AIR-COUPLED ULTRASONIC TRANSDUCERS FOR THE DETECTION OF DEFECTS IN PLATES

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INTRODUCTION

In order to minimise the problems due to the acoustic impedance mismatch between solids and air, the non destructive testing of materials using ultrasonic transducers generally requires either contact transducers or immersion transducers to be used [1]. Air-coupled transducers however would be very advantageous for testing structures which must be not contaminated with couplant and also for all in-situ industrial applications. Although the propagation of ultrasonic waves from laser generation [2] involves air-coupling, the difficulties due to the experimental set-up of this technique and the financial investment it implies are two major disadvantages.

Recently, air-coupled capacitance transducers have been used to generate and detect ultrasonic waves in solids [3]. In parallel, piezoceramic air-coupled transducers have been made using a 1-3 composite design [4]. These are used in the project described by this paper, in order to do single sided material inspection. Because of the large acoustic impedance mismatch between air and solid materials these transducers do not allow normal incidence pulse-echo inspection. Nevertheless, they can be used for the generation and detection of Lamb waves, the receiver being outside the field of the specular reflection. The interaction of such waves with defects in the structure leads to reflection, transmission and mode conversion phenomena which constitute an important basis to develop non destructive techniques [5-6].

This paper presents a study of the generation of Lamb waves in plates from a finite air-coupled transducer, the interaction of these waves with defects, and their detection using an air-coupled receiver. Both short and long range testing are investigated for different kinds of defects like cracks and delaminations.

EXPERIMENTAL DESIGN

Air-coupled transducers

The air-coupled transducers used in this project are made of piezoceramic rods embedded in a polymer. Adjusting the ceramic / polymer volume fraction allows the mechanical impedance of the transducers to be controlled. It has been found [4] that the transducer is most efficient as a transmitter if it is operated at its electrical resonance and that it is most efficient as a receiver if it is operated at its mechanical resonance. Therefore, the two

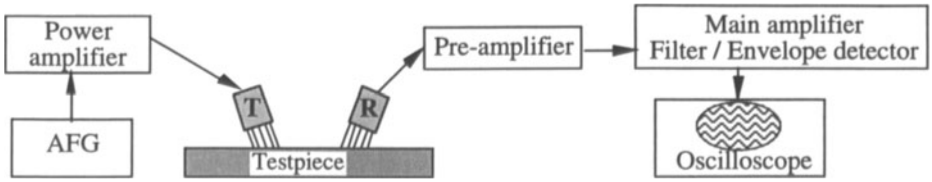

Figure 1 Experimental set-up.

transducers are slightly different, the electrical resonance of the transmitter matching the mechanical resonance of the receiver. Two pairs of transducers have been made : two of them are circular transducers of 30 mm in diameter and the others are 15 mm square transducers.

Experimental set-up

The utility of these 1-3 composite air-coupled transducers is improved by the use of purpose built receiver electronics. A pre-amplifier with a 800 $\mathrm{pV}/\sqrt{\mathrm{Hz}}$ input spectral noise density, an input impedance of 7 kΩ and a bandwidth of 6 MHz has been designed for this project. Also, a special detector unit has been built to process the signal from the receiver comprising a high gain amplifier, a band pass filter and an envelope detector. More details about this equipment can be found in reference [4]. The transmitting transducer was driven from an arbitrary function generator (AFG) connected to a 50 dB power amplifier, the input signal being an 8-cycle 0.57 MHz toneburst enclosed in a Hanning window. Fig. 1 displays the experimental set-up. A rig which allows very accurate angular positioning of the transmitter and receiver has been constructed. Each transducer can be set independently at any angle between 0° and 50° with an accuracy of better than 0.2°.

EXCITATION, PROPAGATION AND DETECTION OF LAMB WAVES

Model

The excitation and detection of plate waves with finite ultrasonic transducers is based on the coincidence principle [7] which defines the optimum angle of both the transmitter and the receiver. This principle can be written as

