Feasibility of Detection of Simulated Defects Using Guided Ultrasonic Waves

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Abstract- This Research work evaluates the ability of ultrasonic guided waves to detect several types of defects in cylindrical structures with different pre-selected wave modes. It will also demonstrate ultrasonic guided wave method [1& 2] as an alternative to standard ultrasonic techniques and how to address their deficiencies. This approach is based on the use of ultrasonic guided waves.

In this work the use of ultrasonic guided waves for thickness mapping of large, partially accessible areas was investigated.

The problem of interest is to evaluate the minimum remaining plate thickness over a large area. Guided waves [3 & 4] have multiple properties that can be used for thickness mapping over large areas.

Firstly, the dispersive nature and variation of the phase velocity as a function of the frequency thickness product of guided waves [5 &6] make them potentially suitable for thickness mapping by time-of-flight tomography and diffraction tomography based on the variation of the velocity in the in homogeneities [7] . The experimental result was validated with FE (Finite Element) profile to arrive at the conclusion.

Diffraction tomography can reconstruct a map of the velocity from the scattered field produced by the interaction of an incoming wave field and a velocity in homogeneity. It has been shown that Diffraction tomography with low frequency guided waves can be used for thickness reconstruction of plates or large diameter pipes.

Low frequency guided waves can be used for thickness reconstruction of plates or large diameter pipes. It has been shown that the scattering from the array of transducers needs to be minimized in order to reconstruct thickness accurately. However when the scattering from the array of transducers is large it is possible to use guided wave diffraction tomography in a structural health monitoring approach and obtain accurate thickness reconstruction.

Keywords: Guided Waves, Frequency, Tomography

I. INTRODUCTION

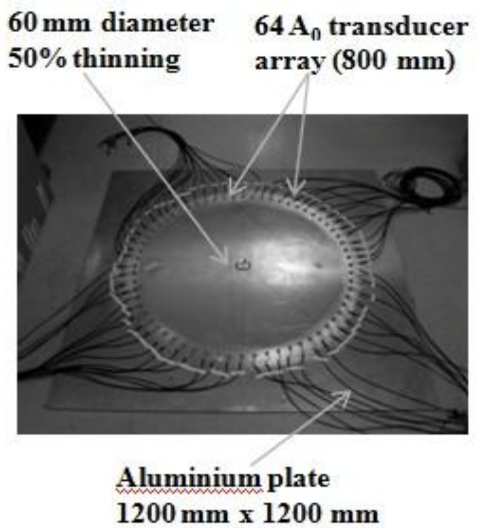
Time-of-flight tomography [8, 9 & 10] is based on straight ray propagation [13], thus ignoring diffraction effects. Straight ray theory is not valid when using low frequency guided waves to detect and size, defects of 60 mm diameter over a propagation distance of approximately 1 m. Straight ray tomography and diffraction tomography [14, 15 & 16] are equivalent when the wavelength approaches zero [17]. In contrast with the time-of-flight straight ray tomography algorithms [11 &12] which reconstruct the thickness from time-of-flight projections, the input to a diffraction tomography algorithm is the wave field scattered by the defects to be imaged.

The practical implication of low frequency guided wave diffraction tomography [18 &19] for the reconstruction of thickness in a plate containing multiple thickness reductions using a circular array of transducers has been considered. The reconstruction is based on the scattering due to the change in velocity of a guided wave mode during propagation through thickness changes. There are two different possibilities to deal with the incident field subtraction of the Born approximation [20]: the so-called structural health monitoring approach and a novel approach which does not require the incident field subtraction.

