data. Models were validated with resonance comparison and x-ray diffraction measurements. Results highlight the value of part-specific material properties for digital twin performance, as well as the ability of PCRT to evaluate and improve digital twin fidelity.
Validation of Process Compensated Resonance Testing (PCRT) Sorting Modules Trained with Modeled Data

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Process Compensated Resonance Testing (PCRT) combines the collection of broadband resonance data with advanced pattern recognition to produce a fast, accurate, and automated non-destructive inspection for aerospace and power generation components. To create a targeted defect inspection test (sorting module) the resonance spectra of statistically representative populations of acceptable and unacceptable parts are needed. In cases where a sufficient number of parts are not available, spectra from real part databases can be supplemented with ‘virtual’ spectra generated with PCRT forward models. This combination of measured and virtual spectra can then be used to train the sorting modules. Previous work\(^{[1,2]}\) investigated the creation of model-trained sorting modules for the detection of creep damage and crystal orientation for coupon and turbine blade geometries made from single crystal Ni-based superalloy. This work discusses how the sorting modules targeting creep and crystal orientation were trained with virtual spectra and then validated with statistically significant populations of physical coupons. Sorting modules were evaluated for defect detection accuracy and correlations between resonance frequency changes and the damage/defect of interest. Model refinement by compensating for acceptable variation in the part population is also discussed.

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References:


Performance of EMATs for robotic inspection of cracks in welded stainless steel canisters
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The capability of electromagnetic acoustic transducers (EMATs) to detect cracks in stainless steel canisters is described within the context of robot-delivered nondestructive inspection (NDI) of dry storage casks (Fig. 1) for spent nuclear fuel. NDI of the canister must be performed remotely because of the limited access to the canister, which is enclosed by a concrete and steel overpack structure. Moreover, the environment inside the cask, but outside the canister, has both elevated temperature and gamma radiation. A potential canister degradation mode that could lead to issues with managing the spent fuel is chloride-induced stress corrosion cracking in the heat affected zone of full-penetration welds. Because access to the outer surface of the canister is limited by guide channels inside the overpack, ultrasonic guided waves are a natural choice for NDI. Shear horizontal (SH) waves sent and received from EMATs aboard a robot are shown to detect flaws in canister mockups.

Figure 1. HI-STORM 100S dry storage cask

Related Work:

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Inter-Digital Capacitive Sensor for Evaluating Cable Jacket and Insulation Aging

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Abstract

An interdigital capacitive sensor has previously been used to measure dielectric properties of cable insulation polymer material when placed in direct contact with the insulation. Often cable insulation is covered by a polymer jacket. The dielectric properties of many cable jacket and insulation polymers are known to change due to thermal and radiation exposure-related damage. These dielectric properties frequently track with other measures of cable aging, such as elongation-at-break and indenter modulus that have been broadly established as cable insulation polymer assessment methods. The external jacket of a cable is likely to have a different permittivity from the underlying insulation and frequently the jacket material exhibits more severe damage than the insulation material due to environmental exposure. Since the jacket serves primarily to guard the cable during installation, as long as the underlying insulation condition is acceptable the jacket condition is relatively unimportant in service.

As part of a continuing program to develop and evaluate nondestructive examination methods that may be applied to cable condition assessment, a set of tools has been developed including 1) a parallel-plate sensor (PPS) to directly measure the permittivity spectrum of flat sheet material and 2) an interdigital capacitor sensor (IDC) and fixture to measure the effect of cable polymer dielectric property change on the sensor response. The IDC consists of two fork-like electrodes facing each other with the fork tines interspersed and separated by a small gap. The electrodes are printed on one side of a flexible substrate that can be conformed to the surface of a cylindrical cable, with tines parallel to the cable axis. The electrodes are connected to a broad-frequency-spectral impedance meter that senses the capacitance between the narrowly gapped electrode tines. This capacitance is known to vary as a function of the permittivity of any material in close proximity to the electrodes. By finite element modeling and experimentation, this study investigates the effect of tine spacing and other design parameters associated with the IDC on the voltage (potential) distribution and electric field depth of penetration. The IDC measurement of an unshielded EPR cable is shown to track with the degree of aging and quantities obtained by established methods. For jacketed cable systems, the IDC response is dominated by the jacket but, by analyzing measurements from IDC sensors with different depths of field penetration into the cable-under-test, the influence of the cable jacket degradation can be separated from an assessment of the cable insulation thereby enabling assessment of the insulation beneath/through the jacket.

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Damage identification based on acceleration and strain sensing skin data fusion

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Abstract

This paper investigates the combined utilization of accelerometers and strain-sensing skin for structural health monitoring applications. The accelerometers are off-the-shelf sensors, while the sensing skin consists of soft elastomeric capacitors (SEC) fabricated by the authors. Of interest is high scalability of the SECs, which are inexpensive and easy to fabricate. They can therefore be arranged in dense network configurations, mimicking biological skin. Here, the sensing skin is used to locate damage through analyzing spatio-temporal changes in capacitance. Acceleration data is used along with a stochastic subspace identification (SSID) and a particle swarm optimization (PSO) algorithm, along with the damage identified and localized by the SECs, to update a structural model for damage quantification, whereas the updating is conducted at or around the locations identified by the SECs for enhanced accuracy. The proposed approach is validated using experimental data collected from a scaled model of a reinforced concrete bridge-like system. Cracks were induced in the system, and the proposed approach was successful at correctly identifying, localizing, and quantifying damage.

Acknowledgement

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Magnetostrictive Cold Spray Sensor for Harsh Environment and Long-Term Condition Monitoring

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Ultrasound sensors and inspection systems are frequently used to generate acoustic waves in metal structures capable of detecting and characterizing cracks, pits, erosion, inclusions, weld anomalies, and other material and structural features. One significant problem with piezoelectric transducers is the difficulty to achieve good coupling between the transducer and the surface being examined. This is particularly true in harsh conditions with high temperatures, cyclical hot and cold temperatures, highly radioactive fields found near nuclear reactors or spent nuclear fuel, caustic or corrosive fluids, and other extreme environmental conditions as well as in long-term monitoring applications where repair or replacement of the sensor is difficult or expensive. Typically, coupling between the surface and the transducer is achieved with water, gel, grease, viscous shear coupling material, or pressure, which might not be possible or appropriate for long-term applications in which the impedance matching materials wear away, evaporate or simply stop functioning due to changes in surface conditions. Fluid couplings can evaporate or drain away from the transducer-substrate interface; glue-based couplings may foul or fail and are notoriously unreliable at high temperatures and in radioactive environments.

This work explores the behavior of a magnetostrictive cold-spray patch that is metallurgically bonded to a stainless steel inspection target surface, and compares it to the performance of a standard adhesively-bonded ferrous-cobalt magnetostrictive strip solution. Cold-spray is a coating process where 10-100 micron powdered metal is accelerated to mach 2 to mach 3 (2-3 x speed of sound) and impacted on the surface to be coated. Each powder particle forms a kinetic bond with the substrate or other coating particles to produce a metalergically bonded layer. If the powder is nickel or cobalt with high magnetostrictive coefficients, this surface can serve as the base of a magnetostrictive sensor suitable for crack or pitting damage inspection and monitoring that is not subject to temporal or environmental degradation. A commercially pure nickel (CPNi) cold-spray patch based sensor on a 2 x 4 ft. \( \frac{1}{4} \) and \( \frac{1}{2} \) inch thick plate was contrasted with a more conventional FeCo adhesive strip to determine feasibility and relative efficacy of the two magnetostrictive substrates. The magnetostrictive coefficient of CPNi is reported as 25-60 ppm while cobalt has a magnetostrictive coefficient of 40-120. Moreover the FeCo strip is prepared with a magnetic bias treatment. As might be anticipated, the FeCo strip showed ~30-36 dB stronger edge-wall reflection than the CPNi patch however both signals were readily detectable. This degree of different responses are manageable within the range of gain-settings of commercial EMAT instruments. Based on the edge reflections, it is inferred that sensitivity to pit or crack flaws would be similarly detectable and therefore, the cold-spray patch would be a viable alternative to a FeCo adhesive strip sensor that is not subject to adhesive degradation. Influences of magnetic bias and cold-spray patch thickness are also explored in this study.

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Resonant acoustic nonlinearity and loss in additively manufactured stainless steel

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Resonant acoustic nonlinearity and loss in additively manufactured stainless steel were measured with the aim of assessing the potential of such measurements for nondestructively sensing defects that degrade mechanical performance. The material was fabricated by laser powder bed fusion (L-PBF) with intentional differences in spacing between laser tracks, which produced differences in porosity and the amount of incompletely melted powder. The composition was that of nominal 17-4 stainless steel. Noncontacting electromagnetic-acoustic transduction was employed with a single solenoid coil exciting and detecting resonant vibrations in a cylindrical sample within the coil. Three configurations of magnetic field, sample axis, and coil axis were employed to selectively excite modes with various symmetries of vibrational displacements, and Ritz analysis was employed to calculate detailed displacement patterns and extract elastic constants from the measurements. Resonant frequencies and loss of the selected modes were determined as a function of excitation level through analysis of resonant ringdown following tone-burst excitation. X-ray computed tomography was employed to image the structure of pores. The acoustic results show resonant frequencies initially increasing with increasing vibrational amplitude and, then, decreasing at the highest excitation levels. The initial sign of the measured frequency shifts vs. excitation level is opposite to that typically reported for various microstructural defects in other materials. However, this sign is qualitatively consistent with theories of dislocation nonlinearity that predict, in some cases, increasing dislocation stiffness with increasing applied acoustic stress. The overall magnitudes of the nonlinearity and loss were found to be monotonically correlated with the number of incompletely melted particles and corresponding porosity in the samples.
Design and Construction of an Absolute Precision Load Gauge: Theory and Experiment

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This paper presents the formulation that calculates an applied uniaxial load on an absolute precision load gauge (APLG) by using the finite deformation theory [1,2] of an elastic solid, which was initially isotropic at strain-free state, and design and construction of the APLG, and validity of the APLG by testing it under the compression machine with maximum capacity of 300 imperial tons. The load-carrying member of the APLG is a cylindrically shaped 7075 aluminum alloy with 120.89 mm diameter, which can carry more than 480 metric tons of load in the elastic range without inducing plastic deformation. The vertically applied load is calculated using four measured data: a lateral dimensional change of a specimen in the horizontal direction and three travel times of horizontally propagating longitudinal, vertically polarized shear (SV) and horizontally polarized shear (SH) waves. These data can be easily measured in experiments with great accuracy. The lateral dimensional change of the specimen is measured with the resolution of 50 nm and travel times of the sound waves are measured with accuracy better than a few parts in 100,000. The theory takes care of the linear and nonlinear elastic contributions of material behavior under finite deformation, contributing to a great precision for the calculation of the applied load. The accuracy of the calculated load is better than 0.1%. The APLG directly calculates the applied load and thus precludes the need for its calibration, providing the advantage over the conventional load cells.

In the finite deformation theory, strain is treated as a finite strain, and its corresponding conjugate thermodynamic stress $\tau_{33}$ is calculated using the complex formulae and the measured data. Dimensional changes are measured in the isothermal condition. The applied Cauchy stress $\sigma_{33}$ is obtained from $\tau_{33}$ and fractional dimensional changes in lateral and vertical directions. Wave propagation is an adiabatic process resulting in the adiabatic second order elastic constants. Third order elastic constants obtained from the wavespeed data and the dimensional change are mixed elastic constants. These adiabatic and mixed elastic constants are converted into isothermal values using the thermodynamics of finite deformation of elastic solids developed by this author [1]. Then isothermal second order elastic compliance constant $S_{11}^T$ and isothermal third order elastic compliance constant $S_{111}^T$ are calculated. Finally applied load $P$ is expressed in an elegant simple form as

$$P = A_0 \tau_{33} \left[ 1 + S_{11}^T \tau_{33} + \left( \frac{1}{2} \right) \left( S_{111}^T - S_{11}^T \right) \tau_{33}^2 + \cdots \right],$$

where $A_0$ is the initial cross-sectional area of the specimen at zero load. The APLG applied loads are obtained under several compressive loads up to 300 imperial tons at the Test Bay of Cornell University.

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References:

Detection of additive manufacturing defects using X-ray computed tomography

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Metal additive manufacturing (AM) is evolving as a future manufacturing technique for various industrial sectors including medical and aerospace. However, the lack of understanding of the AM defects and limited defect detection method hinder widespread adoption of the technique. The defects occurring in AM are currently being categorized in the standards community, and several types of defect were identified for different AM processes, which are different from the defects of conventional manufacturing techniques. The complex internal and external features as well as the inherent surface roughness of typical AM parts pose challenges to many non-destructive evaluation (NDE) techniques. X-ray computed tomography (XCT) generally overcomes these inspection challenges, and it is emerging as a viable NDE technique for metal AM parts. After an XCT acquisition, image processing and thresholding steps need to be applied for an automatic defect detection and quantification. In this presentation, we will present a defect detection algorithm and procedure developed for XCT images. We will present our effort to understand the effect of XCT acquisition parameters on image quality and defect detection. A two-level fractional factorial experiment in which voltage, current, magnification, frame rate, number of images per projection, and reconstruction algorithm were varied was conducted. Our statistical analysis revealed that the number of images per projection most dramatically affects image quality with more collected images leading to higher quality. The experimental results were further extended to understanding probability of detection (POD) for a defect size of interest. The POD results and future direction of POD research will be discussed.

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Intelligence Augmentation Approach to Interfacing Artificial Intelligence Algorithms and Software with Nondestructive Evaluation Inspectors for Optimal Performance

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Abstract:

In recent years, advances have been made in the field of machine learning and artificial intelligence (AI), primarily through developments in deep learning neural networks (DLNN). Challenges however exist with transitioning emerging DLNN algorithms directly for NDE applications. Training deep learning neural networks requires very large, well-understood data sets, which is frequently not available for NDE applications. As well, there are significant concerns about the reliability and adaptability of such algorithms to completely perform complex NDE data review tasks. As a counterpoint to AI, intelligence augmentation (IA) refers to the effective use of information technology to enhance human intelligence. While attempting to replicate the human mind has encountered many obstacles over the years, IA has a much longer history of success. All forms of information technology, from writing cuneiform on clay tables to computers and smartphones today, have essentially been developed to enhance the information processing capabilities of the human mind. This talk will introduce a series of best practices for intelligence augmentation in NDE, highlighting how the operator should interface with NDE data and algorithms. Algorithms clearly have a great potential to help alleviate the burden of ‘big data’ in NDE; however, it is important that operators are involved in both secondary indication review, and the detection of rare event indications not addressed well by typical algorithms. Several past examples [1] of transitioning algorithms for NDE applications will be presented, emphasizing the successful interfacing of operator and software for optimal data review and decision making.

References:


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The NRC has been informed that parts created by additive manufacturing (AM) are being considered for applications in the operating fleet. In 2017, industry prototyping efforts involved use of the direct metal laser melting (DMLM) method to manufacture parts for reactor components. The Office of Nuclear Regulatory Research is beginning to evaluate the technology to gain insight into any technical issues that must be addressed to assure safety and reliability of specific DMLM-produced components that may be accepted by the NRC, including design, precursor materials, finished material properties, structural integrity, nondestructive evaluation, and quality assurance. This welding-based process may be susceptible to, for example, porosity, systematic defects, and anisotropy of properties not currently addressed for conventionally manufactured components.

The NRC is developing an action plan to address the use of additive manufacturing for reactor materials and components. The NRC plans to leverage ongoing research and evaluation of this technology being performed by Federal counterparts. This action plan will focus on topic areas of interest identified at the Additive Manufacturing for Reactor Materials and Components public meeting (ML17338A880):

- Quality of AM materials and components for nuclear power plants
- Codes and standards development for AM
- Properties and structural performance
- Service performance/aging degradation
- Regulatory infrastructure

AM has been identified as a technique that the nuclear industry may use in the future. Prevailing questions are: How will AM be used in nuclear power plants, and when? What is the regulatory infrastructure for determining how safe it is? NRC areas of interest include the quality, properties, and structural performance of AM parts, including their inspectability. The service performance and aging degradation of AM parts are critical. It will be essential to compare the performance of parts from AM and those from conventional manufacturing processes. Challenges to be addressed include the limited understanding of acceptable ranges of variation for key manufacturing parameters, limited understanding of key failure mechanisms and material anomalies, the potential for systematic defects, cybersecurity considerations, lack of industry databases, and lack of industry specifications and standards. The development of codes and standards for AM is key to successful implementation.
Demonstration of Using Signal Feature Extraction and Deep Learning Neural Networks with Ultrasonic Inspection Data for Detecting Challenging Discontinuities in Composite Panels

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To address the data review burden and improve the reliability of the ultrasonic (UT) inspection of large composite structures, automated data analysis (ADA) algorithms and software have been developed to make calls on indications that satisfy the procedure criteria and minimize false calls [1-3]. There are opportunities to improve the performance of ADA for certain challenging inspection scenarios. For example, when inserts are located one ply down from the front wall or one ply up from the back wall, in regions with varying dimensions, ultrasonic signals can be difficult to interpret due to the superposition of reflected signals from the panel surface and the inserted materials. In recent years, impressive advances have been made in the field of machine learning, primarily through significant developments in deep learning neural networks (DLNN). Challenges however exist with transitioning emerging DLNN algorithms directly for NDE applications. Training deep learning neural networks requires very large, well-understood data sets. Relative to many problem spaces like image, voice, and text recognition, nondestructive evaluation is considered ‘data starved’. This work demonstrates the potential of the approach using chirplet feature extraction with the training of a deep learning neural network (DLNN) model for addressing challenging Full A-scan indication calls. To properly classify composite indications, evaluation must simultaneously consider characteristics of the A-scan, such as back-wall signal loss, or presence of superimposed signals, as well as evaluate the local trend in the A-scan signal feature and residual metrics, with respect to its neighboring signals. Typically, for 2 mm (0.080”) x 2 mm scan resolution, indications of 3 pixels by 3 pixels are needed to make a call. For the case study reference panel scans, the 2D raster scan was segmented into 6 x 6 A-scan groups for indication analysis and training purposes. Several data enhancement schemes were also applied to further increase the size of the training set for use with a convolutional neural network. Using this approach, a set of challenge indications were called by the DLNN based classifier and found to be clearly separable from the un-flawed regions of the scans.