$$\theta_m = \sin^{-1}\left(\frac{c_{air}}{c_m}\right) \tag{1}$$

where c_{air} is the phase velocity in the coupling medium (which will be air in our case) and c_m the phase velocity of the Lamb mode m. The configuration of the system is shown in Fig. 2. The transmitter applies a pressure to a local area on the top of the plate. In a first approximation, the incident acoustic beam is assumed to be a collimated beam. The force distribution which is applied onto the plate is calculated from the change in phase of the acoustic rays travelling from the transmitter and using a spatial window to model the amplitude variation over the face of the transducer. The excitation signal is a toneburst enclosed in a Hanning window. The response of the plate to such an input is computed by a 2-D finite element (FE) model [8] which calculates the displacements of every point of the mesh that defines the plate, as a function of time. This program allows different types of defect in the structure to be modelled. The displacements of the plate at points in the "field of view" of the receiver were monitored, the received signal being the integration over the face of the receiver of the plane waves which constitute the collimated beam travelling from the plate. The same spatial window as that used for the transmitter is employed to model the variation in the sensitivity of the receiver across its face.

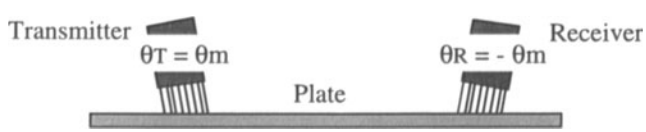

Figure 2 Generation and detection of Lamb waves with air-coupled ultrasonic transducers.

Validity of the transducer model

One stage of this work was to check the efficiency of a collimated beam weighted by an ideal spatial window (Gaussian or Taper window) to model a real transducer. The beam profiles of the available air-coupled transducers have been measured as described in [9]. Fig. 3 shows the results, together with the idealised Gaussian and tapered profiles which were investigated. Firstly, the measured pressure distribution of the 15 mm transducers (Fig. 3a) has been used directly as the input for the FE model. The excitation signal was an 8-cycle toneburst with a centre frequency of 0.57 MHz enclosed in a Hanning window. The transducer was oriented at either 3.8° or 9.7° to launch a pure mode s_0 or a_0, respectively. For these two configurations, the generated Lamb wave resulting from this input was compared with those generated from the collimated beam input weighted by the different ideal spatial windows. The receiver was not considered in this study and only one single point on the top of the plate was monitored. In all cases, there was no significant change in the shape of the calculated waveforms as a result of using a collimated beam with idealised spatial window in the model. This demonstrated that idealised beam patterns could be used in this work. The reason for the lack of sensitivity of the results to the precise beam pattern is illustrated in Fig. 4b which shows the excitation zone obtained when the transducer was set up to excite the s_0 mode. The s_0 mode is excited by the centre of the main lobe of the angular spectrum produced by the transducer, and the a_0 mode could only be excited by side lobes. The amplitude of the side lobes is very small with the experimentally measured beam profile and with both of the idealised profiles so it makes little difference which is used in the predictions ; the results presented here were obtained with a Gaussian window. If a piston-like beam profile were to be used, the side lobes would be larger and could give significant a_0 generation. Also in this case the main lobe amplitude reduces more rapidly with angle than with the other profiles, so the s_0 amplitude would be a stronger function of angle. The directivity pattern of the receiver transducer has not been measured, but since its construction was similar to that of the transmitter, it is reasonable to assume that its directivity pattern will be similar. Therefore the same idealised Gaussian profiles were used for the transmitter and receiver.

RESULTS

Dispersion curves

The excitation and detection of plate waves using ultrasonic transducers first of all require careful consideration of the dispersion curves of the Lamb waves which can be excited and detected in the frequency range corresponding to the transducer bandwidth. In our case, the air-coupled transducers have a narrow frequency bandwidth centred on 0.57 MHz. Fig. 4 shows the dispersion curves for a 1.6 mm thick aluminium plate. Fig. 4a shows the group velocity versus the frequency and shows that only two modes (s_0 and a_0) can be launched in the plate using a 0.57 MHz centre frequency transmitter. Fig. 4b which plots the coincidence angle versus frequency indicates that the angle of the transducers should be ±3.6° and ±8.6° to excite and to detect s_0 and a_0, respectively. These values are smaller and closer together than those for water coupling for which θso and θao would be 16° and 40°, respectively.