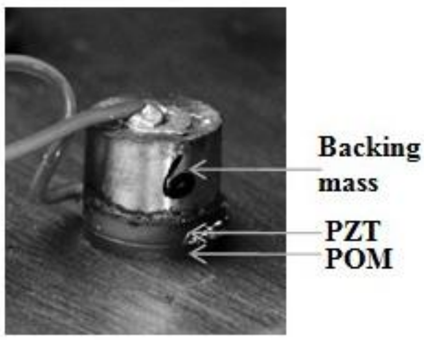
II. EXPERIMENTAL SETUP

The experimental setup presented in figure 1 (a) comprised a 1200 × 1200 × 10 mm aluminium plate with 64 low frequency A0 (Zero order anti symmetric) transducers bonded across a diameter 800 mm. The transducers (figure1 (b)) were developed to excite the A0 mode at low frequency with excellent mode purity. Each transducer has three layers: a thin layer of polyoxymethylene plastic (POM) bonded on the surface of the plate, a piezoceramic element and a brass backing mass. The POM layer and the backing mass are used to decrease the resonance frequency and helps to obtain good transduction at low frequency. The POM layer also has the advantage of decoupling the out-of- plane and in plane displacement of the piezoceramic element and transmitting mainly the out-of-plane displacement to the plate. Further details on the design of these transducers are given in where it is reported that the ratio of A0 to S0 (Zero order symmetric) is more than 30 dB in the frequency range of interest. The diameter of the transducers is 10 mm which corresponds to approximately λ/4 for A0 at 50 kHz and ensures that a point source is a reasonable approximation.

For each transducer the frequency response function (FRF) between the input signal and the out-of- plane displacement was measured on top of the backing mass with a Polytec laser vibrometer. Although all transducers were assembled and bonded on the plate in exactly the same way, some variability was observed. Figure 2 presents (a) the amplitude and (b) the phase of these FRFs between 40 and 60 kHz. At 50 kHz the maximum amplitude difference between the transducers is approximately 15 dB and the maximum phase difference is 30 degree. These FRFs were used in the experimental reconstruction to compensate for the phase and amplitude difference between each transducer. This is to ensure that each transducer is exciting with the same amplitude and phase. The transducers were bonded on the plate with a position error of approximately ±2 mm.

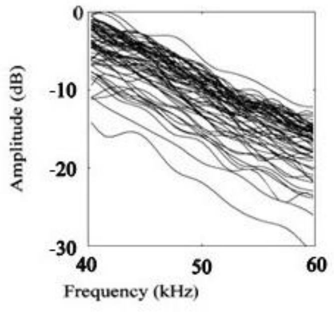


(a)

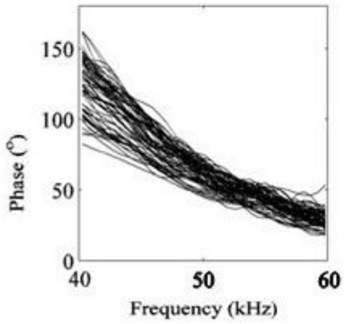


(b)

Figure 1 : (a) Photograph of the experimental setup with a single defect in the centre of array. (b) Zoom on one of the transfer composed of three layers : a backing mass, a piezoceramic element (PZT) and a layer of polyoxymethylene plastic (POM).



(a)



(b)

Figure 2 : Frequency response functions between the input to the transducer and the displacement measured on top of the transducer for the 64 transducer of the array. (a) Amplitude normalized to maximum in dB and (b) phase in degrees.

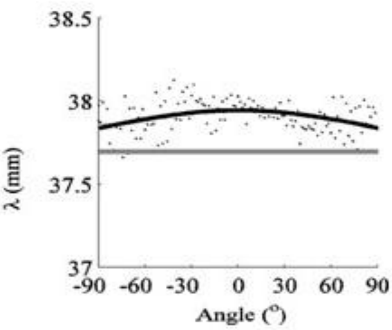


Figure 3 : Variation of the wavelength of the A0 mode in the plate as a function of the angle of propagation in degrees. The black line corresponds to a polynomial t of the wavelength measured (black dots) on the plate and light grey line corresponds to the theoretical value of the wavelength for this type of aluminium.