References:

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Lamb Wave Propagation in a Plate with Step Discontinuities Using Effective Boundary Method

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Structural discontinuities such as ribs, joints and stiffeners affect ultrasonic wave propagation. Hence, it is important to understand the effect of such geometric discontinuities on the characteristics of waves in order rule out any confusion with defects that may occur in the interpretation of ultrasonic data. In the present work, the step jump in the structure is replaced by what is often called "effective boundary conditions". In this method, the stresses around the step are expanded in Taylor series along thickness boundaries to mathematically express the existence of the thickness variation. Consequently, zero traction conditions are replaced by nonzero boundary conditions due to the removal of the step discontinuity. The output of such technique is a model of uniform plate geometry-wise but with varying boundary conditions in which the nonvanishing boundary conditions are used in lieu of the step jump. A near-field solution is calculated and power flows past the step of the plate are obtained. The derived results are compared with those simulated using the commercial software COMSOL® and with already published results.
Progress on Distinguishing Cracks and Non-metallic Inclusions Using Eddy Current Nondestructive Evaluation and Model-Based Inversion

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An important criterion for life management of low cycle fatigue limited turbine engine components is damage tolerance. The use of eddy current (EC) nondestructive evaluation (NDE) techniques to detect damage in aircraft structures and propulsion components is a key part of United States Air Force programs to ensure that the risk of failures meets the desired requirements. Recent work has demonstrated the capability of applying inverse methods to automated eddy current data of surface breaking cracks and notches of various sizes and aspect ratios [1-3]. These results demonstrate advantages over a simple amplitude-based analysis of the data. However, not all eddy current indications in turbine engine component inspections originate from cracks, which can result in the unnecessary removal of engine components from service. For powder metallurgy nickel-based superalloys, non-metallic inclusions (NMIs) and non-metallic particles are frequently present [4]. If an EC inspection can reliably classify NMI indications from crack indications, there would be significant payoff for the USAF. In this work, simulated results will first be presented to highlight differences in eddy current signals from cracks and NMIs. The presentation will address progress on experimental testing to acquire high fidelity eddy current data on cracks and NMI, enhancements to the numerical modeling software, VIC-3D®, to improve both computational speed and accuracy, and the model-based inversion scheme. Lastly, inversion results will be presented that demonstrate the potential to accurately size cracks over a wide range of conditions and distinguish crack and NMI indications.

References:


Acknowledgements:

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Evaluating the Effectiveness of Nondestructive Examinations for Spent Fuel Storage Canisters

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Welded stainless steel canisters are used in dry storage systems of spent nuclear fuel from commercial power reactors in the U.S. These systems were initially licensed for 20 years and may receive license renewals for 40 more years from the U.S. Nuclear Regulatory Commission (NRC). The requirements for license renewal include aging management programs (AMPs) to ensure systems, structures, and components (SSCs) continue to perform their safety function. Nondestructive examination (NDE) plays an important role in AMPs that rely on inspection to detect service degradations such as chloride-induced stress corrosion cracking (CISCC) of austenitic stainless steel canisters so that mitigation actions can be taken to manage the aging effects.

The American Society of Mechanical Engineer (ASME) is currently developing a code case for the in-service inspection (ISI) of dry storage canisters. The nuclear industry is also developing inspection systems for conducting examinations of canisters. This paper is intended to summarize the on-going efforts by the NRC, with support from Pacific Northwest National Laboratory (PNNL), to evaluate the effectiveness of inspection systems to access the canister and detect flaws. This paper also documents efforts by PNNL to develop CISCC flaws on stainless steel specimens in an attempt to compare NDE responses to simulated flaws to assess the impact of flaw characteristics on the NDE performance.
Investigations of Pulse-echo and Pitch-Catch Angled-beam Ultrasonic NDE for Characterization of Hidden Regions of Impact Damage in Composites

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Abstract:

This study explores the use of angled-beam ultrasonic NDE for the potential characterization of so-called "hidden" regions of impact damage in composites [1]. While initial simulations of an angled-beam pulse-echo model showed that both direct and full-skip indications from edge delaminations should be detectable, recent experimental testing has encountered considerable difficulty in detecting oblique signals diffracting from delamination fields. One possible explanation for this discrepancy is the results from recent serial sectioning experiments indicate that the edges of real delaminations have a complex morphology and likely cannot be modeled as an ideal discontinuity.

To overcome this challenge of poor signal to noise with diffracted oblique waves, several alternative pitch-catch configurations are under investigation for characterizing the hidden delamination fields. Placement of secondary sensors is being considered on both the near and far sides of the impact damage region relative to the source transducer. Simulated studies have been performed on using oblique ultrasonic signal in a pitch-catch mode in CIVA FIDEL. Although the model is currently limited to only pulse-echo mode, it is feasible to study the magnitude of propagating and scattered signals through different forms of impact damage and evaluate changes using 2D displacement field calculations.

Clear differences between the signals on the far side of the impact site were observed for changes in the depth profile between columnar- and diamond-shaped damage. With additional complexity including steps in delaminations with connecting matrix cracks, pitch-catch measurements were still found to have sensitivity to the dimensions of the hidden profile. However, care must be taken with this approach to control the position of the oblique beam into the delamination hidden region. Preliminary studies have also investigated the use of pitch-catch transducers on the near-side of the source transducer, with mixed results to date.

References:


Acknowledgements:

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Using X-ray CT to Assess Defects in Additive Manufactured Material to Investigate Process, Structure, Properties Relationships for the Qualification of Aviation Components

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Additive manufacturing (AM) represents an opportunity to improve aircraft availability, readiness and sustainment. Navy aircraft readiness is suffering from part availability, long lead times, and inability to quickly manufacture small quantities of replacement critical parts. AM can address these issues by disrupting traditional manufacturing supply chains. However, reliance on traditional qualification methods to certify AM parts for flight critical applications is very expensive and time consuming. Methods to rapidly and accurately assess risk for AM parts are required. Model-based risk assessments will require accurate relationships between the processing, structure, defects and ultimate structural performance. Characterization of the effects of defects is necessary to define rejection criteria for a production inspection. To use AM for flight critical parts, inspections must be developed that can inspect the entirety of the part, detect AM characteristic defects, and correctly classify defects with respect to rejection criteria.

X-ray Computed Tomography (CT) inspection is useful for AM because it can perform full volumetric inspection of complex geometries that may otherwise be uninspectable with traditional methods. CT also allows quantification of defect geometries, and their distribution throughout parts. Measurement of the effects of defects at different length scales provide data to feed into models and allow assessment of critical defects, or defect distributions, as well as risk assessment of the effects of defects that may remain undetected in the final part. Establishing processing, structure, defects, and properties relationships will be essential to transitioning this technology for aviation. Models for qualification and requirements for inspection that can assure safety-of-flight need to be addressed if AM is to successfully benefit readiness and sustainment for the fleet.

Figure 1: CT measurements of defect density with respect to AM processing energy density

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Friction Stir Weld Inspection Using the Motion Induced Eddy Current Testing Technique

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Friction stir welding (FSW) is a rather novel solid-state joining process that uses a non-consumable tool to join two facing work pieces without melting the work piece material. FSW is particularly found in modern shipbuilding, trains, and aerospace applications. In addition to aluminum alloys, friction stir welding has been used successfully to join other metallic materials, such as copper, titanium, steel, magnesium, and composites [1]. FSW is well-known for its reproducibility and freedom from traditional fusion welding imperfections such as shrinkage cavities or slag inclusions. If FSW should be widely accepted as a joining method, reliable as well as cost-effective process-specific quality assurance activities have to be developed. So far, there is neither a common standard defect catalogue for FSW, which summarizes all relevant irregularities and describes their allowable sizes for different applications nor a standardized test specification for FSW welds. Moreover, it is still not fully understood how different imperfections of the weld are affecting its mechanical properties during static and dynamic load.

The nondestructive testing (NDT) methods proposed for FSW so far (ultrasound, eddy current arrays, and x-ray techniques), are only suitable to a limited extent for application in SME production, because they are expensive, time-consuming and not flexible enough. In addition, however, there are some FSW specific irregularities affecting fatigue behavior and corrosion resistance, such as flat wormholes, oxide lines and blisters, which are difficult to identify with conventional NDT. Therefore, there is still the need for further development of NDT techniques.

In this paper, the motion induced eddy current testing (MIECT) technique [2] has been applied to the nondestructive inspection of FSW, where sheets of aluminum alloy are joined. Aluminum specimens (Al-alloy EN AW 6060 T66; feed rate = 400mm/min; tool rotation speed = 2000 – 3000 rpm; tool force = 8 kN) have been joint by means of the FSW system available in the Production Engineering Lab of the TU Ilmenau. The weld seam has been investigated with MIECT measurements on the multi-purpose measurement platform MMP-15, available in our lab. The main goal of the study was to identify internal defects or other imperfections in or near the welding zone.

The measurement results for the drag force show that due to the friction stir welding the conductivity in the weld seam is changed. Defects in the seam, like lack of penetration or holes lowering the conductivity locally in that region, could be identified. The lift force seems to be more sensitive to the detection of small defects / imperfections in the welding seam. The use of a differential Lorentz force eddy current testing sensor, a sensor designed for near-surface defects or high measurement velocity, leads to a higher sensitivity of the entire sensor system.

References:
Experimental Method to Compare Ultrasonic NDT Devices

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Emerging smart technologies in nondestructive testing demand a standard procedure to compare the performance of a new technology with the standard, certified ones. While there are various established techniques to compare medical ultrasound devices [1-3], there are few in the field of nondestructive testing (NDT). A comparison is often necessary to determine whether an established method and a new method agree sufficiently for the latter to be accepted. This study strives to compare the performance of three NDT ultrasound devices, in the form of their signal-to-noise ratio (SNR) as a function of frequency. The devices in consideration are, Panametrics 5052, Krautkramer USD 15 and PCUS Pocket. The Panametrics device is a classic, reliable analog pulser/receiver that requires an oscilloscope to operate. The Krautkramer device is a portable, digital ultrasonic flaw detector with its own display, and PCUS is a completely digital flaw detector that performs the same pulser/receiver function while being the smallest of them all, with a size comparable to a modern smartphone.

The objective of this study is to define an experimental method that achieves a similar experimental set-up for the NDT ultrasound devices and transducers of varying sizes and manufacturers, and then compare their performance in terms of their signal-to-noise ratio. To establish an approximate identical experimental set-up, each device needs to be characterized and other components, such as transducer, couplant, cables be standardized. A correlation and rescaling of the various parameters in each device is done to achieve a comparable excitation pulse, damping, pulse repetition frequency, input voltage and display that ensure a justifiable comparison. A characterization of noise from different sources that act on the device and the experimental set-up is investigated. Defect response from a series of flat-bottomed holes of Aluminum (low grain noise) and Steel (higher grain noise) and their corresponding frequency content is inspected to draw a comparison of SNR among the three devices.

References:

Recent high-profile successes in machine learning have found solutions to problems that were long-thought to be decades away and has generated renewed interest in artificial intelligence (AI) and machine learning (ML) research. For example, the recent success and rapid commercialization of deep learning has catapulted technical achievements in automatic speech recognition and image recognition. In less than a decade, these deep learning algorithms are now ubiquitous in modern phones and personal assistants. In addition, DeepMind’s use of deep learning, transfer learning, and reinforcement to learn the game of Go has shown that machines can learn (sometimes more effectively) from rules and abstract concepts rather than data.

These successes present new opportunities for advancing nondestructive evaluation (NDE) techniques. This paper reviews new opportunities for the research and development for improving the NDE of materials. We start by reviewing the fundamental components of ML. We then discuss past applications and methods of ML for NDE. We also describe the still unresolved challenges for this field, such as the unavailability of reliable training data. We then discuss current research in ML for NDE that is directed toward solving these challenges. Finally, we outline how the most recent advances in ML, such as deep learning and transfer learning, have the potential to revolutionize how we design future NDE solutions.

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Mechanical components often have challenging requirements in terms of performance and reliability. Furthermore, these characteristics are primarily dictated by the microscopic features of the material that comprises the components. Thus, the ability to quantify the microstructure of mechanical components nondestructively is crucial. In this context, grain size assessment is of particular importance, because mechanical properties such as hardness and strength are dependent upon the grain size. Ultrasound models and methods provide a straightforward approach to quantify elastic properties of samples, while the scattering from the microstructure can be used for characterization. Experimentally verified diffuse ultrasonic scattering models for microstructure characterization have progressed greatly in the past decade and offer the possibility of a wide variety of experimental configurations. An optimization routine is necessary to find the best experimental, thus the best inspection, configurations for the components to be evaluated. The work to be presented provides a deliberate step in this direction. A diffuse ultrasonic backscatter model for a normal incidence configuration under a single scattering assumption is considered [1]. The effect of parameter variations on the model response is evaluated by executing sensitivity analysis [2]. The results of these evaluations indicate that parameters such as frequency and material path dominate the response, as expected. Then, gradient and non-gradient based nonlinear methods of optimization [3, 4], are applied to maximize the normal incidence singly-scattered response. Results for different levels of scattering materials are discussed. As a result, it is possible to estimate the best experimental configuration given some preliminary knowledge of the component of interest.

References:
An Experimental Measurement Technique for Determining Single Crystal Elastic Properties in a Polycrystalline Material with Resonance Ultrasound Spectroscopy

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The models used to predict the performance of new high-performance aerospace engine alloys depend on accurate single crystal elastic properties. Resonance Ultrasound Spectroscopy (RUS) is a nondestructive technique in which the natural resonances of a material are utilized to measure these properties. Determination of single crystal properties with RUS traditionally requires the growth of sufficiently large single crystals of the material of interest, which can be a time consuming and difficult process.

This work explores the development of a measurement technique that enables the determination of single crystal properties without the need to grow large single crystals. Instead, a thin sheet of the polycrystalline material of interest is machined to isolate a single crystal on the end of a cantilevered beam. The cantilever acts to isolate the single crystal from the substrate. Furthermore, a damping material is applied to the substrate to minimize the interaction between the cantilever and substrate. Resonance behavior is predicted utilizing a finite element approach [1]. This configuration is readily adaptable to a variety of materials with varying grain size. Modeling results will be presented and results from a preliminary millimeter scale experimental test on a single crystal Silicon wafer will be shown.

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References

A Supervised Learning Approach for Prediction of X-ray Computed Tomography Data from Ultrasonic Testing Data

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Detection and characterization of impact damage in polymer matrix composites (PMCs) with ultrasonic inspection will enable informed decision making for lifing of composite structures. Post-processing of single-sided pulse-echo Ultrasonic Testing (UT) data produces 2D C-scan images that indicate the presence and extent of delaminations. X-ray Computed Tomography (XCT) characterizes internal damage with a 3D voxel-based representation. Delaminations, matrix cracks, and surface-breaking cracks can be clearly visible in some XCT reconstructions. Single sided UT inspections that provide characterization of impact damage in PMCs in 3D with a level of detail similar to XCT is desirable. This work discusses development of machine learning models to take as input a collection of UT pulse-echo scans of an impacted PMC panel and predict as output the results of an XCT scan in the form of a 3D voxel-based representation of damage. The models were trained on UT and XCT data from previous impacted PMC panels. The approach, including UT and XCT inspection data collection, feature extraction, training of the models, and evaluation of the models on new UT data will be presented. The accuracy of the damage characterization results and challenges with this approach will be discussed.

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Ultrasonic inspection of complex parts with TRL matrices probes mounted on water wedges using an adaptive plane wave imaging approach for combined pulse-echo and pitch-catch modes

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Advanced post-beamforming methods such as Advanced FMC/TFM are powerful approaches for fast and high quality imaging of industrial parts. After complex transmitting patterns, the image reconstruction is obtained using post-processing beamforming. Usually, these acquisition and reconstruction processes need the knowledge of the geometry of the part under test in order to be efficient. Therefore, in the case of parts with complex geometries such as pipes, weld beads or fans, a conventional imaging algorithm gives inadequate results. In this paper, we propose an adaptive method of TFM-like imaging approaches for pieces with complex profiles. Using a single data set, the method estimates the profile of the piece, and performs the image reconstruction. About the experimental setup, we use two TRL matrix probes mounted on flexible wedges that can adapt to complex surfaces without an inspection in immersion. The contribution of this work is that we provide all modes between the two probes (pulse-echo of probe 1, pulse-echo of probe 2, pitch-catch from probes 1 to 2, pitch-catch from probes 2 to 1). The developed adaptive imaging method permits a real-time display of the four modes thanks to massive parallel computations. Results are presented from a steel pipe section containing artificial defects. The employed probes are two matrices having 128 elements (8x16 elements), centered at 1.5MHz, with a 3 mm pitch. The phased-array device is a 256 channel full-parallel from Advanced OEM Solutions (AOS). The proposed method reveals a better flaw and geometry positioning than a naive approach.
Study the vibration behavior and relate individual frequency of induced sound waves and energy consumption in defects in Sonic Infrared Imaging

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Sonic Infrared Imaging (SIR) technology is a novel NDE method in NDE family. This technology is capable of detecting surface and subsurface defects in metals, metal alloys, and composites. SIR combines ultrasonic excitation with IR imaging to give a quick detection response in crack region by observing the temperature change on the structure surface. Nonlinearity phenomena in SIR occurs in the coupling between the target and ultrasound transducer, where a single frequency driving excitation source produces sound waves containing multiple frequencies. This nonlinearity is very important in improving the probability of crack detection significantly. Several factors related to the nonlinearity phenomena are studied. In this paper, we will present our study on nonlinearity in SIR with emphasis on the relationship between the frequency of the induced sound waves and their corresponding energy level in the crack vicinity of samples.

