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Classification of flaw severity using pattern recognition for guided wave-based structural health monitoring

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ABSTRACT

In this paper, the authors present a formal classification routine to characterize flaw severity in an aircraft-grade aluminum plate using Lamb waves. A rounded rectangle flat-bottom hole is incrementally introduced into the plate, and at each depth multi-mode Lamb wave signals are collected to study the changes in received signal due to mode conversion and scattering from the flaw. Lamb wave tomography reconstructions are used to locate and size the flaw at each depth, however information about the severity of the flaw is obscured when the flaw becomes severe enough that scattering effects dominate. The dynamic wavelet fingerprint is then used to extract features from the raw Lamb wave signals, and supervised pattern classification techniques are used to identify flaw severity with up to 80.7% accuracy for a training set and up to 51.7% accuracy on a series of validation data sets extracted from independent plate samples.

1. Introduction

Flaw detection in metals remains an important area of research as the world's aviation and naval fleets continue to age [1]. It is critical that flaws be identified before structural failure, and accurate maintenance planning requires knowledge of a structure's state of health. Lamb waves [2,3] have proven to be a popular technique in structural health monitoring (SHM) [4,5] due to their multi-mode propagation and dispersive properties. Of interest in SHM is that Lamb waves are confined by a structure's boundaries and so follow its shape and curvature, while giving sensitivity to material discontinuities at either surface as well as in the interior of the plate, pipe or shell. Lamb waves also have the ability to propagate relatively long distances [6] and beneath layers of insulation or other coverings [7]. These properties allow Lamb waves to rapidly cover large areas of interest, providing a useful tool for identifying defects in a variety of structures. However, their multi-mode nature is often too complex for direct interpretation.

The majority of the Lamb wave literature side-steps the complexities associated with multi-mode Lamb wave signals. Some inspection techniques include specific assumptions or restrictions that can render them impractical for field use. Many assume a uniform thickness of the plate [8] or rely on comparing signals from damaged and undamaged areas in an instantaneous cross-correlation analysis [9]. A common implementation of Lamb waves for damage detection involves restricting the frequency-thickness product to a regime where only the fundamental modes exist [5]. Doing so promises easier analysis of mode arrival-time shifts, since there is less likely to be mode overlap when the lower-order modes are spread far apart in group velocity. Larger frequency-thickness values give rise to higher-order modes, but result in signals that often prove quite difficult to analyze. Nevertheless, because each mode propagates with a unique through-thickness displacement and stress profile [10], it can be beneficial to use multi-mode Lamb wave signals since each mode has different dispersion characteristics and sensitivity to defects.

Lamb wave tomography (LWT) can produce quantitative maps of damage in plates and pipes with both single-mode and multi-mode Lamb wave signals [11–18]. Approaches for modeling the scattering behavior of Lamb waves have included Mindlin plate theory approximations [12] and diffraction tomography ([14]), while differing measurement geometries [13] and automated analysis techniques [15,16] have also been explored in order to improve reconstruction speed and resulting image resolution. By measuring Lamb wave mode arrival time shifts, a slowness map can be generated that highlights structural flaws such as corrosion. Tomographic reconstructions have been shown to accurately identify defects on an exposed aircraft structure, even when sensors are embedded on the inside, hidden surface [19]. Recent work has resulted in many different reconstruction techniques in an attempt to reduce the computational requirements and/or the large number of transducers required to accurately map an area [20,21]. A subset of tomography that has also received recent

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attention is probability-based diagnostic imaging, which generates maps of damage in terms of a presence probability using only a handful of transducers [22]. Depending on the transducer positions used, these maps may not offer accurate flaw sizing or shape information, and will often produce false-positive artifacts that need to be removed using a subjective threshold. Even though a direct correlation between mode arrival time and material thickness may not always exist for higher-order Lamb wave modes due to overlapping group/phase velocities, these LWT reconstructions are still able to accurately locate and size defects in a scanned area.