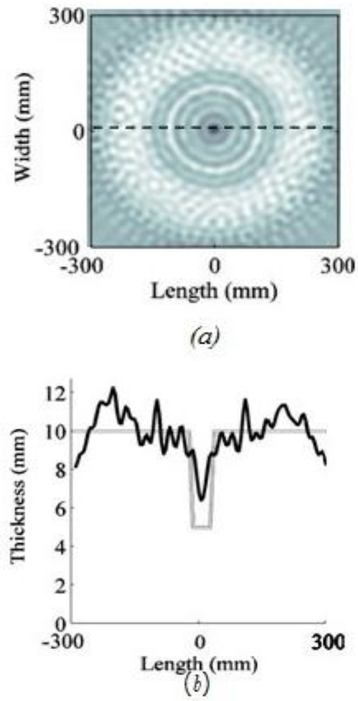


Figure 4 : Experimental polychromatic diffraction tomography reconstruction between 45 and 55 kHz with one thickness reduction at the centre of the array and using only the transmission data of the total field (a) Map of the reconstructed thickness and (b) thickness profile across the defect. The black line corresponds to the reconstructed thickness profile and the grey line to the actual thickness profile.

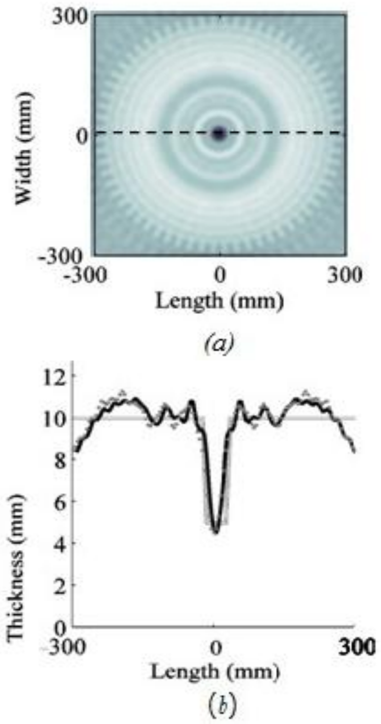


Figure 5 : Experimental polychromatic diffraction tomography reconstruction between 45 and 55 kHz with one thickness reduction at the centre of the array and using only the transmission data of the total field (a) Map of the reconstructed thickness and (b) thickness profile across the defect. The measurement is carried out with a Polytec laser vibrometer.

The wavelength was measured as a function of the angle of propagation. The wave- length was obtained by measuring the phase change between two concentric semicircular arcs separated by 50 mm at multiple frequencies between 45 and 55 kHz. Figure 3 presents a polynomial fit (black line) of the wavelength at 50 kHz measured experimentally (black dots) as a function of the direction of propagation.

The variation of the wavelength as a function of the angle of propagation is approximately ±0.2% compared to the mean value which is 0.5% above the theoretical value for this type of aluminium.

In this study the variation of the wavelength with the angle of propagation was not taken into account but the mean of the measured wavelength was used in the algorithm.

III. EXPERIMENTAL RESULTS

Figure 4 presents an experimental polychromatic reconstruction between 45 kHz and 55 kHz with one thickness reduction in the centre of the array when only the transmission data of the total field is used in the reconstruction, the thickness reduction having a diameter of 60 mm and 50% deep. The reconstruction is not satisfactory; there are multiple large artefacts with some of them going above 12 mm. Moreover the depth of the thickness reduction is not accurately reconstructed. It was found that the poor reconstruction in this case is due to scattering from the array of transducers. The incident field interacts with each individual transducer and produces a wave field that superposes with the scattered field from the defect to produce large artefacts in the reconstruction.

In order to confirm that the large artefacts are due to the scattering of the array of transducers, all but one of the transducers were removed from the plate. When there is a single defect in the centre of the array of transducers the scattered field is the same for all source locations because of symmetry. Hence all the data required can be generated from a single source location and 32 sensor locations. The signal at the 32 sensor location was measured with a Polytec laser vibrometer. In this case there is no variation in the coupling of the transducer because all the data is generatedfrom a single source location. In the reconstruction the defect location, size and depth are accurate. In the thickness profile the grey dotted line corresponds to the FE reconstruction using the same parameters. The FE and experimental profile are almost perfectly superposed. Therefore the artefacts in the reconstruction of figure 4 were due to the array of transducers.