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Figure 1 Friction Energy VS Temperature change @ Different Frequency

References:

Expanding upon the applications of the Partial Wave Method and developing a more detailed understanding of guided waves

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The Partial Wave Method (PWM) is often used to calculate the dispersion curves of an anisotropic waveguide or as a part of the Transfer Matrix Method and the Global Matrix Method for calculating the dispersion curves for layered waveguides. However, PWM can be used for a variety of other useful applications, including conceptual interpretation of numerically-calculated dispersion curves, fundamental understanding of guided wave characteristics, wave-structure calculation, mode sorting, acoustic emission prediction, and as a foundational theory for most elastodynamic guided waves. The paper itself will discuss the general theory involved in each application and how they can be implemented.

![Conceptual sketch of the partial waves that are necessary for the A0 Lamb wave.](image)

**Figure 1.** Conceptual sketch of the partial waves that are necessary for the A0 Lamb wave.
Microstructural and Magnetic Barkhausen Noise Characterization of Temper Embrittled HY-80 Steel

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Processing techniques can affect the microstructural properties of a material and can ultimately determine whether a component will perform its function safely. The steels used in submarine applications are susceptible to embrittlement when they are heated or slowly cooled through the embrittling temperature range of 371 to 599 °C. Evaluation of the state of temper embrittlement in HY-80 steel (submarine steel) can contribute to risk assessments that provide assurance that in-service components will not undergo failure. The present work evaluated the response of Magnetic Barkhausen Noise (MBN) to changes in temper embrittlement in HY-80 cast steel. Three steel samples were subjected to a constant temperature (525° C) at different holding times, to produce different amounts of embrittlement in each sample. The MBN measurement system used a flux controlled waveform, which facilitates reproducibility of the measurements and permits extraction of variations in permeability between samples. MBN signal response was observed to decrease as a function of holding time, which was attributed to migration of impurity elements, which act as pinning sites for domain walls, to prior austenitic grain boundaries. In addition, microstructural characterization was performed on the samples using scanning electron microscope (SEM). A martensitic structure was observed along with numerous very fine carbide particles distributed in the matrix. Mechanical properties, such as hardness and impact toughness, were also evaluated for the temper embrittled samples, and related to measured MBN and magnetic permeability variations.
The production of metals such as nickel, copper, and platinum group metals (PMGs) is typically done by smelting concentrated ores in pyrometallurgical furnaces. The process of smelting involves generating high temperatures by arcing or chemical reactions and separating the concentrate into the product, being metal or matte and the waste, being slag. The density of the metal is generally higher than that of slag and therefore, slag tends to float on top of the metal. It is desirable to determine the position of the metal and slag interface to maximize production efficiency. Reliable and continuous level measurements are desired by smelting operators to determine when to commence tapping (removal of metal and/or slag from the furnace) and monitor the tapping operation. In addition, metal level control is important for the long term structural integrity of the furnace. Today, common methods of estimating metal level in furnaces include mass and energy balance calculations and sounding bar measurements from above the furnace.

To overcome the shortcomings of the current methods, and to improve the utility and accuracy of metal/slag level measurement, a continuous sensing, eddy current based system, embedded in the furnace sidewall, is being studied. The eddy current drive and pickup coil sensor system developed in this study was able to measure the signal in a laboratory setting at a liftoff distance of 300 mm from the simulated metal/slag interface. However, while the electromagnetic fields pass easily through refractory brick, they may be affected by the presence of conducting material in the vicinity of the probe. The effect of such material, such as copper cooling plates in an actual furnace, on the signal response was examined. It was observed that the cooling plate next to the coil configuration increased the signal by 28 % whereas, when the copper plate was placed behind the coils the signal was reduced by 74 %. A decrease of signal amplitude by 92 % was observed when the Cu tubes were placed around the drive and pickup coils. Furthermore, finite element analysis was used to simulate the effect of surrounding material on the signal measurement and to help explain the amplification and/or shielding effects of conductors on electromagnetic fields. The purpose of this presentation is to describe prior art in the field of metal level measurement in pyrometallurgical furnaces, outline the eddy current based system developed by RMC and Hatch and to demonstrate the experimental results of laboratory testing.
Pulsed Eddy Current Probe Optimization for Steel Pipe Wall Thickness Measurement

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Inspection of bulk wall loss, due to far surface corrosion in ferromagnetic steel pipe, is a common requirement across multiple industries, including chemical processing, and oil and gas. In the nuclear industry, a requirement for tile holes and balance of plant inspections, where insulated pipe is present is also required. Inspection is typically done using ultrasonic testing, which necessitates a coupling agent and removal of any insulation. Pulsed eddy current (PEC) technique does not require direct contact and has a larger spot size, thereby facilitating more rapid inspection without insulation removal. To further develop the potential of PEC to inspect under these conditions, a reflection type PEC send-receive probe was examined for inspection of thickness of steel plate. PEC data was taken for different plate thicknesses so that sensitivity to wall loss due to corrosion could be assessed. The PEC signal was analyzed by fitting the tail of the transient decay with an exponential curve, with curve fitting parameters correlated to wall thickness variation. An analytical model was developed and partially validated in order to examine a wider range of factors than is practical in a laboratory setup, such as probe dimensions and number of turns, and magnetic permeability and conductivity of the steel. The modelled data was also used to perform a sensitivity analysis on probe dimensions in order to realise the largest range of wall thickness with highest spatial resolution. This optimization target was chosen because thickness resolution inside the useful range is almost static, while the target range of wall thickness (thin versus thick wall steel, for example) for which the probe can provide a measurement, is much more affected.
Field Deployable Spray-on Ultrasonic Coatings for High-Temperature Applications

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Field testing of structures at high-temperature is a challenge, as commercial transducers rated for high-temperature applications are limited. The gel couplant between the transducer and the substrate evaporates and in-situ measurements are difficult. To solve this, we have furthered the work in applying a practical transducer in liquid form which air dries directly on the substrate. Previous work has been performed using sol-gel, potato starch and PZT (Lead Zirconium Titanate) as the piezoelectric material, but due to their individual disadvantages, other inorganic materials were studied. The transducer consists of a piezoceramic film composed of Bismuth Titanate and a high-temperature inorganic binding agent, Ceramabind 830. A thick film forms on the substrate which is then poled in an electric field to impart piezoelectricity in the film. Pulse-echo measurements for signal voltage over a certain period of time are made to validate its workability.

Another method to produce these spray-on transducers is using organic solvent and binder mixture with the piezoelectric powder. Advantages of this method is the mixture’s dispersive nature. A dispersant (Menhaden Fish-Oil)³ is incorporated to restrict the agglomeration of the powder particles. Due to this, even months after fabrication, the mixture could be stored and reused.

Applications are primarily focused for structures operating at high-temperature such as pipelines used in Nuclear Plants. The final product is stable for both organic and in-organic methods, has quick fabrication time and has an operating temperature up to the Curie Temperature of Bismuth Titanate, 650 °C, well beyond the operating temperature of most piezoelectric materials. A comb transducer arrangement is prepared with a certain number of elements and pre-determined spacing in order to generate prescribed guided wave modes that will interact with defects in the structure.

References

Polar Sparse Wavenumber Analysis for Guided Wave Reconstruction

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The potential of reconstructing guided waves from limited measurements has been explored in several studies. In particular, a compressive sensing (CS) based method called sparse wavenumber analysis (SWA) [1] has been used to recover the dispersion curves of guided waves, exploiting their sparse nature in the frequency-wavenumber domain. The inherent isotropy assumption in the SWA model causes it to fail in predicting anisotropic wave propagation. To account for direction-dependent velocity variations that guided waves experience in anisotropic media, an extension of the SWA model into two dimensions was introduced in [2]. This two-dimensional model incorporates spatial information in the Cartesian coordinates and is capable of reconstructing guided waves from undersampled data by recovering the sparse representation of the waves in the two-dimensional wavenumber domain.

In this paper, we present a new CS based approach to the reconstruction problem that utilizes the information content of the measurements in the polar coordinate system. We introduce a sparse recovery algorithm based on orthogonal matching pursuit that is capable of retrieving the sparse representation of guided waves in a transform domain, showing their radial and angular variations. This representation will then be used to predict the fully sampled wavefield. Figure 1(a) illustrates 100 randomly sampled spatial measurements. Figure 1(b) shows the reconstruction output of our method using these measurements. The reconstructed full wavefield has a total correlation coefficient of about 0.96 with the true full wavefield, shown in Figure 1(c).

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References:

![Figure 1](image-url)
Transfer Learning of Ultrasonic Guided Waves: A Preliminary Study with Autoencoders

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In recent years, the use of scanning laser Doppler vibrometry and full wavefield acquisition has grown to aid the characterization of ultrasonic waves and the detection of structural defects. Yet, these methods require a considerable amount of time to acquire full wavefield data. Therefore, there is a significant need to reduce acquisition time, either by increasing the acquisition speed or by reducing the number of sampled measurements, without significantly compromising the accuracy of our estimate of true wavefield.

In this preliminary work, we present a transfer learning approach for reducing the number of sampled measurements necessary. Transfer learning is designed to transfer knowledge from one related task to another. This method utilizes numerical simulations, combined with a few spatially sampled random measurements from an experimental structure, to reconstruct full wavefield data. Specifically, we use a sparse autoencoder [1] neural network to learn low-dimensional representations of wave propagation from numerical simulations. We then input a few experimental measurements into the neural network to reconstruct full wavefield data.

To demonstrate the ability of transfer learning, we simulate Lamb waves in two aluminum plates: one with only the zero-order symmetric (S0) mode and the other (emulating an experimental system) with only the zero-order asymmetric (A0) mode. Figure 1(a) shows a numerical simulation wavefield snapshot in time that corresponds to an S0 mode. We train our autoencoder with this data. Figure 1(b) shows 500 random spatial measurements from a plate with only A0 mode, which we use to predict the wavefield in Fig.1(c). Figure 1(d) shows the true wavefield of a plate with only A0 mode. We observe that the reconstruction depicts the true wavefield using just 500 measurements with 87% accuracy. In the paper, we extend these results to reconstruct wavefield data of an experimental steel structure.

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Use of Digital Microstructures for Improved Ultrasonic Scattering Models for Elongated Grains

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Microstructure characterization derived from ultrasonic scattering measurements is of great interest, especially when complex microstructures are present within a sample. In particular, grain elongation is known to affect sample formability and workability and can lead to strong anisotropy in the material response. Previous ultrasonic scattering models that have included grain elongation consider all grains to be uniform with ellipsoidal geometry. Such approaches have met with limited success when comparisons have been made with diffuse ultrasonic scattering experiments. In this presentation, an alternative approach based on the Dream.3D software platform is proposed to generate three-dimensional realizations of polycrystalline materials with grain elongation. Then, specific grain statistics are chosen to correspond with electron backscatter diffraction (EBSD) measurements from a sample of rolled aluminum 7475. These digital microstructures are then used in conjunction with ultrasonic scattering models to predict directionally-dependent longitudinal-to-transverse (L-T) diffuse scattering amplitudes. The numerical results are compared with experimental scattering data, obtained using focused 10 MHz probes. The measurements show directional variations of the L-T scattering amplitudes of more than one hundred highlighting the extreme elongations observed in this rolled microstructure. The use of the digital microstructures is shown to improve the scattering predictions and may offer an avenue for improved scattering models.

Acknowledgement:

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Dynamics-based testing to localize macro cracking due to Alkali-Silica Reaction in Concrete

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Reliable methodologies that help diagnose flaws in structural components of nuclear power plants play a crucial role in a plant’s operational and maintenance decision process. In this work, we focus on degradation in concrete structures caused by the alkali-silica reaction (ASR): a chemical reaction between the cement and certain aggregates containing amorphous silica. In the presence of water, the ASR gel, formed as a byproduct of the ASR, expands and leads to diffused cracking. We investigate the suitability of a novel dynamics-based method, namely vibro-acoustic modulation (VAM), for the detection and localization of cracks caused by the ASR. In a VAM test, the structural component is excited using two frequencies. The lower frequency is referred to as the pumping frequency, whereas the higher frequency is known as the probing frequency [1]. If a part of the structural component is cracked, the geometric nonlinearity at the crack (displacement-dependent opening and closing of the crack) results in frequency modulation. The frequency modulation (and hence the nonlinear structural behavior) appears as sidebands around the higher (probing) frequency in the power spectral density (PSD) of the measured response in the neighborhood of the damage zone. A map of the magnitude of such sidebands can be used to detect and localize the damage. Previously, VAM has successfully been used for detection and localization of near-surface delamination in thin composite plates [2]. However, its applicability for detection and localization of cracks in thick concrete walls and slabs has not been studied. We perform numerical and laboratory experiments to investigate VAM-based damage diagnosis in thick concrete components. We conduct numerical experiments on two- and three-dimensional elastic solids (plates and slabs) to assess the effect of various test parameters (pump and probe frequencies, amplitudes, locations; crack depth, size, orientation, etc.) on the accuracy of VAM-based crack detection and localization. We also conduct laboratory testing on two sets of specimens: 1) a cement slab containing four pockets of reactive aggregates placed at known locations, and 2) two concrete slab samples with reactive aggregates distributed evenly throughout the slabs, along with two control specimens (cast using normal/non-reactive aggregate). Our experiments show that VAM-based testing with optimized test parameters and suitable sensor density can potentially be used to detect and localize cracks in thick concrete structures.

Acknowledgement:

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References:


Influence of microstructural grain-size distribution on ultrasonic scattering

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Ultrasonic attenuation and diffuse scattering result from the interaction of ultrasound with the microstructure of polycrystalline samples. Researchers are now using these effects to quantify mean grain size with good success and progress is being made with respect to more complex grain morphologies and macroscopic texture. However, theoretical models of such microstructures can become untenable because the scattering theory requires the covariance of the elastic modulus which is an eighth-rank tensor. For this reason, computational models of polycrystals are often considered for which grain spatial statistics can be calculated directly. In this presentation, the influence of grain-size distribution is examined using such an approach with the Dream3D software platform used to generate three-dimensional (3D) realizations of polycrystalline materials. Representative material volumes are simulated using lognormal distributions of grain size with fixed means but different widths. These realizations are then used to calculate the relevant grain statistics needed for ultrasonic scattering predictions including attenuation and longitudinal-to-longitudinal backscatter. The use of one hundred realizations for each combination of grain-size distribution allows the variation of the ultrasonic scattering to be quantified precisely. The results show the rate at which the scattering increases as the distribution widens and the role of the larger grains on the overall scattering amplitudes. Prospects for measurements of such distributions will also be discussed. These results are expected to aid in the development of simplified models that capture the overall trends of the grain-size distribution.

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Diffuse Ultrasonic Backscatter in Simulated Polycrystalline Materials

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Ultrasonic nondestructive testing has been increasingly used to characterize heterogeneities of polycrystalline materials. With such techniques, the interactions of coherent ultrasonic waves with material heterogeneities such as flaws or grain boundaries result in scattering. Such scattered waves carry information regarding the physical properties of the scatterer. Therefore, microstructural information can be obtained through quantifying the scattered response. Current diffuse ultrasonic backscatter models include several assumptions about the macroscopic and microscopic properties of the polycrystals. In this presentation, the sensitivity of grain size characterization to such assumptions is investigated using simulated microstructures. Several polycrystals with cubic crystal symmetry and randomly oriented grains are simulated using Dream.3D software. This study applies the single scattering models developed by Ghoshal [1] and Hu [2,3] in which longitudinal-longitudinal, longitudinal-transverse and transverse-transverse configurations are considered for the incident and the scattered waves. To minimize higher order scattering, investigations are limited to the weakly-scattering regime. In each configuration, the theoretical results are compared with results from the synthetic volumes at different frequencies. The results demonstrate distinct differences between the theory and the simulation. For example, the theoretical scattering cross section for a Voigt-averaged copper polycrystal at 15 MHz is found to be about three times larger than the value based on the Dream.3D microstructure. These findings will have a significant impact on flaw detection and grain characterization.

Acknowledgement:

Research supported by AFRL under prime contract FA8650-15-D-5231.

References:

Ultrasonic attenuation plays a crucial role in diffuse backscatter calculations and for the characterization of heterogeneities in materials. As an ultrasonic wave propagates through a polycrystalline media, it loses energy because of scattering and absorption. Attenuation is the rate of energy lost due to these scattering and absorption events. Several assumptions are included in the current ultrasonic attenuation models. This work attempts to address those assumptions and evaluate their contribution to the attenuation. Here, Dream.3D software is used to generate polycrystals with cubic symmetry and randomly oriented grains. For each simulated microstructure, attenuations are calculated using Voigt, Reuss, and self-consistent approaches in different directions and frequencies. Comparisons are then made with values of attenuations derived from classical theories. For a statistically isotropic media with narrow grain size distribution, these theories decouple the spatial and tensorial components of the microstructure. They also assume that the spatial correlation function follows the model provided by Stanke and Kino [1]. However, for a simulated microstructure, some of these assumptions are not valid. Therefore, the attenuation is studied here in the most general form. The results for a simulated Voigt averaged copper media at 15 MHz show that the longitudinal and transverse attenuations are about one third of those obtained from the theory. This ratio is observed to be a function of the frequency. Such disagreement is mainly attributed to the difference in the theoretical and simulated spatial correlation functions. The results also show a slight anisotropy in the attenuation which is due to the finite number of grains comprising the polycrystal.

Acknowledgement:

Research supported by AFRL under prime contract FA8650-15-D-5231.

Reference:
Micromechanics modeling of vibrothermography

Stephen D. Holland, Ashraf Bastawros, Bryan Schiefelbein, Tyler Lesthaeghe, Christopher Giuffre, Henry Moldenhauer, and Chevonne McInnis, Center for NDE, Iowa State University

Vibrothermography uses vibration-induced heating to find cracks. The accepted theory is that some sort of frictional process dominates the heating [1], but the precise details remain somewhat nebulous. Friction generally implies shear loading, but cracks are known to heat even in opening-closing mode (normal loading). Crack closure is also known to be a controlling parameter [2]. A viable theory of vibrothermographic heating needs to explain the sensitivity to shear, closure effects, amplitude dependence of heating, and the magnitudes of observed heating. To understand what is going on, we have performed a series of measurements to test both the friction hypothesis and alternate theories.

We present progress in modeling the micromechanics of the vibrothermography process based on observations from these experiments. We focus in particular on understanding the effect of crack surface roughness and its influence on crack heating. Angled asperity contacts due to surface roughness have the potential to transform normal loading into the shearing motion required to give frictional heating. Preliminary calculations indicate that such asperity can explain the crack heating observed in vibrothermography tests.

