ADHESIVE JOINT CHARACTERIZATION BY LEAKY GUIDED INTERFACE WAVES

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INTRODUCTION

Ultrasonic inspection of adhesive joints is usually done either by normally incident longitudinal or shear waves or by Lamb modes propagating along the joint, i.e. in the adherend-adhesive-adherend sandwich as a whole. This paper discusses the feasibility of using guided interface waves propagating in the adhesive layer itself for nondestructive evaluation of bond quality. This layer is usually less than 5% of the whole joint, but all defects are expected in this region or on its boundary. True guided interface waves are probably the most sensitive to bond imperfections [1,2], but they are inherently very difficult to generate and detect, therefore we should settle for the second best, namely leaky guided interface waves which lend themselves quite easily to practical applications. The main purpose of this paper is to demonstrate the superior sensitivity of the suggested leaky guided interface wave technique over the more conventional Lamb wave inspection via examples of adhesive joints with different cohesive and adhesive type defects.

LEAKY LAMB WAVE TECHNIQUE

Fig. 1 shows the schematic diagram of leaky Lamb wave inspection of adhesive joints. The frequency spectrum of the double-transmitted signal exhibits distinct maxima corresponding to Lamb mode resonances of the joint at that particular angle of incidence (a detailed description of this technique can be found in Ref. 3).

Dispersive Lamb modes in multiple layer structures, such as an adhesive joint, can be calculated by a number of different numerical techniques. Defects can be modeled as additional layers of reduced rigidity, compressibility, or both. These calculations can be carried out quite easily on digital computers, and the results show that different modes are affected in very different ways by a certain type of defect [4-6]. According to such predictions there exist modes which are very sensitive to a particular defect, but finding these modes and evaluating the Lamb mode distribution in order to characterize the joint, i.e. solving the inverse problem, still remains very complicated. Fig. 2 demonstrates this difficulty through comparing the measured double-transmission spectra of adhesive joints of very different quality and that of

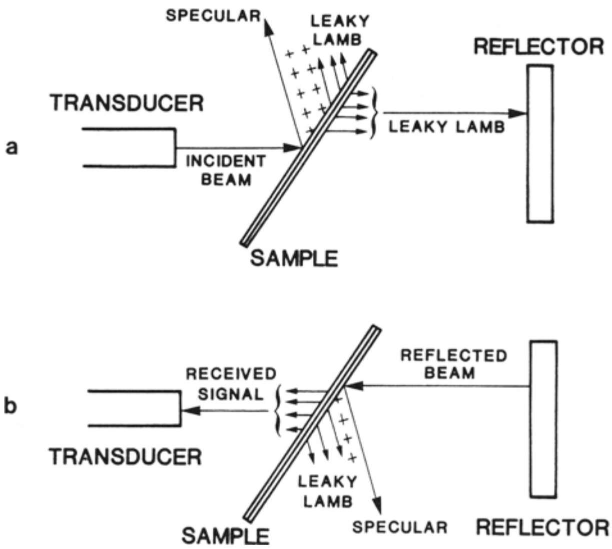

Fig. 1. Schematic diagram of double-transmission leaky Lamb wave inspection of adhesive joints.

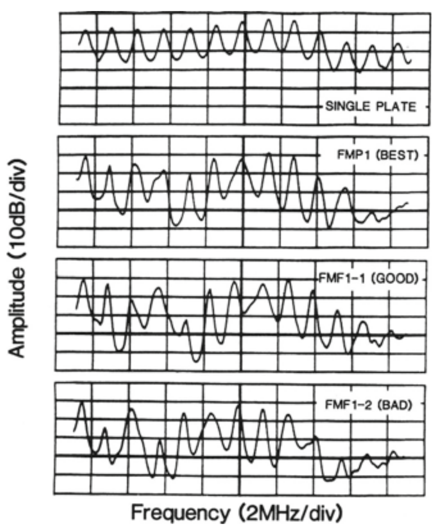

Fig. 2. Double transmission spectra of different adhesive joints and a single adherend plate at 20° angle of incidence.

a single adherend plate at 20° angle of incidence. Although the amplitudes of certain modes are very different, the frequencies are much less affected and the structure is basically the same for all cases including the single adherend plate as well. This indicates that the acoustic coupling between the adherend plates is rather weak partly because the adhesive has considerably lower acoustic impedance than that of the adherend plates, partly because its thickness is far from negligible with respect to the ultrasonic wavelength in it, and, finally, because of the substantial attenuation of the adhesive material. The weak acoustical coupling through an otherwise perfect adhesive layer renders the Lamb wave inspection technique rather insensitive. Since defects can be expected to further reduce the already weak coupling, only the amplitude of these Lamb modes will be affected by minor defects, not their frequency. Naturally, the acoustical coupling becomes stronger at lower frequencies and the joint vibrates more like a double-thickness plate. In this range, the Lamb mode resonant frequencies of the joint are much more sensitive to the overall elastic properties of the adhesvie layer. For instance, the low-frequency part of the Ao mode can be readily used to measure the effective shear modulus of the adhesive layer. At the same time small defects are not fully resolved at low frequencies, therefore we can not take advantage of this stronger acoustical coupling through the adhesive layer for purposes of defect detection and characterization.

