APPLICATION OF GUIDED ACOUSTIC WAVES TO DELAMINATION DETECTION

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INTRODUCTION

The occurrence of delamination in laminate structures is one of the major reliability concerns for using these materials. There are continuing needs for developing delamination inspection techniques to measure specimens of various material structure as well as to accommodate different test environments. In the case of disbond-detection in the skin of an aircraft, for some practical reasons, an efficient technique should be capable of inspecting a large surface area in a reasonably short amount of time and with a high degree of accuracy. While most existing measurements can provide satisfactory accuracy, the required high inspection rate may not be met. Thus, for assessment of large surface area with an ultrasonic technique, our approach is to generate sound waves of particular modes, which are capable of propagating in a relatively extended area on the surface of a plate and at meantime interrogating the structural integrity of the plate.

It is well known in waveguide theory [1-3] that certain modes of sound waves are capable of propagating a relatively long distance in a material of plate configuration, and that their propagation properties are determined in part by the product of sound frequency and plate thickness. Recently, it was found experimentally that, with this thickness dependence, certain modes of these plate waves provided a different approach to probe the flaws in a laminate structure, and with potential application to the large area disbond and crack inspection.

MEASUREMENT AND RESULTS

Low-order modes of plate waves were excited and propagated in single aluminum plates, single aluminum plates with thin epoxy layer of thickness 150-300 µm glued on one side, and plate assemblies. Typically, the thickness of an aluminum plate is 1 mm. Two pieces of aluminum plate were epoxy bonded to form a plate assembly of thickness close to 2.2 mm. For most assemblies, there were areas between plates intentionally unbonded as a simulation of delamination for testing. A 2.25 MHz broad band PZT transducer of 1.25 cm diameter and a function/pulse generator were used to excite pulsed waves. These waves after travelling across the bonded and the unbonded areas were received by another transducer of the same type sitting on the same surface of plate. Amplitude of the received signal was then monitored in a digital oscilloscope as a function of position of an acoustic damper. A schematic diagram illustrating the setup for the measurement is shown in Fig.1.

Waveforms of well-separated wave modes could be obtained for both single plate and plate assembly when the distance between transducers was far enough, typically, larger than 30 cm. Phase and group velocities of these modes were determined by the differentiate method. Checking with the dispersion curves of plate waves for aluminum, the observed waves of particular interest were either S0 or A1 mode. These wave modes, which also show optimal amplitude among the first arrivals in the observed waveforms, exhibit phase velocities close to 4.4 x 10^3 m/sec in an aluminum plate and a plate assembly.

One of the features which differentiates this measurement from other plate waves techniques is mounting the two transducers on the plate surface at a fixed distance (which can be easily larger than 30 cm) and employing an acoustic damper instead of a transducer to locate the structural flaws. It is not unexpected that the insertion of an acoustic damper on the plate surface between the transducers results in a decrease in amplitude of the received signal; However, it was found in the experiments that the amount of decrease when the damper was placed on the unbonded area of a plate assembly was much larger than that on the bonded areas. Taking advantage of this finding, when the acoustic damping probe (with width of 0.5 cm in the testing) is scanned back and forth between the transducers as illustrated in Fig. 1, the observed variation of amplitude of the received signal can be used to locate the

