THE REFLECTION OF ULTRASOUND FROM INTERFACE LAYERS IN ADHESIVE JOINTS

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INTRODUCTION

The detection of a weak adhesive/adherend interface in an adhesive joint is one of the major current challenges in NDE; the lack of a satisfactory non destructive test for this region is retarding the exploitation of the advantages of adhesive bonding in safety critical areas. It is the interface layer which is affected by the common problem of slight contamination due to, for example, grease on the adherend surfaces prior to bonding. The interface is particularly important in aluminium-aluminium joints in which an inappropriate interface structure can cause greatly enhanced susceptibility to environmental attack [1]. Inspection of the interface layer is difficult because it is frequently only of the order of 1μm thick, compared with an adhesive layer thickness of the order of 100 μm.

Many groups have worked on this problem and several workers [see, for example, 2-5] have shown that the ultrasonic reflection coefficient from an interface layer is sensitive to the sort of changes which might be expected in a faulty bond such as a reduction in the shear stiffness of the interface layer. Unfortunately, however, it is generally found that unless SH wave probes, which can generate normal incidence shear waves, are used, the best sensitivity to defects is obtained by monitoring the reflection coefficient at non-normal incidence. Therefore, since the coupling of SH wave probes is difficult, the most likely practical testing configuration is to employ two transducers oriented at the appropriate angle in 'pitch-catch' mode.

In principle this presents no problem if the layer to be inspected is at the surface of the test structure, but this is not the case in an adhesive joint where the crucial layer is embedded under an adherend and, in the case of the bottom interface, the adhesive layer as well. Fig 1 illustrates the problem which is found in a practical inspection. At non-normal incidence, the reflections from an embedded interface due to different combinations of longitudinal and shear wave paths appear at different spatial locations due to the different angles of refraction for longitudinal and shear waves. Therefore, when measurements are carried out with real, finite-sized transducers, the signal received is a function of spatial position. It is therefore necessary to ensure that the receiving transducer is correctly positioned to capture the reflection which is of most interest, the appropriate location being obtained from a simple ray theory calculation. The required reflection coefficient may be estimated by 'focussing' the receiver on the front face reflection from the top of the testpiece and measuring its amplitude

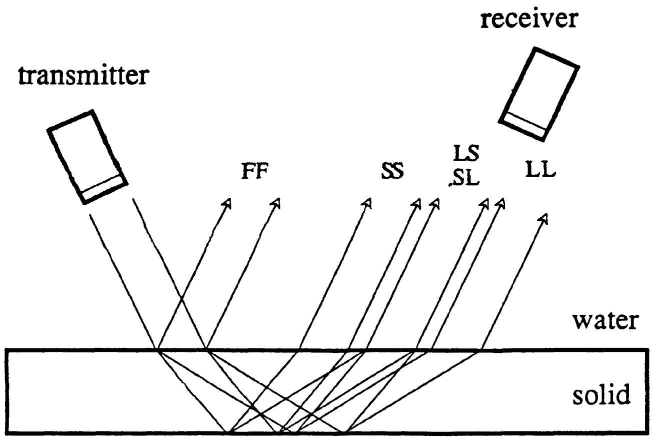

Fig. 1. Schematic diagram of echoes from an embedded interface. FF is front face reflection; LS is longitudinal-shear reflection; SL is shear-longitudinal reflection; SS is shear-shear reflection.

in either the time or the frequency domain; the receiver is then moved to 'focus' on the required reflection from the interface of interest, for example the shear-shear reflection, and its amplitude is measured. If the impedances of the top layer and the coupling medium are known, the reflection coefficient from the top layer can readily be calculated so the required reflection coefficient can be obtained from this and the two measured amplitudes.

However, even if the transducer positioning is carried out perfectly, this procedure still assumes that the ratio of the amplitude of the front face reflection captured by a correctly positioned finite transducer to that predicted for an imaginary infinite transducer is the same as the ratio of the amplitude of the interface reflection captured by a finite transducer to that predicted for an infinite transducer. Beam spreading effects inevitably limit the accuracy of this assumption and it is not certain that the procedure will produce sufficiently accurate comparisons with the predictions of infinite plane wave theory for the subtle changes produced by imperfect interface layers to be quantified satisfactorily. Also, in a practical test, the accuracy required in transducer positioning and orientation must be considered.

