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Specimen-Agnostic Guided Wave Inspection Using Recursive Feedback

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***Abstract*—Lamb waves, a configuration of guided waves are often applied to the inspection of plate like structures. Their complex, multi-modal nature makes them well suited to the inspection of different defects. Control over their propagation direction allows the engineer to increase inspection distance and prospectively locate the defect. Schemes already exist, but they require knowledge of material and its dispersion curves. If the material composition is not known, or external factors are effecting its speed of sound then these schemes may not be appropriate. The recursive feedback algorithm can be used to enhance guided waves in a single direction without a-priori knowledge. In recursive feedback, a guided wave is generated using the first element of an array transducer. Over several subsequent iterations, this guided wave is reinforced by re-transmitting recorded out of plane displacements. In this work, recursive feedback has been applied to two inspection problems; a contaminated kissing bond and a plate with a defect. With the kissing bond, it is shown that the the contamination can be identified as the A_0 mode of generated waves are absorbed. In the defective plate, the defect direction is identified by a 10 dB increase in reflected energy when the guided waves are enhanced in one direction.**

I. Introduction

In non destructive evaluation (NDE), guided waves are often applied to thin plate-like structures [1]. The close proximity of the boundaries means that when the plate is loaded, lamb waves form which are a superposition of longitudinal and shear waves. At any given a frequency, an infinite number of modes exist, each differentiated by their unique phase velocity and shape. The lowest order of these are A_0 and S_0. These low order modes are applied to inspection of joints, welds and for the discovery of large defects like holes. Lamb waves are also applicable to multi layer structures for imaging of defects [2]. Alternatively, the S_0 mode can also be generated for pulse-echo to find defects [2]. Guided waves are often utilised in the petro-chemical industry for the inspection of pipes where one sided is loaded with a fluid [3]. More recently, authors have developed techniques for coupling lamb waves into complex corrugated materials [4]. Guided waves are still an area of intense research, with authors continuing to characterise guided wave [5] behaviour at increasing frequencies [6].

Control over propagation direction is highly advantageous in NDE; it allows the engineer to locate defects and increases propagation distance. Guided wave specific techniques already exist to control propagation direction [7]. However, they require knowledge of the specimen's dispersion curves. This is problematic as the exact material composition may not be known, or external factors, such as temperature may affect the speed of sound. Here, recursive feedback is applied to the inspection of several materials. Using an array transducer, the algorithm allows the direction of propagation of lamb waves to be controlled without knowledge of the material parameters.

It is not within the scope of this work to fully describe the intricacies of the recursive feedback algorithm, it is described elsewhere [8]. However a brief description will be given.

Consider an N element array transducer which is mounted normally to a specimen such as a plate. Before inspection is undertaken, a short process called recursive feedback is undertaken which allows excitation waveforms and delays for each element of the transducer to be found. The process allows uni-directional guided wave inspection to be undertaken. It consists of N short iterations, which are as follows:

1) $i = 1$ Initially, the first element of the transducer is excited with a linear chirp. As the first element loads the material, longitudinal and shear waves combine and create multi modal Lamb waves that travel in both directions. Simultaneously element two records the surface pressure of the material.
2) $i = 2$ Now the first element transmits the same stimulus as it did before. This time however the second element transmits back its recording from the previous iteration. The third element records.
3) $i = 3$ In the third step of the scheme, the first element transmits its stimulus, the second its recording from step one and the third its recording from step two. The forth element records.
4) $i = N$ This process is continued until all N elements are transmitting.