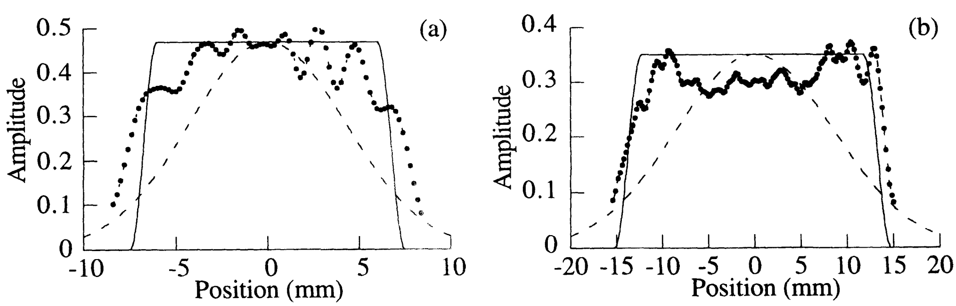

Figure 3 Experimental beam profiles of air-coupled transducers and their modelling ; (-•-) Experimental beam profile, (—) Taper window, (- - -) Gaussian window ; (a) 15 mm square transducers, (b) 30 mm diameter transducers.

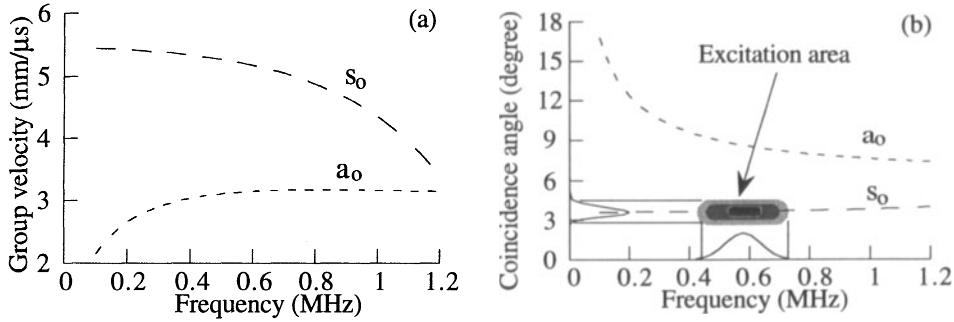

Figure 4 Dispersion curves for the Lamb modes s_0 (– – –) and a_0 (- - -) in a 1.6 mm thick aluminium plate and the angular and frequency excitation zones; (a) Group velocity, (b) Coincidence angle.

This means that it might be more difficult to generate and to detect a pure mode using air-coupling rather than using water-coupling. However, the effective angular aperture of the transducers is very small in air which helps the generation of a pure mode but also makes the set-up very sensitive to the transmitting and receiving angles.

Sensitivity to the angle

Since the angular alignment of the transducers is likely to be critical, the effect of a small error in the orientation of the transducers with respect to the plate was investigated experimentally. In this study, the transducers were set up at the appropriate angles for the generation and detection of the mode of interest and the effect of rotating the plate was investigated as shown in Fig. 5a. This work was done for both the s_0 and a_0 modes propagating in a 1.6 mm thick aluminium plate. Fig. 6 presents the change in the amplitude of the received waveforms of the modes s_0 and a_0 due to a rotation of the plate of 0.6°. Figs. 6a and 6b are the numerical predictions while Figs. 6c and 6d are the experimental results. In the numerical predictions, the excitation signal was an 8-cycle Hanning windowed 0.57 MHz toneburst while experimentally, a 20-cycle Hanning windowed toneburst of the same centre frequency was used. The interest in using a narrow band signal for the experiments is to improve the signal to noise ratio [4]. However, the experimentally detected waveforms contain more than twenty cycles because the transducers are resonant. Nevertheless, the agreement between the predictions and the experiments is very satisfactory and the results clearly show the sensitivity of the amplitude of the Lamb waves to the angular orientation of the plate. A change of ±0.6° in its orientation reduces the amplitudes of the waves by about 50%. Therefore, it appears that air-coupling requires the experimental angular set-up to be very accurate.

Also these results show that the signal to noise ratio is much better for the mode a_0 (Fig. 6d) than for the s_0 mode (Fig. 6c). This is simply due to the fact that a_0 is mainly an out-of-plane sensitive mode at this frequency-thickness product while s_0 is in-plane sensitive. Therefore, the a_0 mode is easier to generate and to detect and so is more appropriate than the s_0 mode for non-destructive testing of structures around 1 to 3 mm thick using these air-coupled transducers.