This paper describes work which is in progress to address these questions. A program has been written which computes the field produced by a finite sized transmitter at a specified angle and then predicts the field reflected from a testpiece composed of an arbitrary number of layers and hence the response received by a finite sized receiver at any spatial location with respect to the transmitter. Early results obtained with the program are discussed, together with those of confirmatory experiments; the work is continuing and will be reported more fully later.

ANALYSIS

A full description of the analysis would be too lengthy for this paper so only a brief outline is presented here.

Following, for example, Chimenti and Nayfeh [6] and Ngoc and Mayer [7], the field from a finite sized transducer at a given angle is represented by a sum of infinite plane waves at different angles, the decomposition being accomplished via Fourier analysis. The interaction of each of these infinite plane waves with the test structure, which may be composed of an arbitrary number of layers, is then analysed to produce the reflected field due to each wave. The full reflected field is then obtained by summing these components and the output of the receiver is predicted by integrating this field over the area of the transducer. The program operates in two dimensions so the transmitter and receiver are effectively considered to be of infinite extent in the direction normal to the plane shown in Fig 1; the analysis could readily be extended to three dimensions, though at considerable cost in computation time.

RESULTS

Aluminium Plate in Water

The program was first checked on the very simple case of a 4.85 mm thick aluminium plate immersed in water. Fig 2 shows the reflected signal predicted by infinite plane wave theory for an incident angle of 10^0, while Figs 3a and 3b show the corresponding predictions for a 10 mm diameter transducer 'focussed' on the front face reflection and on the coincident longitudinal-shear and shear-longitudinal reflections respectively. The transducer output pulse shape assumed in these predictions was that obtained from the 10 MHz, 10 mm diameter, unfocussed transducer which was used in the experiments. As expected, the predicted fields for the finite transducer are very different from those for the infinite transducer.

Figs 4a and 4b show the experimental results corresponding to the predictions of Figs 3a and 3b. It can be seen that very good agreement has been obtained. Similarly good

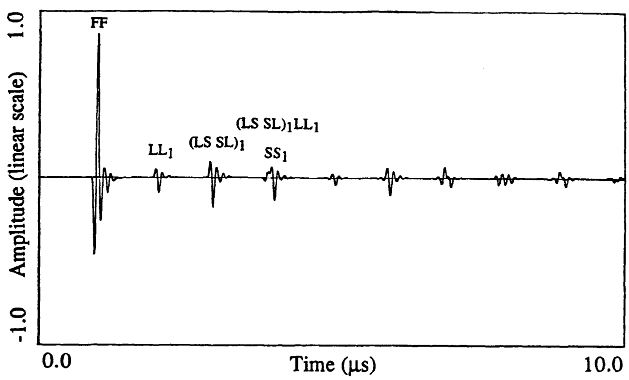

Fig. 2. Predicted response of 4.85 mm thick aluminium plate in water using infinite transducer model. Angle of incidence is 10^0.

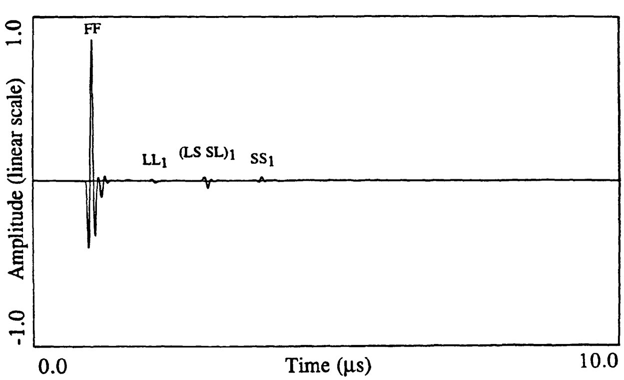

Fig. 3a. Predicted response of 4.85 mm thick aluminium plate in water using finite transducer model with receiver 'focussed' on front face reflection. Angle of incidence is 10^0.

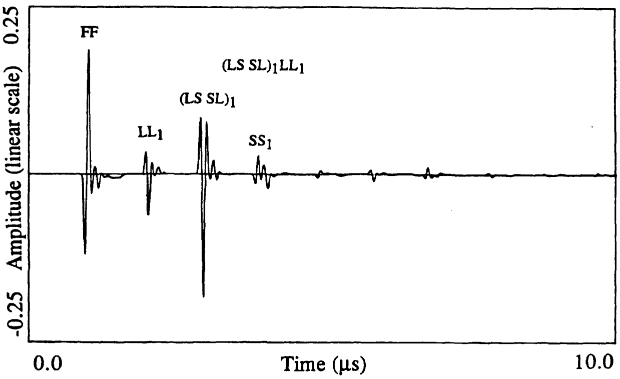

Fig. 3b. Predicted response of 4.85 mm thick aluminium plate in water using finite transducer model with receiver 'focussed' on longitudinal-shear/shear-longitudinal reflection. Angle of incidence is 10^0.