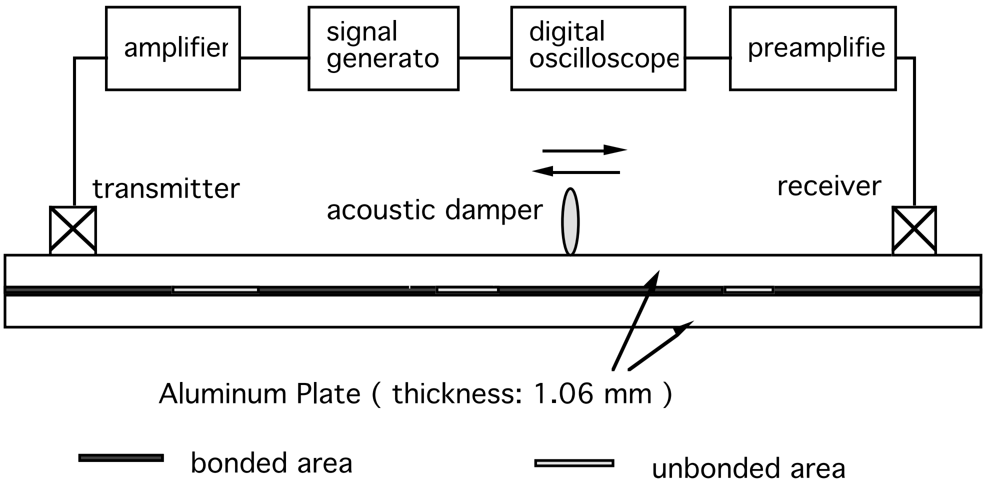

Fig. 1. Schematic diagram of setup for the plate wave measurement.

delamination areas. To demonstrate this effect, one of the measurements was done on a plate assembly, half of whose volume was of two bonded plates and the other half was of single plate. Fig. 2 displays the amplitude variation curve of a wave mode with phase velocity of 4.35 x 10^3 m/sec at 1.8 MHz, as a result of scanning. In the figure, x-axis represents the distance of damping probe from the transmitter. Also illustrated in the inset is the geometry of the plate assembly. As can be seen, when the damper moved across the double to the single plate area or vise versa, the amplitude decreases or increases respectively. Although the amplitude changes were not as sharp as expected, which may be due to the phase cancellation of incoming and scattered waves at the boundary, the data does reveal the thickness variation and imply that the wave mode loses more of its energy in the single plate area than in the double plate area when the local surface condition was changed by the damper.

To further exhibit this loading effect, measurements were performed on a plate assembly with three unbonded areas, as depicted in Fig. 1, of width 15, 12.5, and 9.5 mm respectively and of thickness 0.2 mm in the thickness direction. Monitoring a wave mode propagating with the same velocity as the previous one, the result of scanning is displayed in Fig. 3. The areas with relative minimum amplitudes in the curve shown coincided with the regions in the fabricated sample where no epoxy was put between the plates. In addition, in a similar measurement, a less than 0.8 mm wide simulating crack fabricated in the

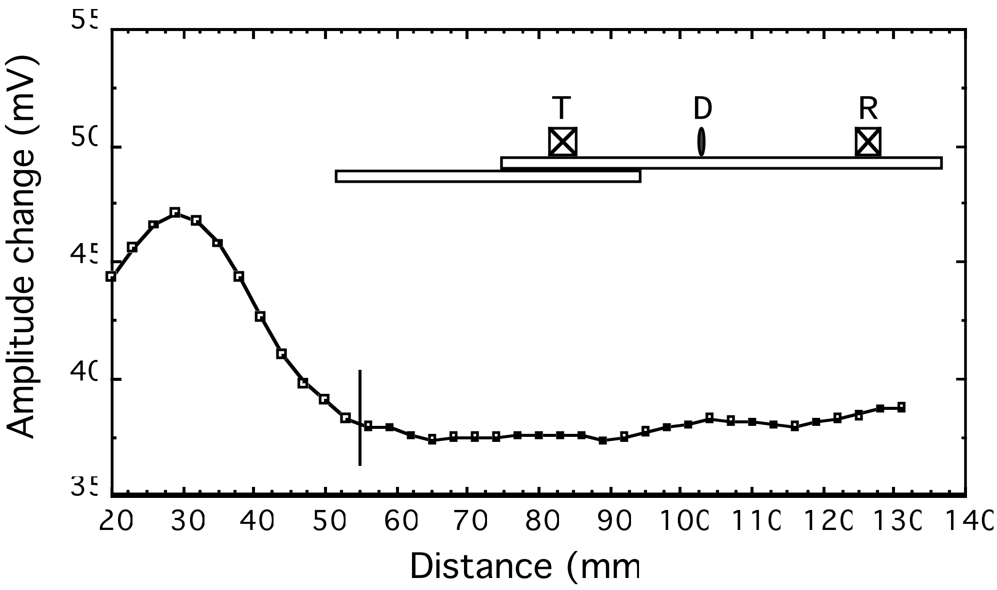

Fig. 2. Amplitude variation of the signal with phase velocity 4.35 x 10^3 mm/ms at 1.8 MHz. When the damper was moved from double plate area to single plate area, signal level decreased as shown. To the right of the vertical line segment is the single plate area. The decrease at distance smaller than 30 mm is due to the mounting effect of transmitter.