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References:
Automated Workflow for Checklist Driven Experiment Logging in the NDE Laboratory

Nathan Scheirer, Stephen Holland, Tyler Lesthaeghe, Center for NDE, Iowa State University

NDE experiments can be intricate and need to be repeatable and consistent [1]. Accurate record keeping is needed to create a meaningful archive of the specimen history. Tools that can assist with record keeping and promote repeatability are extremely valuable. LIMATIX is a suite of tools that assist with record keeping, experimental procedures, and processing. It is built around the idea of checklist-based experiment logging. The technician is guided through an experiment by a series of checklists that get archived and cross-referenced with an experiment log. The checklists can embed instrument controls and macro functionality to minimize unnecessary steps, distraction, or confusion. LIMATIX consists of three components: Datacollect, Databrowse, and ProcessTrak. Datacollect provides the checklist-based experiment logging. Databrowse is a web-based application for viewing the experiment logs, checklists, and experimental results. ProcessTrak helps manage multi-step analysis workflows and tracks the provenance of the processed output.

From the collection of data to viewing the result, LIMATIX helps to convert a conglomerate of experimental data into a repository of semi-structured data that is shareable and interpretable by others. The repository contains an experiment’s entire resulting data set that is both automatically and manually discoverable and searchable. Such repositories will enable future data mining.

A typical experiment that utilizes LIMATIX begins with a formal plan, i.e. an unfilled checklist of instructions. This plan references other checklists for the various subtasks. As you perform and subsequently check off each step, values inputted by the operator (or automatically extracted from the data acquisition system), are processed and recorded into XML-formatted logs. These logs are easily viewed using Databrowse and are ready for processing and analysis with ProcessTrak.

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References:
A new approach is presented for localization of acoustic emission sources in quasi-isotropic composite plates. Only three passive sensors are employed to collect the acoustic emission (AE) signal in this study. Features from both extensional (S0) and flexural (A0) waves from sensors are used to locate the acoustic emission source. A correlation function analysis is applied to the received AE signals in order to obtain the time difference of arrivals (TDOAs) of the extensional (S0) waves. With the TDOAs of the extensional waves, the direction of the source is determined by means of geometric relationships between sensors and the acoustic emission source [1]. Then a continuous wavelet transform is conducted to the entire AE signals to accurately determine the time of arrivals (TOAs) of the flexural (A0) waves [2]. The location of the acoustic emission source can be obtained by the estimated TDOAs and TOAs. Finite element analysis is used to validate the effectiveness of the proposed method.

References:

Design of Signal Processing Filter Specialized for Imaging Water-filled Cavities in Concrete

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²NIPPON PS Co, Ltd., Fukui-ken, Japan

Tendon break has been reported in prestressed concrete (PC) beam of the post-tension type. The break occurs due to the incomplete grunting in the duct. If water, chloride and other chemicals invade the beam and stay in the incomplete grouting part, the PC tendon would have corrosion and break. For the detection of the incomplete grouting part, impact echo method has been developed. However, the reflection of elastic waves is lessened more than 30% if water is filled in the duct, compared to that without water in concrete. We propose an imaging process method for the water-filled duct in concrete structures based on the Ultrasonic Testing (UT). Imaging process applies linearized inverse scattering method with Kirchhoff approximation (K-LISM) [1][2]. A Pre-processing method, which is parasitic discrete wavelet transform (PDWT), of the K-LISM is applied to extract the signals that scatter at the concrete-water interface effectively. The filter of PDWT [3] is specialized to extract the target signal. Figure 1 is an example of the results. The duct imaging is clearly shown. The proposed method is effective for imaging the cavity filled with water.

Figure 1. Specimen and the result of imaging

References:
Spread Spectrum Time Domain Reflectometry for Detecting and Locating Electrical Faults with Arbitrary Impedances

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Wire deterioration is a problem for many aging electrical systems, including aircrafts and power plants. There has been considerable research efforts to nondestructively detect and locate dangerous open faults and shorts in wiring. One widely used and commercialized technique for detecting and locating these faults is Spread Spectrum Time-Domain Reflectometry (SSTDR). SSTDR locates faults by transmitting spread spectrum electrical signals into a wire. Reflections from discontinuities are then received and analyzed to locate faults. Unlike other approaches, SSTDR can be used on a live system [1] and can easily adjust its measured signal-to-noise ratio, which is directly proportional to the length of the transmitted signal.

While SSTDR can locate open faults and shorts in wires, there has not been significant success with more complex electrical systems, such as photovoltaic panels. The faults in these systems have more complex impedances, resulting in more complex reflections. In this paper, we present a preliminary method for identifying multiple impedance discontinuities based on adapting a well-known algorithm, known as orthogonal matching pursuit (OMP) [2], to match simulated waveforms with multiple reflections in an SSTDR waveform. Figure 1 shows the SSTDR signal (solid line) and simulated waveform (dashed line), identifying the first impedance mismatch (left) and the second mismatch (right). The dashed line demonstrates the OMP algorithm correctly estimating load impedances corresponding to the reflections in the SSTDR.

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Figure 1: OMP results of experimental reflected data matching with simulated data. First impedance mismatch(left) & second impedance mismatch (right). The solid lines represent experimental data and the dashed lines represent simulation data.

References:
Singular Value Based Damage Statistics for Guided Wave Structural Health Monitoring

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Guided wave structural health monitoring is used to inspect large structures with ultrasonic waves. From guided wave data, we derive statistics for detecting damage. Many current detection methods use single-signal statistics [1] and batch statistics [2]. Single-signal statistics are derived from a single measurement while batch statistics originate from time histories. In [2], singular value decomposition (a batch approach) compared singular vectors with a step function to identify rapid changes in the data (such as damage). While effective, this approach is time consuming and computationally expensive. In this paper, we study two damage statistics derived from singular values that reduce computationally complexity. We refer to them as normalized singular statistics and Anderson statistics [3].

As a preliminary statistical study, Monte Carlo simulations were used to create guided wave data. From this data, we extract probability distributions and the associated detection thresholds that minimize misclassifications. An experiment with guided waves in an aluminum plate was then conducted to detect the addition of three different masses (simulating damage) to the plate’s surface over time. Figure 1 illustrates our statistics, where each line corresponds to one of the first four singular values of the data. In the results, one of the lines rises above a threshold whenever a new mass is applied to the plate. Overall, the Anderson statistic achieves greater accuracy than the normalized singular value based damage statistic.

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Figure 1. Damage statistics corresponding to the first four singular values (solid lines) affected by three masses (dashed lines). (left) Normalized singular values are sensitive to increasing measurements. (right) The Anderson statistic shows little sensitivity to increasing measurements.

References:
A propagating fatigue crack in a structural member may lead to catastrophic failure of the structural system. Furthermore, actively growing fatigue cracks, which have been detected in many of the highway bridges throughout the United States, are of particular concern for fracture critical bridges. Therefore, monitoring detected fatigue cracks is critically important for making repair decisions before a crack reaches its critical length, leading to fracture. An effective fatigue sensor should be reliable long-term, cost effective, flexible (for fitting into fatigue critical locations), and integratable with conventional repair schemes. Most of the commercially available sensors (e.g., crack propagation gages, electrochemical fatigue sensors) cannot be effectively integrated with conventional repair schemes and provide point-type measurements. In this research, a carbon nanotube (CNT)-based sensing skin was developed and evaluated for fatigue crack monitoring. The sensor consists of a nerve-like network, which significantly improves the probability to detect crack growth across a large area and enables tracking the crack over time. The sensor response was evaluated in laboratory testing under crack propagation and near-threshold crack propagation scenarios using various constant amplitude cyclic loadings. It was found that fatigue crack growth can be monitored using the electrical property changes of the sensing skin. Also, the response of the sensor was stable (i.e., did not report false positives) for near-threshold fatigue crack propagation scenarios. Another advantage is that the CNT-based sensing skin is less expensive than a single conventional point sensor. This paper introduces the sensing methodology, presents the laboratory experiments demonstrating the sensor’s accuracy and reliability to monitor fatigue cracks, and discusses future work.

Acknowledgement

This study is part of a research project funded under the Federal Highway Administration’s Exploratory Advanced Research Program, Award No. DTFH61-13-H-00010.
Nonlinear acoustic/ultrasonic techniques have shown great promise for detecting microscopic damage at early stages of development. However, the uncertainties in the interpretation of the results have hindered the widespread adoption of nonlinear ultrasonic techniques for industrial applications. For example, the relationships between the features of micro-damage and the measured ultrasonic nonlinearity are based on empirical data and thus qualitative. Our recent experimental results [1] have shown that microstructural features at the crack interface significantly influence the measured nonlinearity. This study focuses on their quantitative relations. Dynamic acousto-elastic testing (DAET) [2, 3] with surface wave probes is performed on four fatigue-cracked A7075 aluminum alloy samples with similar crack length but dissimilar microstructural features. One of the samples is fatigued stepwise and tested at each stage. The local nonlinear responses from DAET are then analyzed in relation to the microscopic crack features extracted from Scanning Electron Microscopy (SEM) images. Principal component analysis (PCA) and multivariate regression are used to find the dominant features and construct the complex relations between the measured nonlinearity parameters and corresponding micro geometric features. This study introduces a novel approach to correlate the nonlinear ultrasonic signatures and crack interface features directly and presents a step forward towards quantitative nondestructive micro-damage diagnostics based on nonlinear ultrasonic testing.

Figure 1. A comparison between nonlinear ultrasonic responses for two aluminum samples with fatigue cracks of different microstructural features. The response is measured by DAET (The sketch of test setup shown in (a)) and presented in terms of the strain-dependency of wave velocity and attenuation: (b)(d) relative wave velocity variation vs. strain; (c)(e) relative transmission loss vs. strain.

References:
Listening to Temperature: Ultrasonic Non-Destructive Identification of Material Phase and Temperature

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In the chemical transport field, such as petro-chemicals or food processing, there is a need to quantify the temperature and phase of the material within the pipeline using non-invasive techniques. Using ultrasonic signals, which vary in time-of-flight, intensity, and wave characteristics based on the temperature and phase of a material, a technique is being developed which can provide a multidimensional map of the phase and temperature inside a pipeline. This research uses Ecosoya wax, due to its stable nature and ability to be reheated many times without changing the properties of the wax. Additionally, the wax transitions from an amorphous/semi-crystalline solid to a low-viscosity fluid over a range of temperatures. This behavior is similar to that of a thermoplastic and a slurry experiencing curing. As the spatial temperature within a container of wax increases, both uniformly and non-uniformly, the time of flight for an ultrasonic signal will change. Results presented indicate the ability of the investigated technique to mapping the temperature and phase change of the wax based solely on the ultrasonic signals.

Acknowledgement:

The author would like to thank Sandia National Laboratories for its support of this research. This presentation includes work from: SAND2017-8433 C. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA0003525.
Adaptive Cross Approximation for Accelerating BEM in ECNDE

Yang Bao and Jiming Song, Department of Electrical and Computer Engineering, Iowa State University, Ames, Iowa, US

Eddy current nondestructive evaluation (ECNDE) involves the detection of electromagnetic field irregularities due to nonconducting inhomogeneity in an electrically conducting material, which often needs to treat with complicated geometrical features [1]. The eddy current is produced by sinusoidal excitation of a small induction coil near the surface of the component to be inspected, when scanning the coil over the surface, the flaw detection is achieved by searching for coil impedance changes that imply flaw-induced perturbation of the eddy current density [2]. The eddy current problems can be formulated by the boundary integral equations (BIE) and discretized into matrix equations by the method of moments (MoM) or the boundary element method (BEM). Although BEM can model almost arbitrary shaped NDE problems, the memory requirement, the impedance matrix filling time and matrix vector multiplication time for solving the problem using an iterative approach are of O(N^2) complexity, where N is the number of unknowns. The adaptive cross approximation (ACA) algorithm can accelerate BEM by replacing the well separated far-block interaction with a low rank approximation [3]. Kernel independent and purely algebraic are the key features of ACA algorithm which makes it easily to apply to different BEM problems. With the aid of ACA, the complexity can be reduced to \( O(N^{4/3} \log N) \). Our numerical results are validated with experimental and other numerical results [4] for benchmark cases.

Acknowledgement:

This work is supported in part by the Center for Nondestructive Evaluation at Iowa State University IU Program and by the China Scholarship Council.

References:

Beamforming of Ultrasonic Guided Waves for Search of Discontinuities Using Chaotic Optimization

Karla I. Fernandez-Ramirez 1, Arturo Baltazar 1

In recent years, guided wave generation using a sensor array for detection and location of discontinuities in plate or cylindrical media has been intensively studied. One of the areas of research is the use of beamforming algorithms to fusion the information collected with a sensor array (i.e. with a simple delay & sum algorithm (DAS)) to achieve the identification of an energy source or a discontinuity. To improve DAS, researchers have proposed adaptive beamforming algorithms, time-frequency beamforming, and filter design methods, among others. However, all of them require exhaustive search scanning of the entire working area, which can be computational time consuming. In this work, we propose a new two-step search scheme to improve time of detection of a randomly located source, first is a mapping of the working space using a chaotic logistic function to approximate the actual energy distribution; second, the coordinate location of the maximum energy, as previously identified, is used as initial point of a chaotic walk which is a modified version of the classical Pearson random walk ([1], [2]). The algorithm scheme runs until a convergence criterion is reached. Numerical and experimental results are obtained using Lamb wave propagation parameters. The experimental results confirm our numerical calculations indicating that the proposed algorithm reduces the search time considerably when compared with the classical systematic DAS beamforming searching methods.

![Figure 1. a) shows the chaotic mapping generated during the first step of the proposed beamforming scheme; b) is the chaotic walk (sequence of points) to localize the maximum energy related with the source localization (asterisk).](image)

Acknowledgement:

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References:


Influence of Surface Roughness of Additive Manufacturing on Laser Ultrasonic Measurements

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Additive manufacturing (AM) is viewed as a revolutionary technique as it offers numerous appealing capabilities such as complex geometries, functionally graded properties, build-upon-demand, repairs, etc. However, in order to attain the full potential of AM, nondestructive testing for quality assurance of AM parts is essential. Laser ultrasound is of particular interest as a nondestructive technique for AM as it provides a viable means of in-situ process monitoring that could ultimately provide feedback for process control. Rayleigh surface waves generated by a pulsed laser could interrogate the current layer in the AM build and be received by a laser interferometer.

The surface roughness is one challenge that must be overcome if Rayleigh waves are to be used for in-situ monitoring. Surface roughness has detrimental effects on the quality of measurements of laser ultrasonics due to factors such as speckle noise, non-uniform reflectivity of the surface, and wave scattering. In this research, we have studied the effects of surface roughness on generation, ultrasonic wave propagation and reception of laser-generated Rayleigh surface waves. Further investigations on the effects of surface roughness on nonlinear ultrasonic waves are also being carried out.

Acknowledgement:

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References:


Supervised Deep Learning Techniques for Material Classification with Spectral Computed Tomography Datasets

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Sandia National Laboratories has recently built a spectral computed tomography (CT) system with a photon-counting detector calibrated for obtaining sinogram data up to 300 keV across 128 channels per pixel. Prior studies have showcased the ability of this system to distinguish materials with highly similar composition [1]. Furthermore, recent work has demonstrated the utility of simple machine learning algorithms (e.g. support vector machines) in the context of spectral CT data to automatically identify materials [2]. This study expands on these initial efforts and explores a combination of more advanced supervised learning paradigms to accurately classify materials with spectral CT information. More specifically, the performance of convolutional neural networks (CNN) is investigated for distinguishing similar materials such as copper, lead, and aluminum. To the best of our knowledge, CNNs have not been investigated in the past for industrial material classification purposes with spectral CT datasets. Thus, we determine the necessary CNN architecture (e.g. U-net, ResNet, DenseNet) and associated hyperparameters for optimal performance in this context. Preliminary analysis of a baseline CNN with ten convolutional layers suggests the ability to, for example, discriminate different types of ceramics with 100% accuracy based solely on the materials’ spectral signatures. Collectively, this work highlights the combination of high energy spectral CT and supervised deep learning as a promising tool for a variety of non-destructive evaluation tasks.

Acknowledgement:

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References:

Investigation of white etching cracks in roller bearings by scanning acoustic microscopy

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The formation of white etching cracks (WEC) become a serious problem especially in gearbox bearings of wind turbines. WECs can develop to an effect called white structure flaking, reducing the lifetime of components to a fraction of the predicted lifetime [1]. The underlying mechanisms are not yet fully understood. Therefore, methods of Nondestructive Detection of material changes are very welcome. Following the evolution of the defects by periodic NDE inspections of the identical components would open an additional path for studying the WEC phenomenon as compared to destructive inspection of an ensemble of components in different stages of aging.

Material changes leading to WEC starts below the surface. Thus, NDT based on elastodynamic waves is appropriate. Conventionally phased array ultrasonic testing has been applied before [2] using inspection through the whole thickness of the sample. We suggest the inspection directly from the front side with scanning acoustic microscopy (SAM) at higher frequencies. A device for manipulation of the specimen with a frustoconical surfaced was designed (Fig. 1, left), which allows a SAM-scan of a conical shaped surface. The SAM indications (see Fig. 1, right) are compared with other NDT methods and with cross sectioning.

Acknowledgement:

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Figure 1. Device for manipulating the sample with the frustoconical surface in the SAM water bath (left) and 110 x 38 mm² of the scanned surface with flaw indications in black (right).

References:
Simulation and processing tools for the design and performance evaluation of FMC-TFM techniques
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Phased array Imaging techniques such as Full Matrix Capture-Total Focus Method (FMC-TFM) and derived methods are of great interest and are increasingly used as they improve performance in a wide range of situations. In the same way as for conventional PA processes, it is necessary to provide the means to quantify and demonstrate the performance of a control. This involves relying on new criteria, being able to demonstrate their reliability and assessing the sensitivity of the different parameters. In this paper, we present the potential of simulation and post-processing tools to address these issues. Indeed many alternatives are possible, whether in acquisition techniques (FMC, PWI, ATFM), or processing possibilities (artefact filters, combinations of modes, signal processing). This communication is based on the use of the CIVA simulation and analysis platform, whose recent advances make it possible to accurately assess the sensitivity of all the parameters of a control based on the FMC-TFM technology either at the level of the control method (probe, positioning, geometry, material characteristics ...) or the reconstruction and data processing which is possible to personalize it through a new python plug-in solution accessible to all.