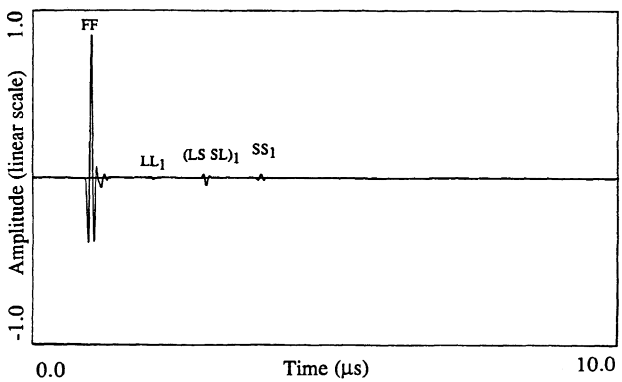

Fig. 4a. Measured response of 4.85 mm thick aluminium plate in water with receiver 'focussed' on front face reflection. Angle of incidence is 10^0.

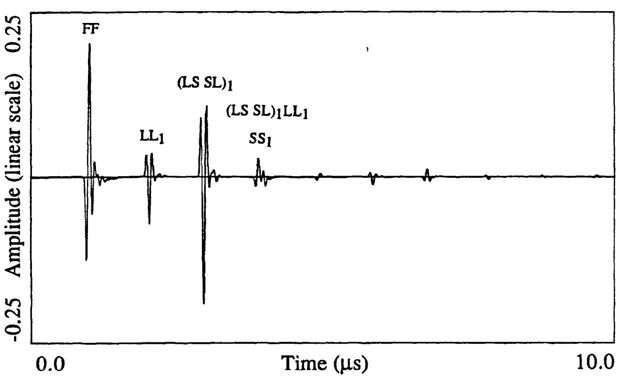

Fig. 4b. Measured response of 4.85 mm thick aluminium plate in water with receiver 'focussed' on longitudinal-shear/shear-longitudinal reflection. Angle of incidence is 10^0.

agreement has also been obtained at other angles of incidence, including angles above the first critical angle.

Glass-Thin Fluid Layer-Glass System

Having shown that the program operated satisfactorily on a very simple system, the next task was to test it on a configuration closer to those of interest in the inspection of adhesive joints. The system chosen was a very thin layer of silicone fluid sandwiched between two 5.9 mm thick glass plates. This fluid layer simulates the case of an extremely bad bond in which, for example, a grease layer is present between the adherend and the adhesive. Glass was used to form the outer layers of the sandwich so that in the confirmatory experiments, the thickness of the fluid layer could be measured by the Newton's rings effect.

Figs 5a and 5b show the predicted received signals for incident and receiver angles of 10^0, with the receiver focussed on the front face reflection and on the longitudinal-longitudinal reflection from the interface layer respectively. In this case, the fluid layer was 0.3 μm thick. Figs 6a and 6b show the corresponding measured results. It can be seen that

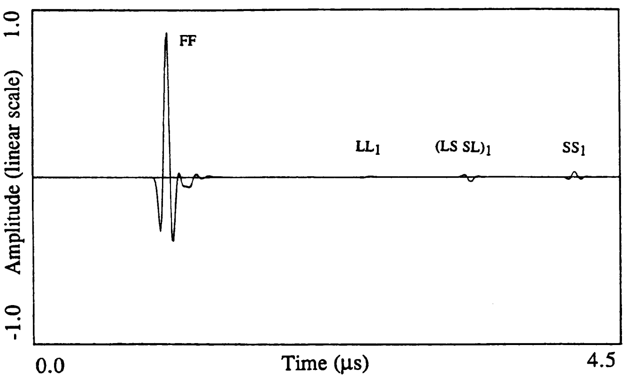

Fig. 5a. Predicted response of glass-silicon fluid-glass sandwich using finite transducer model with receiver 'focussed' on front face reflection. Angle of incidence is 10^0.