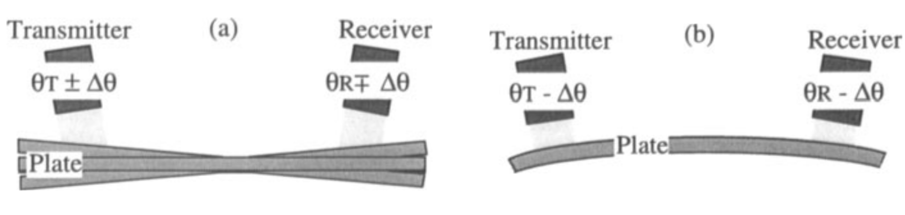

Figure 5 Misalignment of the transducers due to (a) rotation of the plate ; (b) bending of the plate.

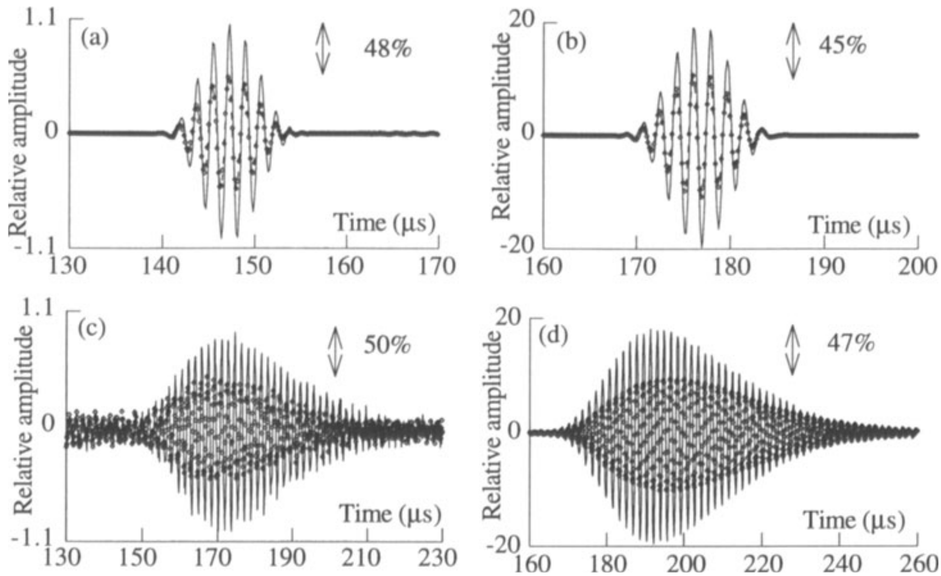

Figure 6 Effect of rotation of the plate on the amplitude of the Lamb modes ; (a) Predicted s_0, (b) Predicted a_0, (c) Measured s_0 and (d) Measured a_0 ; — horizontal plate, ○○○ plate rotated by 0.6°.

A likely practical scenario is the inspection of a structure which is slightly curved as shown in Fig. 5b. As an example, a radius of curvature of 8 meters in the plate produces an angular error of $\Delta\theta = 0.6^\circ$ for both the transmitter and the receiver if the two transducers are 160 mm apart. In such a situation, numerical predictions indicate that the amplitude will be reduced to about 50% of its value when the structure is flat and the transducers are correctly aligned.

NDT APPLICATIONS

Several different transducer configurations can be used in Lamb wave inspection, two of which are illustrated in Fig. 7. The receiver can be oriented to receive reflected waves coming from a defect in the path of the transmitted beam (Fig. 7a), or to receive waves transmitted past a defect (Fig. 7b). In each case, the receiver can be oriented to detect either the mode generated by the transmitter or another mode which would be produced by mode conversion at a defect. These options allow the transducers to be remote from the defect so that a significant area of structure is inspected from a single transducer position. Another possibility is to fix the transmitter and receiver as close together as possible while keeping the receiver out of the field of the specular reflection from the plate surface, and to scan the assembly over the structure, so producing a C-scan output. This is likely to produce better definition of the shape of a defect such as a delamination, but will be much slower than the other options which do not require such fine scanning.

Detection of cracks

A study was carried out to determine the best testing configuration for crack-like defects. The test specimens used were a set of 3 mm thick steel plates with different depths of notches in their bottom surfaces. Notch depths of 0.5, 1.0, 1.5 and 2.0 mm were tested, the notches being 0.5 mm wide and extending across the full width of the plate. Since it is easier to launch experimentally (see previous section), the incident mode was an a_0 Lamb mode. The excitation was again a 0.57 MHz toneburst enclosed in a Hanning window and the transmitter was a 30 mm diameter transducer oriented at the coincidence angle of 7.4°. Although the incident mode was again an a_0 mode, the incident angle was different than that used in previous section due to the change in the frequency-thickness product. The receiver was also

Figure 7 Different configurations investigated for the detection of cracks ; (a) Reflection configuration, (b) Transmission configuration.