References:

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Data-driven temperature compensation on Lamb waves

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Active guided wave based structural health monitoring techniques have been widely studied to inspect the health of large structures. Most of these methods depend on comparing baseline signals collected on the structure before going into service and test signals collected during inspection. Temperature nonlinearly affects the propagation of the wave. As a result, baseline comparison methods fail when the test and baseline signals are collected at different temperatures. Approximate methods that compensate for the effects of temperature on the waves using a signal stretch model have been introduced in the literature. These methods are effective when temperature changes are small and the propagation distance is short. However, they perform poorly when the temperature change is large and the waves propagate over long distances. As a result there is a need for better temperature compensation algorithms.

We present a data-driven approach to compensate for the effects of temperature on sensor signals. The algorithm requires a set of sensor signals collected at different temperatures. One of the signals is considered as a reference signal (RS) and the remaining signals are referred to as training signals. The goal of the algorithm is to learn a mapping function that will transform the RS collected at temperature $T_r$ to the corresponding signal measured at a temperature $T_d$ as follows: 1) The Overlapped mode components in each of the RS and training signals are separated using a mode decomposition algorithm previously developed by the authors of this paper [1]. 2) The parameters of a set of nonlinear models that are functions of temperature and each of the decomposed reference modes (DRM) are learnt using the decomposed training modes. During inspection, the DRM are compensated using the learnt models given $T_d$. We collected sensor signals at 25 different temperatures ranging from $−5 \text{C}°$ to $64 \text{C}°$ on an aluminum plate. The RS was chosen to be the signal collected at $33 \text{C}°$, four other signals collected at temperatures 4, 12, 50 and $57\text{C}°$ were used for training, and the remaining 20 signals were used for testing. The learnt models were then applied to the DRM to map them to the other 20 temperature values of our testing set. Figure 1 shows the correlation coefficient (CC) between the compensated and measured signals in red and the CC between the uncompensated and measured signals in blue. The CC between the compensated signals and the test signals was greater than 0.88 in all cases. The results suggest that the method of this paper is a good alternative to current techniques for temperature compensation of guided waves.

Fig.1 Correlation coefficient between the compensated signals and the measured signals in red. Correlation coefficient between the uncompensated signals and the measured signals in blue.

References:
A recently developed full-waveform inversion approach known as the generalized linear sampling method (GLSM) will be introduced for active ultrasonic imaging of damage precursors in highly heterogeneous composites. The GLSM indicator allows for a non-iterative and concurrent reconstruction of fractures across various scales with an exceptional sub-wavelength resolution and minimal sensitivity to measurement errors. Such attributes pave the way for the next-generation sensing technology capable of real-time geometric reconstruction as well as mechanical characterization of early-stage anomalies in complex background domains. The (theoretical) developments are complemented by a laboratory demonstration of the GLSM performance in capturing an advancing fracture in a composite specimen. This is accomplished by using the non-contact 3D Scanning Laser Doppler Vibrometer (SLDV) that is capable of monitoring triaxial waveforms, with frequencies up to 1MHz, on the surface of specimens (with 0.1mm spatial resolution). In this vein, a two-step experimental procedure is performed as the following: **Step 1.** the geometry of an induced mixed-mode fracture (while propagating) and the spatiotemporal variation of its associated damage zone is computed from the measured near-field data; **Step 2.** GLSM is applied exclusively to the remote wavefield measurements to recover the evolution of fracture geometry and the heterogeneous elasticity of damage zone. The results of **Step 1** are regarded as the ground-truth and compared to those obtained in **Step 2** to illustrate the effectiveness of GLSM as a remote sensing technique.

Figure 1. Sensing configuration and a snapshot in time of the wavefields measured by the 3D SLDV (in the near-field scan grid) before and after fracturing the specimen.
Flash Thermography of Non-Trivial Geometries

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In flash thermography, a specimen is exposed to a heat pulse. The subsequent cooling is monitored with a thermal camera to detect flaws [1]. Thin regions or delaminations in composite materials start to equilibrate faster than thick regions. A variety of confounding factors make interpreting flash thermography data more difficult in complicated geometries. These include registering the thermal images to the physical part, fusing data from multiple angles, non-uniform illumination, different heat flow physics in strongly curved regions, and unintentional excitation of the reverse side of the specimen.

In this presentation we illustrate some of the challenges and lessons learned in attempting to perform flash thermography on specimens with complicated geometry. We discuss the merits and limitations of model-based inversion for analyzing such data. For example, flash lamp illumination is directional. Likewise the thermal camera sensitivity (due to angular dependence of surface emissivity) is also directional. Thus it is often necessary to use multiple excitations to adequately illuminate a curved surface. How to fuse the data from the different excitations to yield a meaningful result? Weighted averaging is simple but leads to horizon and shadow lines in the data that do not represent real defects. Careful blending of the weights can help mitigate such effects but does not appear to eliminate them entirely. Unfortunately blending and averaging can cause defects to be missed if there are errors in registration. We also address the differences in heat flow in highly curved regions but discover that illumination and emissivity artifacts are often more significant.

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References:
The condition of rockbolts and other anchor types is very important since they are critical for the safety of underground excavation or structure safety. However, since they are embedded, their investigation is likely challenging. Numerous infrastructure managers are calling for effective and robust tools and methods that are capable of locating flaws in the embedded anchors, as well as evaluating the anchors condition regarding corrosion.

An experimental study was designed to assess the effectiveness of pulse echo method to detect the state of corrosion in rock bolts. The method was tested on rock bolts embedded in concrete blocks and submitted to accelerated corrosion using the impressed current corrosion method. In addition, an acoustic emission system was used to monitor the corrosion process. Half-cell potential measurements were also performed at the beginning and in the end of the corrosion process.

A quantitative assessment of the energy of the echo from the walls and the end of rock bolts shows a decrease of the energy in the rock bolts when they suffer from corrosion. While the energy of the echoes stays unchanged in the absence of corrosion. Pulse-echo test results showed that a decrease of the energy of the back echo and the trailing wall echo was indicative of the corrosion state. This method enabled locating the flaws associated with the corrosion of rock bolts by the calculation of the normalized energy ratio between the echoes coming from the threads of sound and corroded rock bolts. The method was also tested in situ, on real rockbolt, showing promising results.
Automated Processing for Structural Analysis of Layered Composite Structures with Defects

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Structural analysis of fiber-reinforced composite structures using finite element analysis (FEA) are usually performed using shells due to the complexity in modeling the layers of the composite with 3D elements. However, accurately modeling the residual strength of composites require incorporating concrete definition of defects into layered 3D models, which is not directly feasible with shells. In this work, we have developed an automated framework that can first be used to isolate a region of interest from a shell computer-aided design (CAD) model of a composite structure, model the individual layers in the region, incorporate defects such as delaminations and fiber breakage, and set up the model for structural analysis using FEA. The multiple composite layers in the region of interest are generated using configurable parameters. Data from UT scans is segmented to identify the shape of the delaminated region and is incorporated into the CAD model by splitting the corresponding surfaces of the layer into separate faces. Appropriate contact and cohesive boundary conditions are automatically applied to the delaminated and intact faces respectively of the layered CAD model. Finally, the layered CAD model with defects is coupled to the larger shell model by automatically setting up shell-solid coupling boundary conditions. Using this framework, we can automatically set up structural analysis of a composite structure with defects and assess the impact of manufacturing defects or service damage on its residual life.

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Figure 1: Workflow for automatic incorporation of defects into layered composite models and perform structural analysis. Our framework allows incorporation of defects such as delaminations and fiber-breakage into a layered composite model, apply appropriate boundary conditions, and perform structural finite element analysis.
Multi-mode guided wave scale and corrosion monitoring

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Scaling and corrosion affect the integrity and flow assurance of gas wells. Therefore real-time information about scale build-up or corrosion helps mitigating risks and increases the understanding about the underlying mechanisms. Two frequently occurring scale types are calcium carbonate and iron sulphate bases scales, the latter one existing in many different forms. Some of them are easy to remove from the inside of the tubing, while others are extremely difficult. A guided wave based permanent monitoring system is being developed to be installed in gas wells. The system will be mounted on the outside of the tubing through which the hydrocarbons are produced. The guided waves monitoring system will deploy both torsional and longitudinal fundamental and higher order wave modes. A wide frequency range is used to extract information about the material properties of the scale, its thickness and the tubing wall thickness. Numerical modelling and laboratory experiments demonstrate are used to evaluate the proposed monitoring concept. The data is analyzed using a time frequency analysis, making it possible to handle the extremely complicated wave forms. A quantitative scale and wall loss measurement concept has been developed providing good accuracy. Scale and corrosion sizing is performed using the first arrival times as function of frequency. The figure below shows the time-frequency analysis of modelled signals through a 7 mm thick pipe wall with a 3 mm thick scale layer for both torsional waves and longitudinal waves. The first arrival is picked and inverted to estimate both wall thickness and scale thickness. The used objective function is shown in Figure 1c consisting of the arrival times of both wave types. The combination of both torsional and longitudinal waves provides good resolution for determining both wall thickness and scale thickness.

Figure 1. Illustration of scale and wall thickness measurement using the first arrival time of both torsional and longitudinal waves.
Composite materials such as carbon-fibre reinforced polymers are seeing increased usage in many critical applications, such as the aerospace, energy production and marine sectors. As such it is vital to be able to identify, classify and size defects at the production stage, and throughout the lifetime of the component. Often it is necessary to create a component which is non-planar; for example, a blade root, a pipe, or a corner section. This curvature, combines with material anisotropy, means the ray paths are curved. Problems arise when locating and sizing images due to the significant deviation from a straight-line path.

It is useful to simulate full matrix capture data to investigate such effects on the sizing and locating of different defects. This is often a time-consuming process. We have used Pogo [1] to quickly simulate 64 and 128 element arrays conforming to a curved surface. We have then reconstructed the signals using Dijkstra’s algorithm for ray tracing, as well as straight line approximations. The results show improved sizing of defects, as well as greater control of angle limitation to reduce structural noise.

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References:

Progress on building a Laboratory Based X-ray Phase Contrast Imaging Computed Tomography System

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Sandia National Laboratories is developing a laboratory based x-ray phase contrast imaging (XPCI) computed tomography (CT) system. This system utilizes Talbot-Lau interferometer based on in-house fabricated gratings and a conventional x-ray system. Initial work has focused adding CT capabilities to a 28 keV XPCI system. A new set of gratings tuned for an x-ray energy of 100 keV is being developed. This new grating set will facilitate imaging larger components. System configuration details will be presented as well as a discussion of the challenges associated with building an XPCI CT system. Additionally, initial imaging results will be presented.

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On ultrasonic imaging through a double steel string with the leaky flexural mode

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Imaging through a set of double nested cylindrical strings made of steel is a need that arises in cement evaluation of cased oil and wells where the objective is to assess whether the annular space behind the outer string (annulus B) is filled with cement placed there to establish zonal isolation. The present study investigates the potential of an existing rotating ultrasonic measurement tool that implements imaging with a pitch-catch modality relying on the excitation and detection of a casing (quasi-Lamb) flexural mode by acoustic transducers located within the liquid filling the inner string [1]. As it propagates axially in the inner casing, the flexural mode leaks acoustic energy into the first annular space (annulus A) between inner and outer strings – in the conditions considered, this tends to be filled with liquid. In the absence of a second string, the leaked energy reflects specularly at the borehole wall and propagates back to the receiving transducers through a second leaky (refracted) path in the inner string giving rise to the so-called third-interface echo (or TIE). This study is concerned with the question of whether in the presence of the second string the impinging energy couples to a leaky mode on the second string to provide a non-specularly reflected signal (leaky TIE) that can be harvested for determining the content of annulus B. We conducted numerical and experimental studies to understand the operative wavephysics and answer this question. We find that the coupling to a leaky mode in the second string requires fairly precise phase matching of the flexural modes in the inner and outer strings which implies that they should be of the same material properties and more importantly of the same or nearly the same thickness. When this is not the case, the reflection is dominantly specular and is affected mostly by geometry - rugosity of the outer string inner wall and its eccentricity with respect to the inner string. When we do have phase matching, the amplitude of the leaky TIE as a function of transmitter-receiver spacing carries information about annulus B. However, as outer and inner strings in real wells typically differ markedly-enough in thickness, the opportunity for an inversion becomes rather very limited. We will share the characteristics of the problem and present numerical and experimental evidence of the wave physics. Further, we provide a spectral analytical development of the reflectivity problem that provides an intuitive basis for understanding the numerical and experimental results. It shows the leaky TIE can be treated as a contribution arising from a third-order pole singularity of the reflectivity function. While that for a specular TIE, the singularity degenerates into a product of a second-order and a single-order separate pole.

References:


Sequential Monte Carlo Based Parameter Estimation for Structural Health Monitoring

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Structural health monitoring (SHM) entails continuous sensing of a system with the goal of detecting whether damage has occurred. The traditional structural health monitoring (SHM) problem is fundamentally one that can be described as statistical pattern recognition (SPR), where the goal is to characterize structural damage by statistically correlating features extracted from sensor response data with data features of known damage. However, this typically requires some a priori knowledge of how the structure will behave when it is damaged (e.g. through a baseline state response). Model-based methods, however, do not require knowledge of the baseline structural response, but instead rely on a high-fidelity, physics-based model of the structural health monitoring system that is parameterized with features describing the damage to be characterized. The Markov chain Monte Carlo (MCMC) inverse solution entails recovering the damage parameter posterior probability distributions by repeatedly evaluating the forward model. However, utilizing physics-based models within the MCMC method typically results in two main challenges: 1) if the structural system under investigation changes over time, then the damage posterior probability function of interest changes, rendering MCMC ineffective, as it requires a fixed probability function; and 2) MCMC cannot be easily parallelized because the next sample in the Markov chain depends on the sample before it, resulting in prohibitively long solution times or the use of less accurate surrogate models. The Sequential Monte Carlo (SMC) method addresses both of these issues by considering particles with associated weights that are proportional to the damage parameter posterior probability. The SMC method entails sampling from a sequence of probability functions, allowing for updates in the structural system without the need to restart the inverse solution, enabling continuous monitoring. Additionally, as the particles are independent from one another, the SMC method is embarrassingly parallelizable and can exploit high performance computing capabilities, as is presented here. The SMC inverse solution is demonstrated on a six parameter crack characterization problem through a guided wave ultrasonic inspection consisting of an array of sensors. The ultrasonic inspection computational model is an efficient elastodynamic finite integration technique (EFIT) developed at NASA Langley Research Center.

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An astounding and significant fact about additive manufacturing (AM) is that it possesses two distinct, intrinsic characteristics: 1) design freedom and 2) opportunity for in-process monitoring. The former has not only revolutionized the manufacturing of complex shape physical parts using digital prints, but also enables unique design improvements in shape, hierarchy, material and functions that are not possible with other manufacturing methods. The latter provides options for performing in-process monitoring at the micro- (layer-by-layer in a plane and point-by-point in a line) and macro-levels. Unlike traditional subtractive manufacturing, these can be achieved without any tooling, thus reducing lead cycle-time, weight, manufacturing footprint reduction, and costs. The tradeoff for these enhanced capabilities is uncertainty in product integrity, which has hindered the adoption of AM technologies in the aerospace industry. To mitigate this, the aerospace industry has placed an added emphasis on developing Verified and Validated (V&V) standards for: 1) calibration and optimization of monitoring devices and 2) benchmark for measuring mission-critical properties. In addition, reference standards are needed for validated physics- and properties-based predictive models for AM to predict dimensional/geometry accuracy, material properties, defects, surface characteristics, residual stress, and microstructure. Qualification and Certification (Q&C) practices are mature and work well for conventionally manufactured parts, but AM parts require new advanced approaches for both in-process and post-process Q&C, due to complex-shaped AM parts that have function-critical surfaces and regions that are inaccessible to current NDE technologies. AM practitioners have used process optimization for desired microstructure and properties using finite element modeling and empirical modeling that incorporates destructive and nondestructive testing data, but with limited success. As the AM industry moves towards industrial production, the need for qualification standards covering all aspects of the technology becomes ever more prevalent. While some standards and specifications for documenting the various aspects of AM processes and materials exist and continue to evolve, many of these standards still are not mature or are under consideration/development within standards development organizations and have not been deployed. In this study, authors will provide a roadmap for identifying and highlighting technical gaps, while laying out a strategy that focuses on studying mission-critical properties. We will also discuss the status of different standards being pursued and developed by different organizations, such as ASTM, ANSI, and NIST in the Aerospace industry. In the interest of space, authors will focus only in the areas of AM process sensing and equipment monitoring, Qualification & Certification (Q&C), and will not include any materials on design, process control, diagnostics and prognostics, or modeling and simulation.
Improving the Accuracy of Spatial Registration of NDE Data with Deep Learning

Rafael Radkowski, Stephen Holland, Iowa State University

Geometric registration of NDE data to a 3D model allows the integration of the NDE data into a digital thread / digital twin representation of a product. The digital twin/digital thread tracks the product's characteristics throughout its lifecycle. In the traditional practice of NDE, registering measured data to such a model is sufficiently complicated and time-consuming that it rarely happens. Through the use of 3D object tracking, one can automatically register the NDE data onto a model of the product with comparably little effort. Last year we presented an approach and a system prototype focusing on flash thermography (Figure 1a-b) that utilizes inspection location tracking. The tracking system provides the position and orientation (pose) of the part of interest to the NDE system, allowing the NDE system to automatically map the respective thermography data onto a 3D model as part of the digital twin.

Our initial prototype system unveiled several challenges that, if unaddressed, affect the accuracy negatively. An essential obstacle to high accuracy is error accumulation. Each pose measurement and calibration process introduces errors due to the intrinsic system tolerances. Individually, each tolerance value is small, accumulated all become significant. A more precise calibration of all components can mitigate the problem, nevertheless, does not yield the required accuracy.