LEAKY GUIDED WAVE TECHNIQUE

We found that the feasibility of leaky Lamb wave inspection in adhesive joint characterization is adversely affected by the relatively weak acoustical coupling through the adhesive layer between the adherend plates. There are two related difficulties we must face: (i) the Lamb mode distribution is barely affected by bond defects, and (ii) the amplitudes of different modes are very complicated to evaluate for bond quality. In order to overcome these inherent limitations, we are going to introduce the so-called leaky guided wave technique.

True guided interface waves are not coupled to any of the bulk modes in the surrounding media, therefore they are less suitable for direct NDE applications. One possibility is to use Rayleigh waves propagating along the surface of the adherend plates, which are mode-converted into guided interface waves when going through the joint. This approach was first suggested by Rokhlin, et. al. [2] for adhesive joint characterization and more recently by Simpson [7] for evaluation of braze layers in ceramic joints. A more practical solution is offered by leaky modes having higher phase velocity than the shear velocity of the adherend material. It is well known that leaky Lamb modes in an immersed plate can be readily detected as minima or maxima in the frequency spectra of the reflected and transmitted signals, respectively, at a certain angle of incidence. In a similar way, we can detect leaky guided interface waves in the adhesive layer by measuring, let us say, the shear wave transmission coefficient through the layer.

Fig. 3 shows the schematic diagram of ultrasonic transmission measurement in an adhesive joint. The main problem is that we usually do not have sufficiently thick adherend plates to detect the transmitted pulse without interference from other multiple reflections within the multi-layer structure of the adhesive joint. Fig. 4 shows the double transmitted ultrasonic signals through an adhesive joint and a double- and single-thickness adherend plate, as well, at 20° angle of incidence. The overall structure of the transmitted signal through the adhesive joint is very similar to that of the single-thickness plate. This can be expected for cases of weak acoustical coupling through the adhesive layer, while a

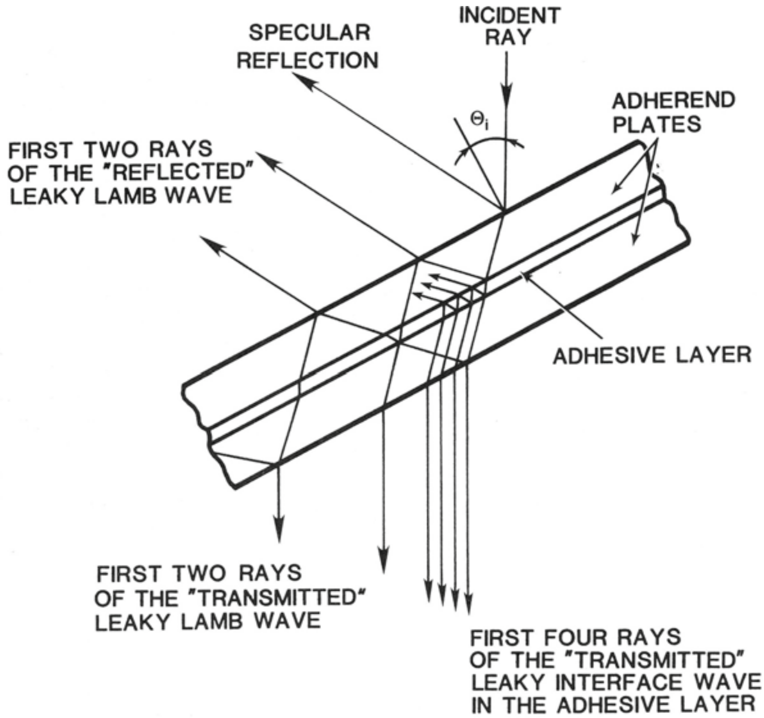

Fig. 3. Schematic diagram of ultrasonic transmission measurements in an adhesive joint.