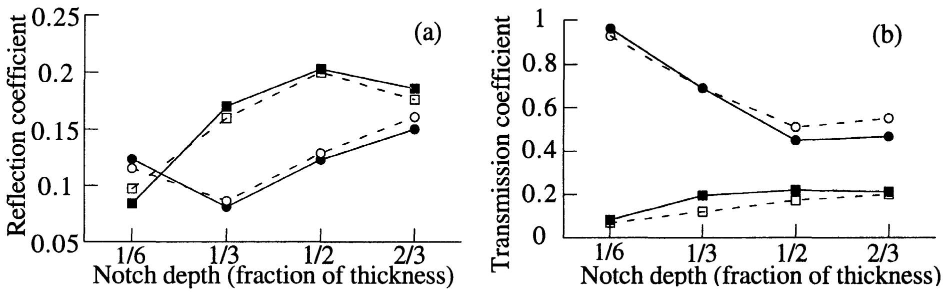

Figure 8 Reflection and transmission coefficients of an incident a_0 mode meeting a notch in the bottom of a 3.0 mm steel plate, as a function of the depth of the notch ; (a) Reflection coefficient, (b) Transmission coefficient ; —●— predicted a_0, - ⊖ - measured a_0, —■— predicted s_0, - ⊟ - measured s_0.

30 mm in diameter but its angle was varied according to the mode which was to be detected (a_0 or s_0).

Figs. 8a and 8b show respectively the reflection and transmission coefficients of the incident a_0 mode after interaction with the various notches. The numerical predictions are in very good agreement with the measurements. By mode conversion of the incident a_0 mode, the cracks lead to reflected and transmitted s_0 modes which have big enough amplitudes to be detected. The reflection configuration is preferable since there is always the risk that the transmitter will not generate a pure a_0 mode and then a received s_0 mode may be confused with the signal from a defect. The transmission coefficient of the incident a_0 mode is greater than 70% for the two smallest notches (Fig. 8b). In a real test, since such a change in the amplitude could be due to a slight bending or misalignment of the plate, as shown in previous section, measurement of the transmitted a_0 mode cannot be a reliable method to detect small defects. The amplitude of the reflected a_0 mode is always big enough (Fig. 8a) to be experimentally measured. From a general point of view, the reflection configuration is preferable to transmission both because no signal is reflected if there is no defect (except the reflection from the end of the plate) and also because the effect of any bending or misalignment of the plate is reduced by the fact that the receiver is close to the transmitter. A similar conclusion was reached in a study of the detection of delaminations in composite materials using Lamb waves [10].

Another important consideration is the maximum length of plate which can be tested from a single transmitter and receiver position. This depends on the attenuation of the waves in the plate, and also on the dispersion of the chosen mode; if the wave is dispersive, the wave packet spreads out as it propagates, so reducing the maximum amplitude and hence the signal to noise ratio. The results shown in Fig. 8 were obtained with a distance of about 450 mm from the transmitter to the receiver via the defect. In a low attenuation material such as steel or aluminium, this distance could readily be extended to several metres, but this may be more difficult in composite materials where the attenuation will be higher.

Lamb wave scanning for delaminations

A C-scan has been done using the two 15 mm transducers placed closed together in transmission mode as shown in Fig. 9a. The sample was a 1.0 mm thick aluminium plate and

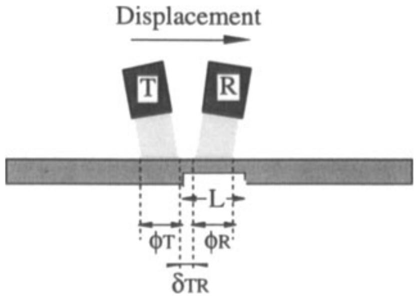

Figure 9a Side view of Lamb wave C-scan over a trough in a 1 mm aluminium plate.