We addressed this problem with deep learning, using a Deep Forest (DF) in particular to train a correction matrix. Simplified, a DF is a decision tree with trained hyper-parameters. Technically, it is a cascade of matrices that can be trained to yield a particular output matrix for specific input values. In this case, the input value is the geometric relation between the flash hood and the specimen, the output a correction matrix. For training, we utilize a checkerboard pattern attached to the product of interest (Figure 1c). This pattern provides ground truth data, and a user needs to record it from multiple directions to collect training data. Once the training procedure terminates, the system can work without it. An inspector can move specimen and flash hood to different positions, and the DF will automatically correct the expected error. The result is accurately mapped thermography data.

The paper/presentation will introduce the system and highlight the challenge. We will describe the DF approach and present experimental data showing the gained mapping accuracy.
Experimental investigation of acoustic features associated with cement damage in double cased-wellbores

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Ensuring the integrity of oil and gas cased-wellbores is of crucial importance to operators around the world to maintain safe production and environmental compliance. While sonic and ultrasonic measurements have been developed for evaluating the well integrity of single casing strings, there is currently a gap in characterizing the cement and annular fill behind two or more casing strings due to the lack of sensitivity of the ultrasonic and the complexity of the sonic response. This abstract describes an experimental study to characterize the sonic response and help fill this gap in conjunction with a theoretical modeling effort that is reported elsewhere.

Scaled laboratory experiments are conducted to acquire reference data used to verify the modeling approach developed to predict the guided modal characteristics of axially-propagating waves in concentric and non-concentric cylindrical structures immersed in fluid. These structures simulate the geometries and environment encountered downhole when conducting acoustical measurements to evaluate the cementation of oil and gas cased wells. Typically, cement is expected to fill the annular space between the two nested steel casing strings and between the outer string and rock formation. Nevertheless, cement damage such as fluid channels, partial cement coverage, and weak bonding interfaces inevitably occur due to the harsh downhole environment and downhole operations. Measurements are made in a dual-string steel pipe of quarter scale in an immersion tank or in a sandstone formation with concentric as well as a variety of eccentric configurations. A set of samples are prepared with the cement in annulus B (the space beyond the outer casing) with purposefully introduced fluid channels in a controlled manner. A comparison of the experimental and numerical results indicates features in the sonic response that are indicative of channels in annulus B as distinguished from eccentricity effects. These results suggest a new well integrity evaluation work-flow to characterize cement quality and coverage in annulus B taking advantage of the rich acoustic features in the sonic response.

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References:

The Development of Spinal Surgery Training Model

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Training for spinal surgery for young surgeons is a difficult and expensive task; most spinal models are expensive and focus only on one issue. Preparing surgeon students requires a long training process before a surgeon is allowed to deal with real patients. This model is designed to assist training surgeons by providing live feedback information during a simulated surgery.

Nondestructive evaluation tools are essential to investigate the effects on the spinal cord model during the surgery training. The aim of the model is to asset and investigate the amount and type of pressure exerted on the spine during surgery. This is done by placing an array of sensors inside the model, and by analyzing the data from those sensors, we can identify the amount and type of pressure exerted on the spine during the operation. Then by consulting a physiciation we can drive the values for how much pressure is safe for the spine to withstand.

This research is conducted using simulation tools as well as experimental setup. Simulation was conducted using COMSOL Multiphysics and Solid works, the aim of the simulation was to compare the accuracy and practicality for different types of sensors.

In the Experimental setup Force Sensitive Resistor sensor was used, which is found to be promising, easy to fabricate, and easy to adjust to fit in the design. Optical Sensors are also investigated, based on published sensor performance; and we compare the two types.

Depending on the developed spinal cord surgery model, we can reduce the cost and time of training of surgeon trainees and thus enhance the efficiency of medical treatment system for patients who have spinal cord injury.
Challenges and Solutions for Ultrasonic Phased-Array Inspection of Polymer-Matrix Composites at Production Rates

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More than ten years of Research and Development focused on phased-array inspection of Aerospace Polymer Matrix Composites (PMCs) is presented. This work includes basic research designed to understand the propagation of ultrasound through composite materials, as well as optimization of phased-array probes and inspection strategies for composite parts [1]. Successful implementations of these strategies for fully automated on-line inspections are presented including a discussion of how challenges were overcome and the promise of new acquisition and analysis tools. Composite materials present unique challenges for ultrasonic inspection including complex shapes and a wide range of potential flaws and defects. For automated inspections, part-to-part variability and the need to inspect at production rates pose additional challenges. The methodologies presented are based upon laboratory experiments performed in conjunction with modeling/simulations, which are used to optimize inspection strategies. To analyze detection capability and sizing resolution, calibration samples are designed and fabricated. A significant challenge that should not be underestimated is creating these samples with realistic defects of known size and location that can be independently verified. In projects with industry and the Air Force Research Laboratory (AFRL), work has focused specifically on using surface-adaptive techniques to inspect parts with complex shapes including small convex and concave radii that are typically found on stringers, blades and wing structures. Experimental and simulation results have been evaluated for flat and curved linear arrays as well as matrix arrays, which are used with and without surface-adaptive techniques for purposes of comparison. Fully automated on-line inspections that have been operating for several years [2] as well as recent large-scale implementations demonstrate the ability to inspect a wide range of different composite parts at production rates. Rapidly increasing computer processing power together with ultra-high data-transfer rates will continue to enable computationally intensive signal and image processing in near real time. These advancements hold promise for greater use of automated inspection and the ability to incorporate sophisticated data acquisition and analysis tools into portable systems that can then be used in the field, for example, in depots and onboard ships.

Acknowledgement:

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Titanium alloys like Ti-64 and Ti-6242 are used for critical aerospace components such as gas turbine engine disks. Titanium alloys in disks are designed to be isotropic, but processing variation may produce Microtexture Regions (MTR’s), which are localized collections of grains with similar crystallographic orientation. Disks with MTR’s have exhibited significantly reduced dwell fatigue lifetimes [1 - 3] and susceptibility to in-service failures [3]. Legacy Nondestructive Evaluation (NDE) methods are time consuming and can miss MTR’s. Process Compensated Resonance Testing (PCRT) is a fast and accurate full-body NDE method that has been proposed for the detection of MTR’s in titanium turbine disks. PCRT excites a part’s resonance frequencies and correlates the resonance spectrum to the part’s material and/or damage state. Disks with MTR’s will have different resonance spectra than fully isotropic disks. Both the MTR’s geometric parameters (i.e. size, location, and orientation) and microstructural parameters (i.e. texture strength and orientation) will influence the magnitude of changes in the resonance spectrum. Using a Monte-Carlo approach, this work developed Finite Element Method (FEM) model populations of disks with and without MTR’s. These populations were analyzed to predict the effects of MTR parameter variation on resonance spectra and evaluate PCRT sensitivity to MTR’s in the presence of normal geometric and material property variation. The feasibility of detecting MTRs in titanium disks using PCRT is presented and discussed.

This research was supported by the U.S. Air Force Research laboratory (AFRL) through a Materials and Manufacturing Directorate (AFRL/RX) Structural Materials Broad Agency Announcement (BAA) Contract FA8650-15-C-5208 and an AFRL Small Business Innovation Research (SBIR) Phase II Contract, FA8650-15-C-5074. This abstract has been cleared for public release under case number 88ABW-2018-1985.

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Horizontally polarized shear (SH) ultrasonic guided wave modes are considered to infer adhesion changes at different interfaces. Earlier studies reported the sensitivity of SH0 to interfacial adhesion [1], [2]. In this study, the physics of SH0 interaction with different lap joints are investigated. Experiments were performed on aluminium-epoxy-aluminium samples. Aluminium surfaces were prepared in a specific way to vary the adhesion. SH modes are generated and received using periodic permanent magnet (PPM) electromagnetic acoustic transducers (EMATs), the periodicity of which is equal to the wavelength of the transducer. SH0 is generated in the plate that comprises the lap joint at different frequencies (and wavelength). Different modes of reception i.e. in transmission, in reflection, etc. were explored. Distinct signatures were observed for different samples. To investigate the physics of interaction with tri-layer and to corroborate the experiment results, 3-D finite element (FE) models were developed. The model uses a multi-physics approach to simulate EMAT generation of SH waves. Lorentz force is calculated in the electrodynamic module and then coupled to the elastodynamic module to generate ultrasonic waves. Different cases of interfacial adhesion were simulated by changing the boundary condition at both aluminium-epoxy-aluminium interfaces. This work shows the potential of SH modes for quantifying properties at adhesive interfaces.

References:


A Machine Learning Approach for Classification Tasks of ECT Signals in Steam Generator Tubes nearby Support Plate

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Within the Nondestructive Testing (NdT) community, automated data analysis systems for classification purposes has become a very attractive research domain [1]. Nevertheless, the readability of the entire process is a very critical issue still deserving further study. In this paper, we present a preliminary study towards automatic classification of Eddy Current Testing (ECT) signals in the framework of Machine Learning (ML) techniques. More precisely, our objective consists in developing a supervised ML strategy targeting classification tasks for ECT signals, which are collected during Steam Generator Tube (SGT) testing near support plates.

Four distinct cases, which are matter of interest within the NdT community, have been selected for this study. In particular, a SGT with and without 2D groove encircled by a support plate and a SGT with and without 2D groove encircled with a support plate with magnetite powder deposit are considered. In order to generate the set of data required to fed to the machine learning algorithm [2], a parametric database (i.e., the training set) is built exploiting CIVA software [3] upon a set of typical inspection parameters (i.e., different groove geometry parameters, deposit shapes, etc.). Subsequently, the ML algorithm is fitted on the training set. In the ML literature, a plethora of algorithms has been developed in the last decades. In this work, we will focus on the most common ones (e.g., Support Vector Machine (SVR), Gaussian Process (GP), Random Forest (RF), etc.) and we will compare their performance with respect to more basic approaches like Naïve Bayes for instance. The results obtained will be discussed from the perspective of classification performance and robustness with respect to Additive White Gaussian Noise (AWGN) corruption.

References:
Design of the detection probe based on ACFM

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The technology of alternating current field measurement (ACFM), which is the core principle of this paper, is originally developed for detecting and sizing the cracks, especially in the surface of objectives [1]. Based on the current technical characteristics of alternating current field measurement (ACFM), a practical inspection device presented in this paper is designed for a higher-resolution. As the executive component of the device, the ACFM probe adopted the pair of excitation coils arranged in parallel. Compared with other existing forms of excitation coils, a larger uniform magnetic field was generated at the front end of the probe, which provided a more ideal detection effect. Meanwhile, the mathematical modeling and software simulation was carried out to provide the theoretical support and perform finite element analysis for the structure design. Considering the skin effect, a 3D computer model that represented the distribution of the magnetic field around the defect in the inner-surface of the pipe was established and analyzed by combining the crack model in semi-elliptical which was very close to real pipe defects, and the excitation coil model through multi-physics simulation software. On this basis, a parametric sweep model was developed, which represented the movement of the excitation coils and magnetic sensors along the direction of the length of the defect. This sweep model was used to simulate the detection/scanning process of the probes in pipelines, thus the numerical solution to the distribution of the magnetic field along the length of the flaws was obtained. According to the simulation model, some standard defect samples and detection probes were made. And experiments in consistent conditions with the computer simulations were conducted in a real pipeline with a diameter of 610mm. By comparing the actual operation results with the simulation, it was verified that the design in this paper had the ability to detect defects in the pipeline and had a high detection accuracy.

Acknowledgement:

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![Figure 1. Detection result in real pipe (axial)](image)

References:

Effect of Wire Length in Meander-line-coils on Crack Detection using Surface Wave EMATs

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Surface wave EMATs, consisting of magnet and meander-line-coil, is a non-contact detection means[1] and widely used for crack detection[2]. However, the wire length in meander-line-coils can affect the measurements of reflection and transmission coefficients at cracks. This paper investigates the influence of wire length on the excitation and reception performance of surface wave EMATs and the quantitative characterization of crack depth using surface waves. The frequency characteristic and acoustic beam directivity of meander-line-coils with different wire length were measured experimentally. The results show that the frequency characteristic is independent of wire length, while the directivity of acoustic beam and the spatial resolution is closely related to it. With the increasing of wire length, the radiation half angle of surface waves beam decreases. When the EMAT is used as a receiver, the space resolution of EMAT reduces with the increasing of wire length. Then, grooves in aluminium specimen were detected and the measured reflection and transmission coefficients of Rayleigh waves were contrasted to reference curves obtained by FEM simulations, as shown in Figure 1. It shows that the reflection and transmission coefficients can be measured accurately only when the wire length of meander-line-coil in receiving EMAT is smaller than the groove length.

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Figure 1. Comparison between the reference curve and the measured reflection and transmission coefficients.

References:

Finite Element Simulation of Vibrothermography of Cracked and Notched Plates

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Ultrasonic vibrothermography is a non-destructive technique commonly used for detection of cracks and delamination in solids. The dynamic loading causes the defected areas to act as heat sources that results in a small local increase in temperature close to the defected area. The resulting temperature increase is identified by a thermography system.

We developed a finite element model of vibro-thermography of cracked and epoxy filled EDM notched plates to predict their temperature rise. Two horns excite the plate simultaneously at frequencies of 20 kHz and 30 KHz. We investigated the effect of defect size and loading conditions on temperature rise for a Titanium plate clamped at one or both ends. Our model captures the temperature rise of the cracks and epoxy filled notches due to the ultrasonic elastic waves. It also predicts zones where defected areas are insufficiently excited by the ultrasonic waves and therefore do not generate significant heat.
Classification of Haploid Corn Kernels Using Terahertz Time Domain Spectroscopy and Machine Learning

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Terahertz technology has been rapidly expanding both in its uses and in attention given it. Mathanker [1] reports THz has been developed for numerous applications including quality control in the food and agriculture industries. A possible application is in corn breeding using the doubled haploid method, involving inducing haploid kernels in corn plants. These haploid kernels must be separated from the surrounding diploid kernels, and presently this is done by extensive manual labor using visual markers [2]. This work represents a proof of concept that haploid classification can be automated using terahertz time domain spectroscopy (THz-TDS) paired with a machine learning algorithm like a probabilistic neural network (PNN). In this work, a THz imaging system was used to collect time domain waveforms from a number of mixed corn kernel samples. Variables such as emitter focus and kernel geometry were controlled by taking multiple scans. A watershed image segmentation technique was used to reduce the data and organize it by kernel. The waveform data were then transformed to frequency domain and further classified by PNN with a training set random subsampling technique. Leave-one-out and k-folds cross-validation procedures were used to train the model. The preliminary results show promise, yielding 85 percent and 91 percent correct classification of haploid and diploid kernels, respectively.

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Figure 1. Statistics from the k-folds cross validation procedure. Each instance represents one cycle of training on four-fifths of the kernels and testing on the remaining fifth.

References:

The use of Air Coupled Ultrasonics, particularly for industry applications, is fast becoming a reality largely due to the advent of highly efficient and even wide-band transducers, the selection of wave modes that have lower acoustic impedances, the improved understanding of the physics of guided wave interaction with features of the structure as well as defects, and finally the emergence of advanced signal processing methods. The coupling through air allows for a wider use of the ultrasonic NDT technologies when compared with the conventional couplant based methods. The increased speed of inspection, the portability of the systems (since couplants are not required), the sensitivity to defects, inspection of hidden regions, etc. are some of the key advantages of the air coupled ultrasonic techniques. The dis-advantages of the technique include the limitation of the frequency of operation and the requirement of high voltage for excitation. In this paper, the application of Longitudinal, Shear, and Lamb wave modes that are excited and received by air coupled ultrasound transducers will be discussed. The technique is applied to aerospace components, composite pipes, and adhesive bonded components, among others. The defects considered include weld inspection, delamination characterization in composite structures, interfacial weakness in bonded components, etc. that are made with metals and or composites. Some of the recent work on turning modes based defect sizing, meta-materials based imaging, and wave-field visualization will also be presented.
Pore scattering is known to be a major cause of energy loss and dissipation in electromagnetic wave propagation and has been studied previously in transmission mode [1, 2]. In this work, we investigate terahertz (THz) beam attenuation due to scattering from porosity that is embedded in a layered ceramic media in reflection mode. Laser profilometry and optical microscopy were employed to map out the distribution of porosity visible at the surface of multiple cross sections of a ceramic coated sample at different depths. Each cross section was also raster scanned by a THz imaging system to generate a corresponding C-Scan image. Using the pore distribution maps, we then developed an ad-hoc measurement model to estimate the reflection strength of the THz wave after it has impacted the cross-sectional surface. Separately, a material inversion algorithm was formulated to determine the dielectric constant map across the same cross-sectional surfaces. Good correlations were found between the three mappings, i.e. the measured and model THz C-Scan images and the dielectric constant map. These results clearly provide direct experimental verification of the effect of scattering from porosity on THz beam propagation in such ceramic media. We also study the changes of these three maps as they vary with depth and lateral dimensions.

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References:
In-situ monitoring for metal additive manufacturing using process acoustic signatures

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Additive manufacturing (AM) is the process of part production based on layer-by-layer addition of material to build a three-dimensional component. AM has many demonstrated advantages over conventional manufacturing processes such as decreasing the cost and waste of the manufacturing process. AM process provides unique opportunities to investigate the quality of a material as it is deposited [1]. Development of in-situ monitoring methodologies is a vital part of the assessment of process performance and parts quality. Detecting quality issues during the build can reduce or eliminate the time and cost of ex-situ inspection and repair of the parts. Acoustic signatures are used for in-situ monitoring of the metal Direct Energy Deposition (DED) additive manufacturing process operating under a range of process conditions. Correlations were demonstrated between acoustic signal features and various process conditions [2], [3]. A development of statistical classification algorithm is used for classification of different process conditions, and quantitative evaluation of the classification performance in terms of cohesion and isolation of the features. The identified acoustic signatures, quantitative clustering approach, and the achieved classification efficiency demonstrate potential for use in in-situ acoustic monitoring and quality control of the additive manufacturing process.