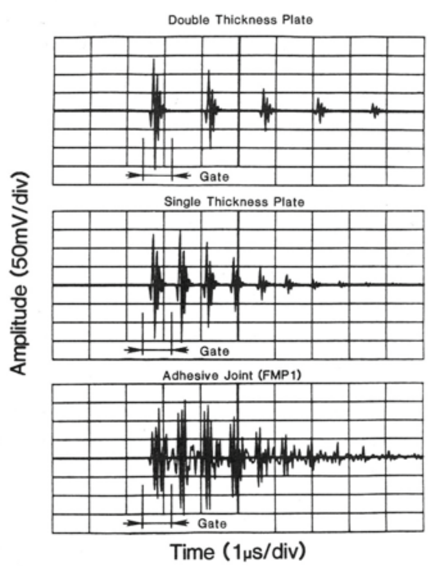

Fig. 4. Double-transmitted ultrasonic signals through an adhesive joint and a double- and single-thickness adherend plate.

very thin, high acoustic impedance, attenuation-free layer would result in a Lamb mode distribution more like that of the double-thickness plate. What is more important now is that the first pulse of the transmitted burst through the adhesive layer includes lagging reradiated components of the leaky guided interface wave, too. Whenever these guided modes are strongly attenuated by leaking energy to the adherend material, the leaky components decay very fast and the first transmitted pulse is fairly well separated from other multiple reflections. Time gating and subsequent spectrum analysis of this first arrival reveals the existence of leaky guided modes excited at this particular angle of incidence. Naturally, the first arrival in the transmitted burst through a single adherend plate is simply the broadband signal characteristic to the frequency response of the ultrasonic instrument, and it can be used for normalization purposes.

In the following, we are going to compare the Lamb mode and guided interface mode distributions of different adhesive joints containing adhesive and cohesive types of defects in order to demonstrate the superior sensitivity of the suggested guided wave technique. Quantitative evaluation of these leaky guided interface spectra exceeds the scope of this preliminary study, but we would like to mention that the analytical tools for theoretical calculations are available in the literature in great variety [7-10].

Fig. 5 shows the Lamb wave and guided interface wave distributions in a defect-free adhesive joint at two different points separated by approximately 1". The only appreciable difference between these two spots was a roughly 10% higher adhesive thickness at point 1. As we expected, the Lamb mode resonance frequencies are not affected at all by this small difference, but the amplitudes of certain modes change a lot. For instance, the 5th detected mode is greatly attenuated while the 6th one

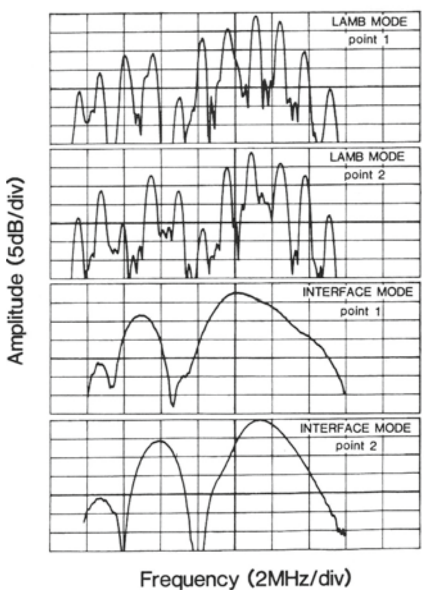

Fig. 5. Lamb mode and guided interface mode distributions in a defect-free sample at 20° angle of incidence (sample #FMP 4).

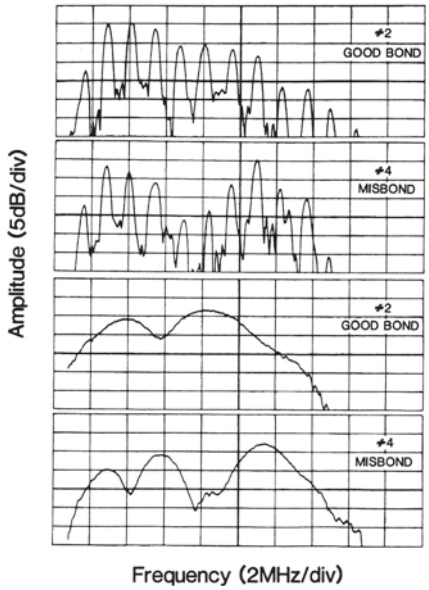

Fig. 6. Lamb mode and guided interface mode distributions in a frekoted sample at 20° angle of incidence (sample #EAF 2).