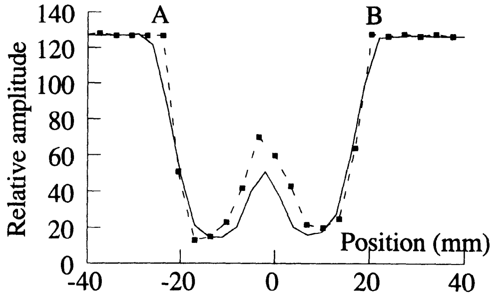

Figure 9b Lamb wave line-scanning over a delamination-like defect ; (—) prediction (–•–) measurement.

the defect was a 20 mm long by 0.5 mm deep trough in the bottom of the plate, which was designed to simulate a delamination. The excitation signal was a 10-cycle, 0.57 MHz toneburst enclosed in a Hanning window and the incident angle was $\theta_T = 9.7^\circ$. The receiver also had a fixed angle $\theta_R = -9.7^\circ$ and was placed as close as possible to the transmitter while remaining outside the field of the specular reflection. The angles of the two transducers were the coincidence angles to launch and to detect an a_0 mode in the plate. These values are greater than those referred to in the previous section where an a_0 mode was propagating in the 3 mm thick plate simply because the plate is now thinner. This system constitutes a scanner which was moved step by step above the plate (Fig. 9a), the variation of the amplitude of the forward travelling a_0 mode being recorded by the receiver at each position, giving a 3D representation of the defect. Since the FE model works in 2D, a slice of this experimental 3D plot has been compared to the numerical predictions of a line-scan over the defect. Fig. 9b shows the change of the amplitude of this mode when the centre of the scanner was displaced by ±40 mm with respect to the middle of the trough. The predicted values have been normalised to the maximum experimental amplitude. The numerical predictions agree very well with the measurements. The magnitude of the change in amplitude is linked to the depth of the defect and the width (AB) of the curve is related to the length of the trough by the relation

$$AB \approx L + \varnothing_T + \varnothing_R + \delta_{TR} = 20 + 15 + 15 + 4 = 54\,\text{mm} \tag{2}$$

where L is the length of the trough, $\varnothing_T$ and $\varnothing_R$ are the diameters of the transducers and δ_{TR} is the distance between the incident and radiated acoustic fields on the surface of the plate, as shown in Fig. 9a. The two large dips on each side of the curves correspond to one of the transducers being exactly above the defect, where the thickness of the plate is 0.5 mm. Then, according to the dispersion curves, the coincidence angle is no longer ±9.7° but ±14° and the generation and detection of the a_0 mode are severely affected when the transmitter or receiver is above this region. For this configuration to be satisfactory, the diameter of the transducers has to be smaller than the length of the defect. The small peak in the middle of the curves corresponds to the middle scanner being exactly above the centre of the defect. In that situation, the two transducers have the same proportion of their "field of view" above the good region of the plate and the received signal is increased. This local maximum would not be seen if the defect was larger than $\varnothing_T + \varnothing_R + \delta_{TR} = 34$mm.

CONCLUSIONS

The generation and detection of Lamb waves propagating in plate-like structures is now possible with air-coupled ultrasonic 1-3 composite transducers. The resonant characteristic of the transducers simply increases the duration of the time history of the modes. This is not a problem for use of the a_0 mode which is dispersive in the low frequency-thickness region investigated, so a small bandwidth reduces dispersion. Moreover narrow band excitation improves the signal to noise ratio.

A numerical method and experimental set-up have been designed to study the detection of defects in plates using air-coupled transducers. In general, the predictions agree very well with the experimental results. The approximation of the transducer input and output by collimated beams weighted by an ideal spatial window is satisfactory to model the generation and detection of a pure mode.

Two Lamb wave techniques for the single sided inspection of plate-like structures have been investigated. The first is a long range test in which the Lamb waves travel a significant distance along the plate from the transmitter before being detected by the receiver. In this case it was shown that a reflection configuration in which the receiver detects waves which are reflected from defects back towards the transmitter is the most satisfactory. It was shown that notches 16.7% of the plate thickness deep can readily be detected in this way.

The second technique was a Lamb wave C-scan over the surface of the plate in which the transmitting and receiving transducers are placed close together. This technique is more time consuming but is complementary to the previous reflection approach since it gives more information about the geometry of the defect. The FE model allows a line-scan to be modelled and then numerical predictions to be compared to a slice of the experimental 3D plot. The correlation between theory and measurements for a line-scan over a delamination-like defect is very good.

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