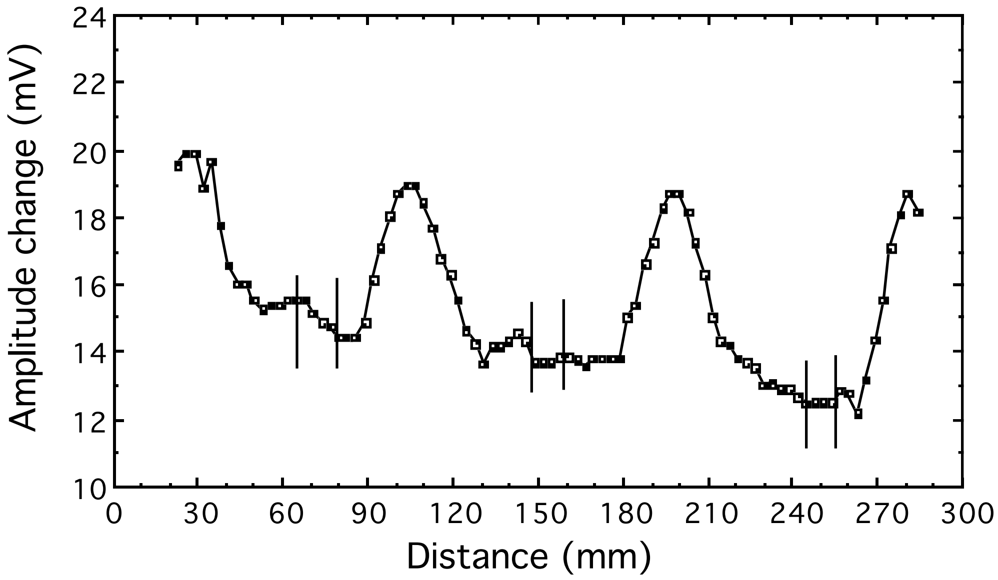

Fig. 3. Amplitude variation of the signal with phase velocity 4.35 x 10^3 m/sec at 1.8 MHz.as a function of distance from transmitter to the damper. Inside each pair of vertical line segments is the region where plates are unbonded.

bottom plate was detected by scanning damper on the surface of the top plate. With these results, it seems to be evident that this measurement is capable of detecting delamination and cracks.

The parameter measured is the amplitude of ultrasonic signal as a function of distance. Therefore, if the only concern in the measurement is to find and locate the structural flaws, the scanning speed can be fast. In the above case, the changes of amplitude responding to the disbonds are so obvious that it took less than 20 seconds to scan a 35 cm distance and found the three unbonded areas. However, the degree of variation of amplitude is a function of the width of unbonded area, that means, inspection rate should be slowed down for flaws of smaller dimensions. If a third acoustic transducer is placed on the other side of the transmitter but on the same plate surface, the inspection area is then doubled.

DISCUSSION

The described approach for flaw detection is basically using waveguide effect in bonded plates. Here, the laminate structure serves as a waveguide for the sound waves to propagate. There are several interesting features either for technical or theoretical concern may be worth mention.

In the measurement, it was found that the low order plate modes of longitudinal and flexural waves (or identified as symmetrical and antisymmetrical modes of Lamb wave) had been generated and traveled more than 30 cm in the assembly. This distance can be much larger when propagating in a sample free of structural flaws. Shear wave transducer is better than longitudinal wave transducer for producing cleaner desired wave modes, which were the signals with the phase velocities between 4.0×10^3 and 5.0×10^3 m/sec at 1.8 MHz. However, the relative orientation of polarization of a shear wave transmitter to that of a shear wave receiver is crucial for obtaining these wave modes. It was also observed that waves with phase velocity near 4.4×10^3 m/sec exhibited the optimal amplitude, and showed the most measurable capability for flaw detection. This capability may be attributed to the existence of out-of-plate particle displacement with the Lamb waves.