The effect is that Lamb waves tend to travel in the direction of the array's spacial influence. Each element reinforces the travelling wave using its recording. Lamb waves will still

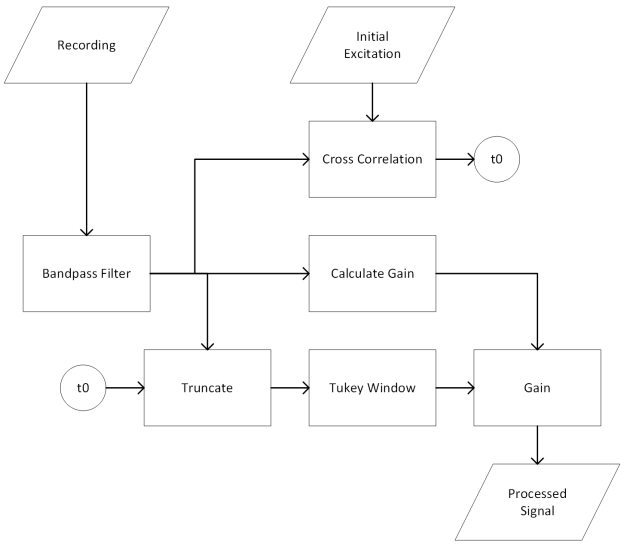

Fig. 1. Signal processing chain. The chain rejects noise and ensures that the region of interest is re-transmitted.

propagate in the opposite direction but with less energy. The scheme will amplify forward any modes generated by the first element.

A degree of signal conditioning is required: Lamb waves are dispersive, so excitation sequences grow in length and the algorithm by design will amplify forward any noisy un-conditioned signals. To solve this, recordings are cross-correlated with the original excitation on the first element. This approximates delay, a process similar to pulse compression in medical imaging. From here the playback can be truncated and Tukey windowed. A bandpass filter is also applied to reject frequencies outside the bandwidth of the original excitation. Finally gain is applied to equate the signal maximums. The chain is shown diagrammatically in Figure 1.

II. Method

For the first time, the recursive feedback scheme will be applied to two inspection problems. The problems will be described and tested. In each problem a different material will be used, but an identical pitch transducer and excitation frequency will be used. The first problem will highlight the scheme's ability to excite several modes without a-prior knowledge of the material's properties. The second will be show that the uni-directional capability can be used to resolve the direction of a defect.

In both cases, an 8 element transducer is simulated with pressure loads separated by 3 mm. The contact area is 400 μm. The excitation is a 700 - 800 kHz chirp. This simplification reduces simulation complexity.

A. Contaminated Kissing Bond Inspection

Kissing bonds are common place in aeronautics, they consist of two plates that are glued together with an overlap. Causes of failures include inclusions (contamination) and voids. These are caused by poor curing, poor surface preparation or stress.

Fig. 2. A kissing bond that has been contaminated. Two plates are epoxied together. Guided waves are generated in the lower plate and will couple into the top plate.

A cross section of a kissing bond with an inclusion is shown in Figure 2.

When poor quality kissing bonds are subjected to guided waves, mode conversions, phase velocity changes and attenuation occur when the waves interact with contaminants. The amplitude of the S_0 mode can indicate the location of a delamination [9]. The A_0 is most sensitive to bond state, and the easiest to transduce [10]. Fully cured bonds transmit the most energy and inclusions introduce fluid modes. The A_0 mode will become a multilayer mode ($2h$) while it crosses the bond [10]. In this experiment, a kissing bond will be modelled using an FEA tool. 2 mm thick aluminium sheets will be used for the plates. 600 μm thick epoxy and a 200 μm thick inclusion of castor oil will be used for the defective joint. The defect consumes a third of the 60 mm wide overlap and is placed 500 μm from the incoming edge of the epoxy.

Recursive feedback will be performed on the lower of the two plates with the aim of generating a guided wave toward the joint. The process will be repeated on an uncontaminated joint so that a comparison can be made.

B. Defect Localisation in a Titanium Plate

In this experiment, guided wave inspection will be applied to a 500 mm wide, 2 mm thick titanium plate with a defect. At one end lies the edge. At the other end lies a blind hole, 5 mm in diameter and 1 mm deep.