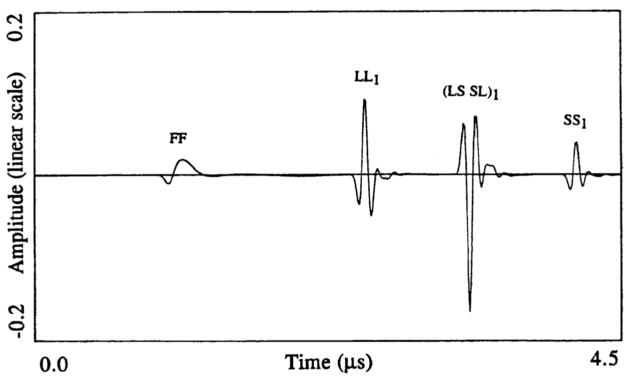

Fig. 5b. Predicted response of glass-silicon fluid-glass sandwich using finite transducer model with receiver 'focussed' on longitudinal-longitudinal reflection. Angle of incidence is 10^0.

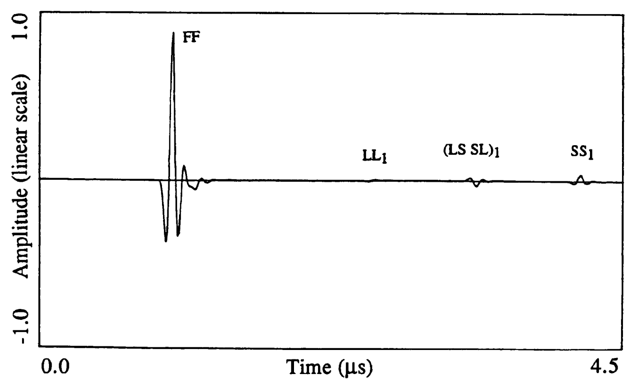

Fig. 6a. Measured response of glass-silicon fluid-glass sandwich with receiver 'focussed' on front face reflection. Angle of incidence is 10^0.

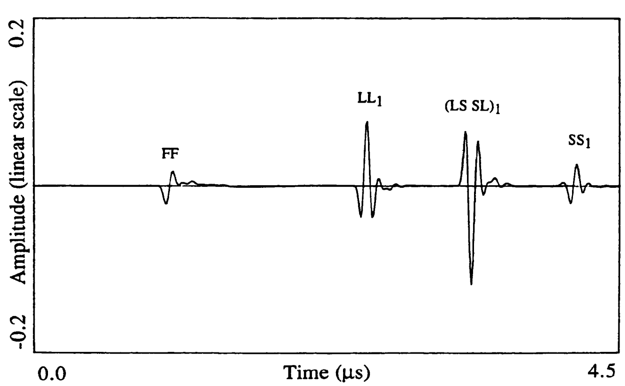

Fig. 6b. Measured response of glass-silicon fluid-glass sandwich with receiver 'focussed' on longitudinal-longitudinal reflection. Angle of incidence is 10^0.

there is good qualitative agreement between the measurements and predictions, though the predicted amplitudes of the reflections from the interface are slightly larger than those measured. This is probably due to uncertainty in the measured layer thickness. The measured front face reflection shown in Fig 6b contains more high frequencies than the predictions of Fig 5b. This is because these initial predictions assumed a Gaussian distribution of displacement over the transducer surface which produces smaller 'sidelobes' than were observed with the real transducer. This effect is most pronounced when the receiver is 'focussed' on the longitudinal-longitudinal reflection since this reflection is spatially farther away from the front face reflection than the shear-shear and shear-longitudinal/longitudinal-shear reflections (see Fig 1). Future predictions will assume a displacement distribution closer to that of a piston source.

CONCLUSIONS

It has been shown that the finite transducer model gives very accurate predictions of measurements made by real transducers in reflection coefficient experiments. It will therefore be valuable in the development of practical testing strategies for adhesive joints since, for example, it will enable the effect of small errors in transducer location or variations in adherend thickness to be quantified, so enabling the selection of test configurations which are sufficiently insensitive to these problems.

The next phase of the work is to compare the reflection coefficients which are predicted by infinite plane wave theory with those obtained by processing the predictions of the finite transducer program when the program is used to represent the experimental procedure described in the introduction above. This will show, for example, whether the use of a finite transducer introduces frequency dependence into the experimentally derived reflection coefficient. The results of these calculations will be reported later.

The program can also be used to investigate the field produced in leaky Lamb and Rayleigh wave experiments [6,8,9] and so will be a valuable tool in the development of these techniques.

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