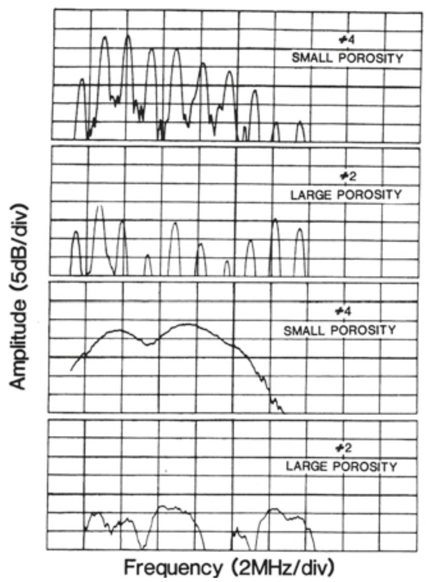

Fig. 7. Lamb wave and guided interface wave distributions in a porous adhesive joint at 20° angle of incidence (sample #EAF 1).

is strongly amplified by the excessive thickness at point 1. At the same time, the amplitude of other modes such as the 7th or 8th is more-or-less the same at both points. This indicates that although there is plenty of information in the amplitude distribution of these Lamb modes, it is very complicated to characterize the adhesive joint by evaluating these results.

The guided interface modes of Fig. 5 seem to be much simpler to evaluate. Since the sound velocity could not change so much between these two points, it is quite clear that the thickness of the adhesive layer is approximately 10% higher at point 1, which is in good agreement with independent caliper measurements. Naturally, evaluation of such transmission spectra in terms of guided interface modes necessitates the determination of the adhesive thickness as well. This can be done by measuring the total thickness of the adhesive joint and subtracting the known thickness of the adherend plates, or by additional ultrasonic measurements, preferably at normal incidence [11,12].

As mentioned earlier, it was predicted by numerical calculations that certain Lamb modes are especially sensitive to changes in the adhesive bond [4-6]. Fig. 5 suggests a very simple explanation for this phenomenon. Due to the rather weak acoustical coupling through the adhesive layer, Lamb modes of the adhesive joint are appreciably affected only by substantial changes in this weak coupling. This occurs in the vicinity of anti-resonances of the guided interface modes when even small changes, e.g. defects, result in strong changes in coupling through the adhesive layer. The sharp minimum in the guided interface wave spectra coincides with the most sensitive Lamb modes of the joint, while in the vicinity of the broad maxima, the Lamb modes are not affected by the excessive thickness at all. We can say more generally that Lamb modes of the adhesive joint are only indirectly affected by bond properties through the strong dependence of the acoustic coupling on the guided interface modes.

Fig. 6 shows the effect of lack of adhesive bond on the corresponding Lamb mode and guided interface mode distributions in a frekoted sample. Adhesion between the aluminum adherend and FM300 epoxy was deliberately reduced by chemical treatment of the sample surface before bonding. This sample exhibited a varying degree of misbond over the bonded lap-joint area. In particular, point 2 was found to be apparently flawless while point 4 was severely defective on one side of the adhesive layer. Again, the Lamb mode distribution is basically the same at both spots although there is some change in amplitude and even in frequency (see e.g. the 6th mode). Much stronger substantial changes are apparent in the guided interface wave spectra. The adhesive layer at point 4 is held rigidly on one side, but it is fairly loose on the other side, therefore resonant frequencies at point 2 correspond to antiresonances at point 4, although there is still a weak remanant maximum at around 8.5 MHz indicating the presence of partial bonding.

Fig. 7 shows the Lamb wave and guided interface wave distributions for an adhesive joint with an appreciable level of porosity. At point 4, there was a large cluster of pores resulting in substantially reduced cohesive strength, but even this gross defect left the Lamb mode resonances unaffected, although the amplitudes were strongly attenuated. It well demonstrates the superior sensitivity of the suggested technique that the guided interface modes were completely eliminated by this defect.

CONCLUSIONS

We showed that conventional Lamb wave inspection of adhesive joints is mainly sensitive to the properties of the adherend plates and much less to those of the adhesive layer and the interfaces between them. Due to the usually rather weak acoustical coupling through the adhesive layer between the adherend plates, only the amplitudes of certain Lamb modes are strongly affected by bond defects, not their frequencies. As a result, the Lamb wave inspection technique is often not sensitive enough to detect weak defects and the results are rather difficult to evaluate. Guided interface waves were shown to be much more sensitive to both adhesive and cohesive type defects, and the results are quite easy to interpret. True guided interface waves are very difficult to generate and detect in most practical applications, therefore we suggested the use of leaky guided modes. We showed that such waves can be readily excited and detected by the same double-transmission technique used for leaky Lamb wave inspection with the addition of appropriate time gating. This relatively simple technical modification seems to be a small price to pay for the superior performance of the guided wave technique.

ACKNOWLEDGEMENTS

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