The recursive feedback will be used in two ways. Firstly the scheme will be used to excite toward the edge of the material. In the second operation, the waves will be directed toward the hole. The out of plane surface displacements over the transmitting area will be monitored for reflections. Comparisons between the two enhancement directions should indicate from where the defect lies. The higher intensity reflections from the two directions will indicate which direction the defect exists. Exact localisation is difficult because of the dispersion of the propagating waves. In Structural Health Monitoring (SHM) however, this can be compensated for [11]. Dispersion relations will be acquired to observe any specific attenuation or reflection of modes.

III. Results and Discussion

Figure 3 shows the dispersion relations for a kissing bond with and without contamination. The dispersion is acquired from the top of the two plates. The out of plane surface displacements are recorded at several locations. An array can be used to do this, or alternatively a single element transducer can be moved to different locations. Authors have developed single multi element sensors for SHM that negate the need to

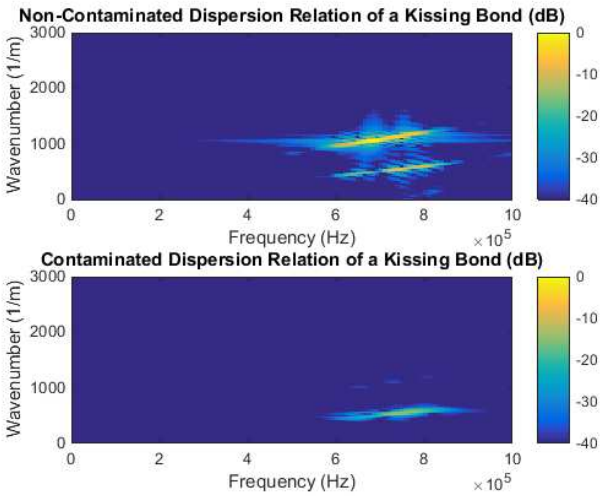

Fig. 3. The dispersion relations of kissing bonds with and without contamination. The peak value of the uncontaminated has been used as a reference. Attenuation and mode conversions have occurred in the contaminated case.

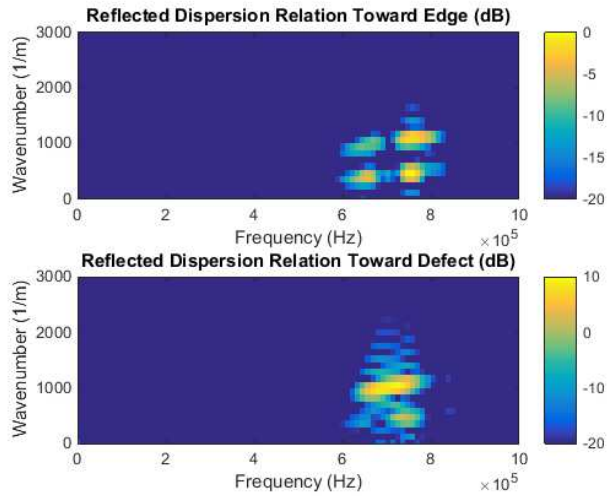

Fig. 4. Dispersion relations reflected from a defect in each enhancement direction. Top: Guided waves are enhanced in the opposite direction to the defect, there is a small reflection from the defect. Bottom: Guided waves are enhanced toward the defect, there is a much larger reflection.

move the sensor [12]. Transducer choice is important as modes behave differently when interacting with different materials [13]. Laser vibrometery is desirable for this reason [5] as it is non contact. When two dimensional Fourier analysis is performed, an image that shows the relationship between frequency and wavenumber is produced [14]. This technique is commonly used to quantify the interaction of lamb waves with defects [15]. Phase velocity dispersion relations are often more useful but are harder to obtain experimentally, although authors have obtained them using opto-acoustics [16]. The same process is applied to the defective plate experiment, results of which are presented in Figure 4. The results are given in power (dB). In the case of the kissing bond, the reference is the maximum value taken from the non-contaminated recording. In the case of the defective plate, the maximum value from the edge enhanced direction dispersion is used.