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Figure 1. Clustering results for data from one sensor using peak amplitude (PA) and centroid amplitude (CA) of spectral data obtained using the Fourier Transform in low frequency band.

References:


Additive manufacturing (AM) is the process of joining materials in a layer-by-layer fashion, as opposed to more traditional, subtractive manufacturing methods. The method enables the inclusion of features not possible with classical methods such as complex internal and external features, and gradations of material composition for some processes. While these geometries and composition variations are an enabling capability for design freedom and customization, uncertainty remains in the resulting material properties and defect distributions for AM parts as well as identifying appropriate means and methodologies to inspect them [1], [2]. AM is well suited for low production volume, complex, high value components and thus, real-time, in-situ characterization on a part-by-part basis of these materials has become of interest to academia and industry. Acoustic methods have been utilized for monitoring cutting, milling, welding, and laser processing of metals and polymers in the past. In this work, an acoustic monitoring array was utilized to monitor directed energy deposition of Ti-6AL-4V onto a steel substrate. Temporal waveforms were recorded intermittently and passively, and later analyzed using temporal and spectral methods. Metallographic analysis and comparison of crack densities with acoustic metrics are shown to correlate well as a material damage indicator. Low amplitude process noise is also shown to correlate with the process state, of which 3 variations around nominal deposition parameters were tested.

Acknowledgment:

Aspects of this paper were developed as part of a Core Project review and planning activity performed by the Center for NDE (CNDE), Iowa State University, while a Phase III NSF Industry University Cooperate Research Center (IUCRC). CNDE became a graduated Center on January 1st 2016.

References:


Ultrafast Phased Array Imaging: an Application to Closed Crack Characterization

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Ultrafast imaging in ultrasound refers to imaging with a frame rate higher than thousands of frames per second (fps). The high frame rate is typically achieved by transmitting plane waves or some other forms of unfocused beams into the region of interest, eliminating or minimizing the needs for beam scans. Recent biomedical ultrasound research has been largely progressed by ultrafast imaging [1,2]. In this paper, we present ultrafast imaging in NDT to observe the nonlinear dynamics of the closed cracks.

The combination of a pump wave at low frequencies and a probe wave at high frequencies has been widely studied to examine the elastic nonlinearity, e.g. in closed cracks, for simultaneous high vibration amplitude and good probing spatial resolution. Constrained by the frame rate of typical phase array imaging, dynamics of closed cracks was previously studied only in very low frequencies using the servohydraulic tensile stress pump [3] and the thermal stress pump [4], with limited insights gained from the subject. In this study, the sample is pumped at its resonant frequency ~7 kHz with a PZT disk, and at the same time, the closed crack responses are imaged using the ultrafast imaging technique with an effective frame rate > 50kfps (interleave multiple frames acquired at thousands fps). The slow motion replay resolves the closed crack dynamics with good sensitivity, contrast and temporal resolution. The pixel intensities in the region change as the crack opens and closes. The intensity curve suggests the most energy resides in the fundamental resonant frequency with small spreading over to the higher order harmonics. The method could be useful applied to detect closed or micro- cracks and fundamental to study nonlinear dynamics in solids.

References:
Stress estimation in weak anisotropic material by using acoustoelastic effect of Rayleigh waves

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Acoustoelasticity is a property of ultrasound velocity changes according to stress. By using this property, residual stress or applied stress can be estimated. Until now, however, bulk waves such as longitudinal waves have been used mostly. In contrast, Rayleigh waves have advantages on measurement accessibility than bulk waves, because there is no need to know the precise thickness in advance and it is possible to set the propagation distance easily and accurately. Therefore, studies on the acoustoelasticity of Rayleigh waves have been also actively performed [1,2]. However, most of the research was limited to isotropic materials. The acoustoelasticity in anisotropic material has also been carried out, but they are very complicated and difficult to use in practice.

This study proposes a stress estimation method for material with weak anisotropy, which modified the simple equation [2] for isotropic case. In this method, the ratios of the Rayleigh wave velocity when the stress acts to the Rayleigh wave velocity when the stress does not act at three directions are used. For the experimental verification, the proposed method was applied on two specimens; one is isotropic and the other is weak anisotropic. Rayleigh wave velocities at three directions were measured while applying tensile stress. Note that the proposed method is applicable even if the direction of principal stress is different from the direction of velocity measurement. Results showed that the stress was estimated with error less than 6% even for anisotropic material. Principal stress axis was also in good agreement with the given axis with error less than 4°.

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An Approach to Current Leaking Cracks in Eddy Current NDE Modeling

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It has been known, through the industry experience and in-laboratory studies, that tight cracks respond to eddy current NDE measurements with significant signal variations under different stress conditions. In particular, laboratory experiments observed the signal variations quantitatively, by exposing cracks to tensile and compressive loads across the crack face. However, no eddy current NDE models have been prepared to describe such variations of the crack signals under stress, because there is a fundamental obstacle: A leaky crack is by nature a tight crack. It has been the practice to formulate a mathematically idealized crack of an infinitesimal width under the quasi-static approximation, i.e. by turning off the displacement current. As soon as one permits current leakage with a small but finite conductivity, the traditional approach becomes inapplicable and the crack becomes essentially transparent under the zero-width limit. In short, the two limits are not interchangeable. This paper presents a way to address this basic problem, by proposing a specific limiting procedure to overcome the difficulty in formulating a leaky crack modeling. The scope of the paper is to formulate the above-described problem, and to outline the solution process mathematically, where we introduce a notion of “conductance per unit area” through the tight crack face to define an adequate limiting procedure.

This work was supported by the Pratt & Whitney Center of Excellence Program conducted at Iowa State University.

Keywords
Eddy current modeling; Leaky cracks
Historians and librarians are interested in watermarks and mould surface patterns in historic papers, because they represent the “fingerprints” of the antique papers. However, these features are usually covered/hidden by printing, writing or other media. Different techniques were developed to extract the watermarks in the paper, avoiding interferences from media on the paper. Beta radiography provides good results, but cannot be widely used because of radiation safety regulations and the long exposure times required due to week isotope sources. In this work, we compared two promising methods that can extract digital high-resolution images for paper watermarks: electron radiography and low energy X-Ray radiography. For electron radiography we created a “sandwich” of a lead sheet, the paper object, and a film in a dark cassette, and exposed it at higher X-Ray potentials (> 300 kV). The photoelectrons escaping from the lead sheet penetrate the paper and expose the film. After development, the film captures the watermark and mould surface pattern images of the investigated paper, which are then digitized by a X-Ray film digitizer. The film could be replaced by special imaging plate type with very thin protection layer to directly generate digital images by CR. For the second method, we use a low energy X-ray source to expose the paper, placed on the DDA, and generate a low energy digital radiography image directly. Both methods provide high quality images without interference from the printing media, and provide potential to generate a “fingerprint” database for antique papers. The second method, using a low energy X-Ray source, has the potential to be integrated in a portable device with a small footprint and user safety features. Differences in the two methods will be shown and discussed.
A Framework for 3D X-Ray CT Iterative Reconstruction Using GPU-accelerated Ray Casting

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X-Ray Computed Tomography (CT) is a powerful nondestructive evaluation (NDE) tool to characterize internal defects and flaws, regardless of surface conditions and sample materials. After data acquisition from a series of X-ray 2D projection imaging, reconstruction methods play a key role to convert raw data (2D radiography) to 3D models. For the past 50 years, the standard reconstruction method have always been analytical methods based on filtered back-projection (FBP) concepts. Numerous iterative methods that have been developed have shown some improvements on certain aspects of the reconstruction quality, but have not been widely adopted due to their high computational requirements. With modern high performance computing (HPC) and GPU technologies, the computing power barrier for iterative methods have been reduced. Iterative methods provide more potential to incorporate physical models and prior knowledge and correct artifacts generated from analytical methods. In this work, we propose a generalized framework for iterative reconstruction with GPU acceleration, which can be adapted for different physical and statistical models in the inner iterations during reconstruction. The forward projection algorithm is an important part of the framework, and is analogous to the ray casting depth map algorithm that was implemented in an earlier work [1] and accelerated using the GPU. Within this framework, different sub-models could be developed in future to deal with different artifacts, such as beam hardening effect and limited angle data problem.

Acknowledgement:

This work is supported by the Center for Non-Destructive Evaluation (CNDE) Industry-University Cooperative Research Program at Iowa State University.

References:
Determination of Porosity in Additively Manufactured Metal Parts Using X-ray Computed Tomography
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There has been a strong interest recently in the nondestructive testing/evaluation (NDT/E) of additively manufactured (AM) parts. The AM community has expressed the need for NDT/E methods for part inspection, analysis, and certification. There is also the need for NDT/E methods for research purposes and process optimization in parallel with development of new AM methods and materials in order to facilitate the fundamental understanding and control of the microstructure. X-ray computed tomography (XCT) has shown some potential in these areas, especially for void analysis and part tolerance quantification, given its capability to sufficiently map and represent three-dimensional volumes. Part certification and qualification is also very important to the additive manufacturing community and while laser-based methods can provide a quick scan of the outer surface, XCT is advantageous for more complex geometries that have internal channels or chambers that a laser would be unable to reach. The Army Research Laboratory (ARL) has recently been using XCT for inspection, evaluation, and analysis of internal AM test parts in a variety of areas, which is currently a focus of ARL’s major AM program. Examples of quantitative porosity determination in AM metal parts, including highly attenuative steel, using XCT with advanced image processing techniques will be discussed. Physical scan considerations of highly attenuative materials like metals will also be addressed.
Estimation of System Nonlinearity in Measurement of Ultrasonic Nonlinearity Parameter

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The ultrasonic nonlinearity parameter defined by ratio of second harmonic displacement amplitude and squared fundamental displacement amplitude has been used as a quantitative index to evaluate material degradation such as thermal aging, fatigue and micro-void. However, experimentally measured ultrasonic nonlinear parameter includes system nonlinearity generated by a driving source and a commercial transducer made of PZT. Therefore, the system nonlinearity must be eliminated to measure pure ultrasonic nonlinearity of the material. In this study, the process to eliminate the system nonlinearity from the ultrasonic nonlinear parameter measured by experimental system consisting of a high-power tone-burst driver and PZT transducer was proposed. Firstly, in simulation, sound field of second harmonic wave generated by material nonlinearity mixed with the system nonlinearity was computed based on the distributed point source method [1], and then the average sound pressure across the transducer surface was calculated. Figure 1 shows the variation of the average sound pressure according to the propagation distance in fused silica with comparison between with and without system nonlinearity. In experiment, the amplitude of the second harmonic wave was measured with respect to propagation distance. Secondly, the initial second harmonic wave amplitude induced by the system nonlinearity was estimated through matching the calculated amplitude in the simulation with the measured amplitude in the experiment. Finally, the initial second harmonic amplitude was subtracted from the experimentally measured second harmonic amplitude to obtain the pure ultrasonic nonlinearity parameter of material. In conclusions, finally obtained ultrasonic nonlinearity parameter had good agreement with literature values and we could confirm that the proposed process is reasonable.

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![Figure 1. Comparison of simulation results for fused silica between with and without system nonlinearity](image)

References:
Estimation of Acoustic Nonlinearity Parameter in Al6061-T6 using Acoustoelastic Effect

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The acoustic nonlinearity parameter is regarded as a damage index of material since it can be used to evaluate the micro-structural degradation of material such as fatigue and thermal aging nondestructively [1]. Up to now, a piezo-electric technique using a through-transmission method has been used to measure the acoustic nonlinearity parameter, that is defined by using amplitudes of the fundamental and second-harmonic frequency components. Alternatively, this study suggested a method to estimate the acoustic nonlinearity parameter quantitatively based on the acoustoelastic effect. The acoustoelastic effect describes the slight changes in ultrasonic propagation velocity according to the stress, which is caused by changes in the density or micro-structure of the material depending on the variation of tensile or compressive stress [2]. It has a similar relation to the nonlinear characteristics of ultrasonic waves in that the propagation velocity of waves depends on the applied stress.

The proposed method can be more convenient than the piezo-electric technique using the transmission of ultrasonic longitudinal wave because it can be measured by the simple pulse-echo technique. For demonstration, value of the acoustic nonlinearity parameter in Al6061-T6 measured from the piezo-electric technique was compared with the value of which obtained from acoustoelastic effect. In order to measure the acoustoelastic effect, two longitudinal and one transverse waves in three-different orientations were used. The acoustic nonlinearity parameter obtained by the conventional piezo-electric technique and also agreed well with the existing literature value. Therefore, the proposed method can be used not only as an alternative to the conventional piezo-electric technique, but also as a means of verifying the piezo-electric technique.

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References:
Collimated acoustic beams are directional in nature and propagate with very little angular spread. They find applications in particle manipulation, underwater communications, and imaging. We describe a novel approach [1] to generate collimated acoustic beams by utilizing radial mode vibration of a single piezoelectric disc transducer. First, we discuss the resonance and vibration characteristics of the radial modes of the piezoelectric discs [2]. Then, we present numerical and experimental results that discuss the role of radial modes in low-frequency collimated beam generation. We then discuss the transducer design for generating collimated acoustic beams. Finally, we present some potential applications of the proposed technique.

References

In-process monitoring of electrohydrodynamic inkjet printing using machine vision

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Electrohydrodynamic inkjet printing (e-jet printing) is one type of micro/nano scale 3D printing techniques that automatically deposit functional materials to form 3D structures on the substrate. Unlike traditional thermal or acoustic inkjet printing, e-jet printing utilizes high electrical forces for the ink to overcome surface tension at the tip of micro needles. The droplets and filaments coming out from the needle have dimensions much smaller than the dimension of the needle, thus to print geometries in micro and nano scale. E-jet printing process parameters can affect the final quality attributes of fabricated constructs. Currently, assessment of these critical geometries and attributes information must be performed offline using optical microscopy or scanning electron microscopy. This drawback affected the efficiency of micro/nano printing from translation to industrial practice. The research in this paper focused on fundamental research to enable in-situ monitoring of e-jet printing using a real-time images characterization technique. In conclusion, the study in this paper investigated using machine vision for real-time monitoring of micro/nano scale 3D printing. The method worked well for micro-filament detection in e-jet printing, and may be further implemented into feedback control system of complicated e-jet printing. However, the optical machine vision was limited to micro scale detection. One of the future research topic is to develop nano scale in-situ detection mechanism for e-jet printing.
Experimental model of impact damage for guided wave-based inspection of composites

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The objective of this work is to assess to which extent the interaction of anti-symmetric ultrasonic guided waves with an impact damage can be captured with an experimental model consisting of a single artificial delamination in composite structures. The structures of interest are composed of unidirectional prepreg carbon fibre reinforced polymer (CFRP) with a quasi-isotropic layup. The artificial delamination is introduced into the laminate using two circular Teflon tapes during manufacturing and the realistic damage is simulated by impacting the samples at two energy levels. Two co-localized rectangular piezoceramics are used to generate an anti-symmetric mode and non-contact measurement is performed using a three-dimensional laser Doppler vibrometer (3D-LDV) to extract the required information for evaluation of the reflection, transmission, as well as the scattering behaviour of the anti-symmetric mode. The corresponding coefficients as a function of frequency, incident angle, and type of damage are extracted. It is found that the amplitude of the coefficients and directivity patterns of scattered waves are barely affected by incident angle but significantly by the impact energy. In light of the results, design guidelines are proposed for efficient guided wave inspection of composite structures submitted to impacts.

Keywords: Composite structures, Structural health monitoring (SHM), Non-Destructive Testing (NDT), Guided wave propagation, Damage detection, Impact, Delamination
Infrared-assisted acoustic emission process monitoring for additive manufacturing

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A known limitation of additive manufacturing (AM) with laser powder bed fusion machines is the long build time. Real-time monitoring of the additive process can provide an early alert if the process exceeds preset limits of the processing parameters. This has a significant advantage over conventional post-manufacturing nondestructive testing methods. In-process monitoring can be used with feedback to either start a set of corrective actions or terminate the build early to save machine time and powder.

One of the monitoring technologies that has been investigated by several research groups is acoustic emission (AE). The signals from the AE sensors can be correlated with several parameters of the AM process such as laser power and volumetric energy deposition. The difficulties exist in interpreting the AE signals. For example, the layer-to-layer geometry variations or hatching pattern variations can produce relatively large changes in magnitude or frequency of the AE signals that could be misinterpreted as a process abnormality.

This work describes an investigation conducted at CCAM for the purpose of improving the interpretation of the AE signals. To do this, infrared thermographic imaging was used to better interpret the cause of the AE signal variations. A low cost infrared camera with a microbolometer sensor was used to acquire a series of infrared images during the AM process, in addition to recording the AE signals. A comparison between the position of the laser beam on the part and the AE signals resulted in understanding conditions under which the AE signal was produced. This provided additional input to the event interpretation process. The combined application of these two technologies resulted in a better separation of the AE signals into clusters related to a particular change in the AM process recipe.

Future work will be devoted to combining infrared and AE data to reduce signal deviations caused by the change in the laser beam pattern. This will improve reliability in detection process abnormalities that reduce quality of the additive components.

Keywords
Additive manufacturing, process monitoring, acoustic emission, infrared thermography
Non-destructive testing of additively manufactured metal test artifacts

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Additive Manufacturing (AM) enables to manufacture parts with complex geometry. Non-destructive testing (NDT) of such complex parts presents significant challenges for qualification and certification of them for critical applications. Todorov [1] has ranked the AM parts in 5 groups according to their design complexity and to their NDT inspectability. The parts from group 5 are the most complex ones, such as lattice structures. Todorov reported that the only NDT methods suitable for all groups are X-ray computed tomography (XCT) [2] and resonant ultrasound spectroscopy (RUS), such as resonant acoustic method (RAM).

NIST and LNE are involved in the standardization group ISO TC261/ASTM F42 JG59 “Non-destructive Testing (NDT) of Additive Manufactured (AM) Parts”. Within this group we are developing a guide that will include post-process NDT of AM for metallic parts. Among other topics, this guide will present current NDT capabilities to detect flaws in the AM parts. To illustrate the potential of the current NDT methods, star-shaped test artefacts with series of well-defined defects have been designed to be additively manufactured in different materials, and inspected by different NDT methods.