Figure 5 presents Schematic of the measurement for a single defect in the centre of the array taking advantage of the symmetry of this case with one source location and 32 sensor locations measured with a Polytec laser vibrometer.

The black line corresponds to the experimental reconstructed thickness profile, the grey dotted line to the FE reconstructed thickness profile and the grey line to the actual thickness profile. From the amplitude of the recorded wave field, it was observed that this variation was up to 8 dB. The variation in the coupling of the source was not compensated for in the reconstruction.

The experimental reconstruction is very similar to the FE reconstruction. In the thickness profile the grey dotted line corresponds to the FE reconstruction using the same parameters. Once again the FE and experimental profile are almost identical. This therefore demonstrates that it is possible to reconstruct the thickness of a plate with low frequency guided waves by using only the transmission data of the total field when there is no scattering from the array of transducers.

IV. DISCUSSION

Diffraction tomography can reconstruct a map of the velocity from the scattered field produced by the interaction of an incoming wave field and a velocity in homogeneity. The velocity in homogeneity has the same properties as the background medium except a different propagation velocity. Although a corrosion patch does not have all the same properties as a clean plate, this concept can be applied to guided waves if the point of operation, frequency and guided wave mode are carefully selected.

It has been shown, with FE simulations and experiments, that low frequency guided waves can be used for thickness reconstruction of plates or large diameter pipes with diffraction tomography within the Born approximation. Multiple defects of diameter as small as 50 mm were accurately detected and sized in FE simulations. It has been demonstrated that anapproximation of diffraction tomography within the Born approximation can be obtained by using only the transmission data of the total field. This is potentially very useful as thickness can be reconstructed over a large area of a plate or large diameter pipe from a single measurement of the total field. It has been shown that the scattering from the array of transducers needs to be minimised in order to reconstruct thickness accurately. However when the scattering from the array of transducers is large it is possible to use guided wave diffraction tomography in a structural health monitoring approach and obtain accurate thickness reconstruction.

Non contact transducers such as EMATs [20 & 21] could potentially be used instead of the bonded piezoelectric devices used here. They would generate less scattering and should therefore improve the diffraction tomography thickness reconstruction.

V. CONCLUSIONS

It has been shown, with FE simulations and experiments, that low frequency guided waves can be used for thickness reconstruction of plates or large diameter pipes with diffraction tomography within the Born approximation. Multiple defects of diameter as small as 50 mm were accurately detected and sized in FE simulations in a 10 mm plate. It has been demonstrated that an approximation of diffraction tomography within the Born approximation can be obtained by using only the transmission data of the total field. This is potentially very useful as thickness can be reconstructed over a large area of a plate or large diameter pipe from a single measurement of the total field. It has been shown that the scattering from the array of transducers needs to be minimised in order to reconstruct thickness accurately. However when the scattering from the array of transducers is large it is possible to use guided wave diffraction tomography in a structural health monitoring approach and obtain accurate thickness reconstruction.

VI. SUGGESTIONS FOR FUTURE WORK

A considerable amount of work is required before implementing diffraction tomography in the field. In the experimental implementation of guided wave diffraction tomography, the scattering from the array of transducers was shown to generate large artefacts in the thickness reconstruction. Non contact transducers such as EMATs could potentially be used instead of the bonded piezoelectric devices used here. They would generate less scattering and should therefore improve the diffraction tomography thickness reconstruction. Electromagnetic acoustic transducer (EMAT) is a transducer for non-contact sound generation and reception using electromagnetic mechanisms. EMAT is an ultrasonic nondestructive testing (NDT) method where couplant is not needed since the sound is directly generated in the material underneath the transducer. Due to this couplant free feature, EMAT could particularly be useful for the NDT applications of automated inspection in hot and cold environments.

EMAT may be an ideal transducer to generate Shear Horizontal (SH) bulk wave mode, Surface Wave, Lamb Wave and all sorts of other guided wave modes in metallic and ferromagnetic materials.

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