For subtle corrosion flaws, the goal is to detect a small change in the arrival time of the Lamb wave modes as they speed up or slow down slightly when crossing a region of the plate that is thinner. Severe defects are much more challenging since the Lamb waves will also scatter and mode convert when they interact with the flaw. Several techniques have been explored to analyze these strongly scattering defects. Diffraction tomography incorporates ray bending effects to correct the straight ray assumptions used by most tomography algorithms [14], resulting in improved defect flaw sizing capabilities within the reconstructed images at the expense of significantly increased computational requirements. Mindlin plate theory approximations have been implemented to derive the complex scattering fields from through holes [11], confirming the streaking effects seen in Lamb wave tomography images of holes larger than the inspection beam size. Another semi-analytic model based on mode superposition has been presented to study the scattering field of the S_0 mode from circular through-thickness holes [23]. These techniques all consider through-thickness flaws, a symmetric problem with respect to the mode interaction. Flaws that are deep but not completely through the material introduce mode conversion within the material, adding to the complexity of the signal analysis. Mindlin theory has more recently been used to explore S_0 to A_0 mode conversion for partial-thickness cylindrical defects [24]. Results compared well to both 3D simulation data and experimental measurements, however only steady state monochromatic waves are supported in the scattering model. Using different transducer polarizations for the transmitting and receiving transducers has been shown to identify mode conversion effects associated with asymmetrical-thickness damage in materials for instantaneous identification of damage [25]. This approach, however, requires transducer installation on both surfaces of a material and only returns information about the presence of damage, not the severity. An analytic solution has been recently presented that allows scattering of irregularly-shaped flaws to be considered by dealing with the cylindrical coordinate z and θ dependencies in the boundary conditions separately, first applied to solving scattering fields for through-thickness cavities [26] and then flat-bottomed cavities [27] of irregular shape. Results were verified with a finite element model to show excellent agreement, however this approach breaks down due to numerical instabilities when the geometry of the scatterer includes tight curves.

Three-dimensional (3D) modeling is the only approach currently available to fully understand guided wave interaction with defects. While very computationally intensive, multi-mode scattering effects can be studied in detail using 3D elastodynamic finite integration simulations [28–30]. Even for relatively simple geometries, however, supercomputers are required to explore the 3D behavior of the scattered Lamb wave fields. It is still not practical to generate a full catalogue of possible defect scattering fields in this way to use for damage detection applications.

Because LWT reconstructions are able to size and localize flaws, including strongly scattering flaws, they present a mechanism to automatically identify which waveforms have interacted with the material defects present. Pattern classification techniques [31–34] can then be used to provide a formulism which exploits the scattering and/or mode mixing information in the waveforms in order to determine the flaw depth. Emerging applications in the fields of biology, medicine, financial forecasting, signal analysis, and database organization have resulted in the rapid growth of pattern classification algorithms. Sohn et al. [35] present a review which discusses the statistical pattern classification models currently being used in SHM. Most implementations involve identifying one specific type of ‘flaw’, including loose bolts and small notches, and utilize only a few specific features to separate the individual flaw classes within the feature space [36–38]. Biemans et al. [39] detect crack growth in an aluminum plate using wavelet coefficient analysis generated from guided waves. The use of wavelet analysis for feature extraction has also been explored by Jin et al. [40], where wavelet-based features are used for damage detection in polycrystalline alloys. Gaul and Hurlebaus [41] also use wavelet transforms to identify the location of impacts on plate structures.

In most applications of pattern classification, the distribution of classes within a feature space is not important as long as the classes are optimally separated within that space. With damage detection, if a sequence of flaws is used to train a classifier, each class can be thought of as a step in a physical process which changes over time. For example, corrosion is a continuous process where severity of damage can only increase with time. If corrosion is binned into incremental thickness loss steps, each step can be assigned a different class label. It follows that this order of class distribution within a feature space will be important, and should be sequential in order. That is, each class should ideally border the classes before and after it when sequentially ordered. This concept is referred to here as the ‘sequential’ ordering of classes, and will be important in down-selecting the feature space.

In this paper we use higher-order Lamb wave modes to identify and characterize flaws which simulate plate thinning due to corrosion. We incorporate several different analysis techniques including Lamb wave tomography, wavelet-based feature extraction, and formal pattern classification to create a fully-automated analysis scheme designed to locate, size, and identify severity of unknown flaws. Using wavelet-based feature generation, we create a high-dimensional feature space which is then intelligently reduced using several feature selection routines, keeping the sequential ordering of classes in mind. Our goal is to develop a formalism that can be used to easily locate and diagnose thickness-loss flaws. The classification results described in this work provide insight into the complicated multi-mode Lamb wave behavior with flaws which range in severity from unflawed to a through-thickness hole.

2. Method

The data used in this study is collected from a 305 mm × 305 mm × 3.15 mm aluminum plate with an incrementally increased 76 mm × 30 mm flat-bottom hole. Two 2.15 MHz, 6.35 mm diameter longitudinal, piezoelectric contact transducers are arranged in a pitch-catch configuration to transmit and receive the signals. A Matec TB1000 tone-burst card is used to generate a 5-cycle sine wave at 2.15 MHz to excite the transmitting transducer. The receiving transducer’s signal is fed back though the Matec card for amplification and is then digitized using a Gage CS8012a A/D converter. Each transducer is fitted with an 11.5 mm cylindrical acrylic delay line with glycerin couplant used at both the transducer face and the plate surface.

The transducers are stepped through 100 locations per side in 2 mm increments in a double-crosshole geometry [15]. This technique uses linear slides to mimic a four-sided perimeter array of transducers surrounding an area of interest. The motion of both