To investigate the capabilities of these NDT methods in metal AM applications, we have built the star-shaped test artefacts in Co-Cr and have characterized them using XCT and RAM methods. This presentation will summarize the comparisons of measurement results.

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Infrared Evaluation and Analysis of Electric Cables in Nuclear Power Plants

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Electric cables are essential components in nuclear power plants (NPPs). In the NPPs’ harsh environment, the electric cables have been exposed to various thermal and radiation sources during the past few decades, which potentially resulted in severe aging degradation and damage. In order to provide better maintenance to these NPPs and to prevent the occurrence of disastrous events, it is very important to understand the aging mechanism of the cables and the severity of the damage. In this work, we conducted a systematic and thorough investigation using polyethylene (PE) and crosslink polyethylene (XLPE) samples aged in a wide range of degradation conditions. To assist in evaluation of such degradation and damage, we employed electromagnetic Fourier-transform infrared spectroscopy (FTIR). High-precision FTIR data in the mid-infrared range were acquired from these samples and analyzed by spectroscopic interpretation. Advanced data processing were further applied and followed by chemometric analysis using partial least-squares (PLS) and probabilistic neural network of machine learning.

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![Figure 1. Examples of FTIR spectra of PE samples (top) and PLS calibration of FTIR data from XLPE samples (bottom).](image)
Estimating Fatigue Crack Harmonic Generation using Contact Acoustic Nonlinear Theory with a Distributed Interface Stiffness

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There are many instances where the remediation of a damage is through the application of compressive forces to close the unwanted cracks. However, a closed crack does not have a significant acoustic impedance mismatch with its surrounding media. As such, characterization of its crack length is challenging for post remediation assessments. By increasing the amplitude of the acoustic wave, the dynamics of the crack interface changes. One can think of the acoustic wave as being strong enough to open and close the crack while it cycles through both compressive and tensile pressures. This is demonstrated experimentally utilizing two interfacing and polished cylinders. The acoustic wave passing through the cylinders is only distorted if the tensile pressure of the acoustic wave exceeded the pressure closing the interface. To model the dynamics of the acoustic wave, contact acoustic nonlinear theory (CAN) was utilized. However, it was demonstrated that this theory did not sufficiently model the harmonic content observed experimentally. It was hypothesized that the error in this measurement was a result of variation in the interfacial contact pressure due to surface roughness. The nature of the surface might dictate particular distributions of compressive forces holding the interface together. However, in this work, a normal distribution was assumed. The dynamics of an acoustic wave passing through this interface were modeled by replacing the discontinuous stiffness function used in CAN theory by an effective stiffness predicted using a normal distribution. It was demonstrated that the harmonic content predicted using this modified CAN theory, was dependent on the mean interface pressure, as well as, the standard deviation. The estimated harmonic content is compared to experiments on contacting stainless steel cylinders as well as to a fatigue cracked specimen.
Modeling Ultrasound Propagation in Curved Composite Laminates
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This paper reports on model development for ultrasound propagation in curved CFRP composite laminates. Propagation in a planar laminate can be rigorously studied using a Fourier integral analysis which treats each ply as a homogeneous transversely isotropic continuum. Continuity of displacements and tractions at ply interfaces provides the Fourier integrand as the solution to a boundary condition matrix equation. For the curved laminate, the analysis is more complicated: the ply elastic properties are no longer spatially homogeneous, but rather display a spatial dependence due to the curvature of the ply. A model for the curved laminate is constructed by approximating the curved laminate as an assembly of circular wedge segments of small angular width, where each wedge segment is internally comprised of a planar laminate, fig.(1). Wave motion on the adjoining surfaces of the wedge assembly is formulated as a boundary integral equation using the Fourier integral evaluation of the Green function for the planar laminate, and is computed numerically using the boundary element method (BEM). Results will be presented showing curved laminate propagation characteristics obtained using the numerical model. Additionally, results of analytical work will be presented aimed at deriving effective approximate models which treat the laminate as a homogenized continuum. Predictions obtained by the approximate homogenized models are benchmarked against the curved laminate BEM model to establish limits of validity in wavelength and curvature.

Figure 1. Curved composite laminate modeled as assembly of planar laminate wedges.

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Model development for UT Inspection of Anisotropic Materials

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This paper reports on work in the modeling UT inspection of anisotropic materials. 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 AGF 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.

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Overview of different On- and Offline-NDE methods in Additive Manufacturing of aircraft engine parts

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For aircraft engines additive manufacturing is used to build nickel-base material parts with Selective Laser Melting (SLM). SLM is a 3D-printing-process which provides the possibility to construct complex geometries by layered manufacturing of components with metallic powder.

In aircraft industry the non-destructive evaluation of all parts is predetermined. Additive manufacturing brings new challenges to NDE. At MTU Aero Engines several approaches were analyzed, which will be presented in this talk. The finished part can be inspected using Fluorescent Penentrant Inspection (FPI), Computer Tomographie (CT) and White Light Scan. The limitations for other NDE methods will be shown.

Online Process Monitoring Systems are more promising than typical NDE methods. There are different approaches: optical tomography, ultrasound and laser thermography.

In optical tomography (OT) a high-resolution camera system is used to record the welding light intensity of each welded layer. The obtained image stacks are analyzed with image processing algorithms and then can be converted into 3D models by using computer tomography software.

A process is developed to ensure the integrity of the OT system using CT. In some cases layered structure during the SLM process results in very thin, flat bonding defects which are difficult to detect with computed tomography. To find the small lack of fusion defects and in order to describe them statistically special the tensile specimens were plastified in order to increase the volume of the defects (crack opening).

Furthermore Ultrasonic Testing (UT) can be used to evaluate the building jobs statistically.
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Digital Process Control System Software for Metal Additive Manufacturing with Aerospace Alloys

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Today the time and cost associated with validation of the manufacturing process for aerospace quality components can be on the order of 15 years and $200MM. The “make and break” qualification approach is too costly. For metal Additive Manufacturing (AM) to transition to production there is a need for a rapid process qualification of metal AM components that achieves part specific performance and affordability goals. In this presentation, a digital In-Process Quality Assurance™ (IPQA®)-based approach is proposed that demonstrates that in-situ probabilistic sensing and routine data-capture capabilities can be transferred to the manufacturing environment to reduce qualification costs.

Experiments were performed to characterize aerospace titanium- and nickel-base alloys using a state-of-the-art, Directed Metal Laser Sintering (DMLS®) AM system and non-contact, in-situ sensors. Quantitative, digital In-Process Quality Metric™ (IPQM®) data, aka, Quality Signature™ data or Thermal Energy Density™ (TED™) metrics were mined, fused and calculated from optical and thermal sensor data traces collected at 50,000 samples per second per channel and correlated with process input parameters selected to stress the process. Worst-case conditions were selected that challenged the process to discover how post-inspection quality metric data and in-process quality metric™ data varied as process input variables were changed. These process capability studies were used to define acceptable in-situ, digital Quality Signature™s that were subsequently correlated to post-inspection testing results (e.g., part density) and used to define alloy-specific AM process maps.

These studies demonstrated that it is possible to use digital in-situ monitoring data to rapidly qualify engineering alloys using an AM process map approach using quantitative, digital IPQM® data or Quality Signature™s coupled with conventional, post-inspection test results. Such alloy-specific AM process maps allow process engineers to develop confidence in a digital, IPQA®-based approach to process qualification using in-situ Quality Signature™s and traditional statistical process control techniques.
Optimal design of experiments was used to extract sensitive parameters for eddy current probe characterization to further develop uncertainty quantification and validation procedures of forward and inverse models in non-destructive evaluation research. Verification and validation techniques in low frequency electromagnetic modeling are not well defined, and do not provide promising methods to effectively quantify uncertainty in eddy current signals as well as uncertainty in the simulations. To properly validate complex computer models, individual experiments mimicking validated benchmark studies require intentional design to ensure calibrated, quantified, and fully verified eddy current data. This work provides multiple efficient experiments that are designed to optimize signal output from coil lift off, coil tilt/orientation, calibration, probe mounting consistency, and specimen leveling. Notch size, length, shape, conductivity value, and probe type are fully defined in all experiments. A sensitivity analysis is conducted on each parameter and applied towards uncertainty quantification studies of the probe and subsequent models. A fully parameterized finite element simulation is used to develop surrogate models for rapid evaluation. Error due to the surrogate model is analyzed to maintain proper convergence relative to the experimental error. This effort will lead to a workflow aimed at validating new models that represent complex probe geometries, varying probe orientations, and customizable probe dimensions. This effort will also benefit model assisted probability of detection, inverse modeling, and tailored eddy current probe design for non-destructive inspections.
Simultaneous reconstruction of velocity and density using acoustic multi-parameter full waveform inversion

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In this paper, a quantitative ultrasonic imaging approach based on the acoustic multi-parameter full waveform inversion (FWI) is introduced to reconstruct velocity and density of metal components. Density is very difficult to reconstruct in multi-parameter FWI because different parameters with different natures have the coupled effects on the wave response for the propagation region from transmission to reflection. Also, different parameters have different influences on amplitudes in the wave-field, which can make the inversion ill-conditioned. To mitigate the coupled effects and rescale amplitudes of different parameters, a robust estimation of the inverse Hessian operator is very important in multi-parameter version. Simultaneous estimations of velocity and density using the truncated Gauss-Newton method is investigated, in which the inverse Hessian is taken into account by using a matrix-free conjugate gradient solution of the Gauss-Newton normal equation. Simulation and experimental results of the centred inclusions confirm that the truncated Gauss-Newton method can effectively alleviate the traded-off effects between velocity and density with the consideration of the Gauss-Newton approximate Hessian, especially its off-diagonal blocks; therefore, the velocity reconstruction is accurate and the estimated density is well achieved.
Subsurface moisture content in Portland cement concrete structures indicates the short-term (cement hydration) and long-term (durability) of these structures and can be used in the nondestructive evaluation (NDE) and structural health monitoring (SHM) of concrete structures. Subsurface moisture content of concrete structures provides insightful health-related information such as the potential of steel rebar corrosion and alkali-silica reaction (ASR) inside concrete. However, existing approaches for moisture measurement are either intrusive (e.g., embedded moisture sensors) or not applicable in the field (e.g., gamma-ray attenuation, neutron scattering). This paper presents a field-applicable, NDE technique for characterizing subsurface moisture content of concrete specimens, based on synthetic aperture radar (SAR) imaging. Laboratory concrete specimens made of three water-to-cement (w/c) ratios (0.4, 0.5, 0.55) were cast and conditioned to create various moisture contents in the range of 0% (oven-dried) to 4% (saturated). Concrete specimens were inspected by a 10GHz SAR imaging sensor to generate radar images for predicting both the w/c ratio and moisture content of each specimen. From our experimental data, it is found that the amplitude of SAR images can be used to predict the moisture content of concrete specimens. It is also found that critical contour area (distribution of SAR amplitudes) of SAR images increases with the increase of moisture content, serving as a useful indicator for subsurface moisture distribution inside concrete. An empirical model capable of predicting both the w/c ratio and moisture content from an SAR image is proposed. Research approach is finally summarized in a procedure for future applications.

**Keywords:** Subsurface moisture content, microwave NDE, Portland cement concrete, water-to-cement ratio, radar imaging, synthetic aperture radar, critical contour area
Efficient Inspection of Concrete Bridges using Aerial Radar Imaging on a Drone Platform

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Efficient inspection of deteriorated reinforced concrete bridges is one of the major challenges faced by civil engineers around the world. The large area to be inspected per bridge, types of possible defects, number of bridges, and short time frame for bridge inspection have become a driving force for civil engineers to explore novel solutions for efficient bridge inspection. In this paper, our research work on the development of an aerial radar imaging sensor on a drone/UAV (unmanned aerial vehicle) platform for efficient bridge inspection is presented. A portable, wireless synthetic aperture radar (SAR) imaging sensor (carrier frequency = 10GHz, bandwidth = 4GHz) and a video camera were integrated with a drone platform for collecting radar images and digital photographs of a highway concrete bridge (Lowell, Massachusetts) for surface and subsurface inspection. Digital photographs (effective pixels = 12.4 M) are converted into a three-dimensional (3-D) point cloud model of the bridge via 3-D photogrammetry for surface sensing. Radar images are processed and interpreted to identify surface cracks and subsurface steel rebars. Processing steps for data visualization and fusion are presented. It is found that the use of 3-D point cloud models can assist civil engineers on monitoring surface cracks of bridges. Subsurface features of bridges such as steel rebars location can be revealed in SAR images. The use of a drone platform in bridge inspection can eliminate the requirement of bridge inspection vehicles and accelerate inspection efficiency as long as the proficiency in drone operation can be ensured.

Keywords: Bridge inspection, aerial radar imaging, concrete bridges, drone platform, UAV, synthetic aperture radar, 3-D photogrammetry, data visualization
Nonlinear Rayleigh Surface Wave Technique to Characterize Microstructural Damage of Cold Worked Stainless Steel 304

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This research presents a new approach of the second harmonic generation (SHG) technique for the nondestructive evaluation of cold worked 304 Stainless Steel (SS). A noncontact, air-coupled ultrasonic transducer detects nonlinear Rayleigh surface waves. From the ratio of the amplitude of the second harmonic and square of fundamental amplitude, the acoustic nonlinearity parameter $\beta$ is determined [1]. The advantage of the present technique is its higher sensitivity to micro-damaged materials in comparison to linear ultrasonic techniques, especially in determining dislocation arrangement, residual stress, and dislocation density [2]. Additionally, in many situations, the manufactured components are installed and conventional longitudinal wave techniques are restricted due to their need to access to both sides of a component. With the Rayleigh surface wave technique and the non-contact, air-coupled ultrasonic transducer, this restriction can be eliminated, and is thus very suitable for many cases. The cold rolled 304 SS materials experiences various microstructural changes due to increase in dislocation density, dislocation sub-structural changes and formation of strain-induced martensite [3]. The task of this research is to determine the nonlinear parameter $\beta$ of different percent of cold worked SS304 to provide effect of microstructural damage of cold work using nonlinear Rayleigh surface wave technique with non-contact, air-coupled transducer.

References
This paper will present a review of the use of Air coupled coupled ultrasonics for nondestructive evaluation of wind turbine blades. Results will show the use of air coupled ultrasonics to scan thick composite sections of 40m wind turbine blades including the spar, the leading and trailing edges, and the root section. Detection of defects such as slots, holes, fiber waviness (both in-plane and out-of-plane waviness), delaminations and dry fibers will be presented. Other features like adhesive length measurement and fiber waviness in trailing edge and root sections will also be presented. The use of air coupled UT is not limited to just detection, but also characterization of the detected defects. Results highlighting the use of ultrasonic velocity to characterize defects will be presented. This includes defining damage index in terms of velocity, as well as development of stiffness maps to show reduction in structural stiffness based on the defect. Additionally, the challenges of NDT of wind turbine blades using conventional ultrasonics will also be presented.
Photoacoustic detection and monitoring of oil spill

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The detection and monitoring of oil spills in marine environment are crucial to respond rapidly and efficiently and it is especially important in ice covered areas. Detection and quantitative characterization of the affected areas as well as monitoring of remediation measures are critical for optimised cleaning operation and minimal environment impact. In the recent years, techniques of oil spill detection from under the ice with Remote Operated Vehicle (ROV) or Autonomous Underwater Vehicle (AUV), have been explored and have shown promising results. These techniques are based on ultrasonic or sonar technologies to quantify the oil volume and optical techniques to obtain a chemical signature of the oil presence.

In this paper we present a new promising technique based on photoacoustics for detection and sizing of oil spill under the ice, encapsulated within ice, or on open water. Based on photoacoustics, the technique has the advantage to provide signal in the presence of oil and no signal in its absence as shown in Fig. 1. The technique is also much less sensitive to alignment compared to ultrasonic and sonar techniques. Experimental results on detection of oil under the ice are presented and discussed. A first prototype with a scanning unit that can be operated in ROV is presented. The solution proposed should be especially useful as a tool for emergency response, but should also be suitable when operated in AUV for monitoring high risk areas due to navigation and transportation.

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Figure 1. Cross section of a volume of oil partially encapsulated on ice and floating in water, where the oil presence can be readily and quantitatively evaluated.
Qualification of Additive Manufacturing Parts using Predictive Modeling Tool for Mechanical Performance and Inspectability

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As the use of additive manufacturing (AM) parts become more common in different industries, especially aerospace and defense, Sentient has developed a predictive modeling tool for components built using AM to assess their performance, with rigorous consideration of the microstructural properties governing the nucleation and propagation of fatigue cracks. The feasibility and validation of our modeling tool is verified using multiple experimental coupon and component testing. Sentient’s predictive tool is able to account for temperature and microstructure variation as the function of process parameters and scanning strategies at various AM processes. Microstructure variation at different geometrical features can be modeled in our tool. This provides a technically effective and economically efficient way for part qualification and product design in metal additive manufacturing. DCC predictive modeling tool can account for different materials both single phase and 2-phase (for example, Ti-6Al-4V, 15-5 PH, 17-4 PH, C64). Through different applications and fatigue testing of multiple parts from different materials, it is shown that our predictive modeling tool is properly applicable for the additive manufacturing materials. The Microstructural features and behaviors specific to AM materials developed for our tool under this work are: the effect of the AM build process on the residual stress left in the part after the build process, surface roughness created on the surface of the part after the build completion, and the microstructure resulted due to build process parameters. We simulate the AM build process considering the parameters (laser intensity, laser speed, hatching space, powder layer thickness, orientation of build, etc.) involved during the build process in order to generate the microstructure of AM part which is the outcome of the build process.

Aerospace OEMs (hardware suppliers) need to incorporate inspectability considerations into design. Sentient is developing the modeling technology to improve inspectability without negatively impacting reliability. Sentient is developing its physics-based life predictions and inspection simulation software to provide a modeling framework to simultaneously optimize for inspectability and reliability before designs are finalized. This modeling technology helps to optimize the design of the additive manufacturing parts. These parts could be in drive train and structure of different aircrafts and other military vehicles. Using this technology the AM parts will have a higher mechanical performance and better inspectability. Special consideration of AM parts microstructure is an advantage of our modeling tool compared to other tools.

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