The propagation of plate waves in a test material [1-3] requires the relationship among the plate thickness (B), the shear wave velocity (V_s) as well as the longitudinal wave velocity (V_l) of the material, the phase velocity of plate wave (V) , and the frequency (f) of imposed sound waves to satisfy the plate wave equations and the plate boundary conditions. The particle displacements in the plate induced by these waves are the combinations of those of pure longitudinal and pure shear waves in bulk specimen. Lamb waves are those modes with both out-of-plate and in-plate particle displacements. The ratio of out-of-plate displacement (D_o) to the in-plate displacement (D_i) of two Lamb wave modes at the plate surfaces [2] can be described as

symmetrical mode

$$\frac{D_o}{D_i} = \frac{2\sqrt{1-\left(\frac{V}{V_l}\right)^2}}{2-\left(\frac{V}{V_s}\right)^2}\,\mathrm{Tanh}\left[\pi f B\frac{\sqrt{1-\left(\frac{V}{V_l}\right)^2}}{V}\right]$$

and antisymmetrical mode

$$\frac{D_o}{D_i} = \frac{2\sqrt{1-\left(\frac{V}{V_l}\right)^2}}{2-\left(\frac{V}{V_s}\right)^2}\,\mathrm{Coth}\left[\pi f B\frac{\sqrt{1-\left(\frac{V}{V_l}\right)^2}}{V}\right]$$

respectively. As can be seen in the above two expressions, the maximum absolute value of D_o/D_i may be obtained when $V = \sqrt{2}\, V_s$, which is approximately 4.4×10^3 m/sec for aluminum. Technically, longitudinal wave transducer drives the out-of-plate displacement (D_o) in D_o/D_i. Due to the value of D_o/D_i tends to be infinity when $V = \sqrt{2}\, V_s$, and the limited input power to the transducer makes D_o finite, the value of D_i could then be small or even too small to propagate a Lamb wave. On the other hand, under the same conditions, with the same reasoning, shear wave transducer excites the in-plate displacement (D_i), which would make the out-of-plate displacement D_o as large as it can, and that is what we obtained in the experiments. The resultant relatively large value of D_o makes the signal easily measurable in a long distance.

The purpose of applying an acoustic damper on the plate surface is to locally change the boundary conditions at the contact area of the damper with the test plate, which in fact changes the local loading condition of the plate. The response of the particle displacements to this loading at the bonded area differs from that at the unbonded area, which results in the quantitative difference in the change of the received signal levels. Since the response occurs immediately after the contact, the optimum scanning rate of the acoustic damper is determined by the rate of the measurement of amplitude.

It is not clear at this moment that what is the main mechanism causing the different responses to loading by bonded and unbonded areas. One possible interpretation is that the structural flaws, which are disbonds or cracks in this case, reduces the thickness of test sample in their locations, and act as wave scattering centers. Accompanying with the wave mode conversions occurred at the boundary of scattering center, the scattering effect results in a different wave energy distribution from that of a flaw free sample or a flaw free portion in the same sample. The acoustic damper functions as a probe to map the variation of this energy distribution. To prove this suggested model, understanding of energy distribution of wave modes in plate becomes necessary. Measurements on various geometries of plate assemblies are undergoing, which may provide further information of sound waves propagating in a plate configuration.

As to the application to large area integrity inspection, this measurement has several advantages for the future development; In this measurement, the transducers are at fixed positions for each inspected area which can easily span more than 60 cm in length, and thus reduce the effects of coupling variations between transducer and test specimen surface, which encountered in the other ultrasonic inspection techniques. As matter of fact, as long as the requirements for generating plate waves described in the previous paragraphs are met, the method for generating waves is not essential to the measurement. It is possible to employ other non-contact techniques, such as optical and magnetic means, to excite and detect the expected mechanical waves. Furthermore, in order to extend the physical dimension of inspection, three linear arrays of transducers: one as transmitters and the others as receivers, can be arranged to produce and receive parallel beams of plate waves; In this case, by using comparison method, the occurrence of structural flaws may be determined, and a long acoustic damper can be used to scan and find the flaw location.

In summary, guided plate waves are able to interact with structural flaws such as delaminations and cracks due to their propagation properties highly sensitive to the thickness change in materials. A technique which employs an acoustic damper to probe the results of this interaction and then to locate flaws in a relatively short period of time is developed. With its technical advantages, this technique shows its potential application to large area structural integrity assessment.

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