Returning to the uncontaminated kissing bond, two modes are visible, A_0 at the top and S_0 at the bottom. The A_0 mode is the most predominant. Both modes are centred around the 700 kHz-800 kHz frequency range which is the bandwidth of the excitation waveforms. The same is true for both the dispersion relations in Figure 4.

There is a significant loss of energy in the A_0 mode when a contaminant has been introduced into the kissing bond. Either the contaminant has absorbed the A_0 entirely or there has been general attenuation of signals and a mode conversion has taken place from A_0 to S_0. By comparing with the dispersion relation of a known good joint, it has been shown the the bond is defective.

In the defective titanium sheet (Figure 4), A_0 and S_0 modes can also be found. In the top image, guided waves have been excited toward the edge and thus away from the defect. Although the enhancement direction is away from the defect there is some small reflection from the residual energy propagating in the opposite direction. The modes are not complete in the edge direction, there is some loss of both modes at 700 kHz. When the guided waves are directed toward the defect, a 10 dB increase of A_0 and a 5 dB increase in S_0 is observed. From this magnitude increase it can be deduced that this is the direction of the defect.

Further investigation of the kissing bond dispersion might indicate more about the defect to the engineer. The exact cause of loss of the A_0 mode attenuation might become apparent if a multi-layer dispersion relation were acquired from the overlap of the two materials. Phase velocities might also pertain to the composition of the inclusion.

The method used here for the inspection of the bond requires knowledge of the dispersion relationship of a known good bond for comparison. Alternatively, the dispersion of the guided waves prior and post entry to the bond may be compared to identify a flaw.

With the defective titanium plate, computational limitations meant that only 8 pressure loads were applied to the material. This achieved a 10 dB increase in power when directed toward the defect. Practically, it's feasible that this increase will be significantly larger. Modern transducer arrays often contain 64 or more elements and it has been shown in prior work that the recursive feedback scheme's ability to direct guided waves improves as more elements are used [8].

IV. Conclusion

The suitability of guided waves for the inspection plate like structures is well known. Lamb waves, a form of guided waves are the most useful. They consist of multiple modes of oscillation, each one behaving and interacting with defects differently. Control of propagation direction and mode is possible with a wedge transducer or an array probe. However, this requires knowledge of the material's dispersion relation which may not be known.

Recursive feedback is a scheme that allows propagation direction to be controlled without full knowledge of the specimen's parameters. In recursive feedback, the first element of an array is excited. Simultaneously the adjacent element records the shear component of the propagating wave. In the next iteration, this recording is transmitted in conjunction with the initial excitation of the first. The 3rd element records. This process is continued until all elements in the array are transmitting. The effect is that guided waves travel in the direction of the array's spatial influence.

In this work, recursive feedback has been applied to the inspection of two specimens. The first was a kissing bond, a cured epoxy joint between two aluminium sheets. The kissing bond was compared with an otherwise identical joint with an inclusion of castor oil. The second application was a titanium sheet with a blind hole defect.

In both applications, the dispersion relation was acquired from an FEA tool. Out of plane displacements across at a number of points were recorded. Two dimensional Fourier analysis is then undertaken to find the frequency-wavenumber dispersion relation.

For the defective plate, dispersion relations are acquired from the transmitting excitation area. The guided waves reflect off the defect and back over the transducer. The scheme enhances in each direction and the dispersion relations are compared. Since there was a 10 dB increase in reflected power from one direction, it is deduced that this is the direction of the defect.

With the kissing bonds, guided waves are generated in the bottom plate and they propagate through the bond into the top plate. Dispersion relations are acquired from the out of plane displacements on the top surface. The contaminated and un-contaminated bonds are compared. Attenuation of the A_0 mode has occurred, but may possibly have converted to S_0 as there is still some energy present here. Further work might involve comparing dispersion relations acquired at different parts of the joint; before the joint and at the multi-layer overlap.

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