AIR-COUPLED ULTRASONIC INSPECTION TECHNIQUE FOR FRP STRUCTURE

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Abstract

An investigation of the air-coupled ultrasonic technique, which could be done from one side of a testing material, was carried out in order to detect cracks in Fiber Reinforced Plastics (FRP) by non-contacting. The accessibility of probe should be improved to apply this technique for examination of cracks in FRP at maintenance fields of airplane, because in general some obstacles are located on its test surface. In this study, the probe layout was arranged to examine whole test area and some experimental investigation of this technique was carried out using testing specimens. As a result, all cracks located in the testing specimen can be detected clearly. Also it was confirmed that small cracks of 5mm in length could be detected and that the air-coupled ultrasonic technique can be used to detect invisible cracks.

1. Introduction

Fiber reinforced plastics (FRP) that are the most popular composite materials help to lighten components, because of their superior strength-to-weight ratio. Therefore, they have come to be utilized as parts of aerospace etc. Composite materials have already been used for secondary structures of commercial aircrafts, such as vertical and horizontal stabilizer as well as skin plate of wing. Moreover, some commercial aircrafts in which composite materials are used for major structures are developed.

Under this situation, reliable and efficient examination techniques by which composite materials are examined need to be developed. Though tapping testing, ultrasonic testing, soft X-ray radiography and infrared thermography testing have been applied to composite material as non-destructive examination techniques, their recording ability, efficiency and accuracy are required to be improved.

Ultrasonic testing is applied to composite material of airplane during both construction and maintenance, because it is the advantageous inspection technique of a planer defect like as crack or delamination. However, conventional ultrasonic testing has a disadvantage that liquid coupling medium such as water and oil are necessary and cleaning must be done before and after testing. Moreover stable coupling between probe and material to be tested must be kept, because it affects the examination result. For the purpose immersion technique can be applied at the manufacturing stage, but it is difficult to apply it at the maintenance stage, and large-scale system is necessary for large component.

Under these backgrounds it is meaningful to establish the speedy and quantitative inspection technique that executed without any coupling medium of a liquid. The purpose of this study is to develop the practical air coupled ultrasonic inspection technique. Moreover, we decided that the technique executed only from one side of an internal or external surface (it is hereafter called the One Side Access Inspection Method) would be developed in order to make inspection at the maintenance stage easier.

2. Air-coupled ultrasonic inspection method

In order to transmit ultrasound effectively, liquid is usually used to couple a probe with a material to be tested in the conventional ultrasonic testing. Equation 1 indicates echo transmittance that is a ratio of the sound energy back to the transducer after transmitting through a interface (*P'*$_T$) to the original energy (P_I) as shown in Fig. 1.

$$T_{1\to 2} = \frac{P_T}{P_I}\cdot\frac{P'_T}{P_T} = \frac{4Z_1Z_2}{(Z_1+Z_2)^2} \qquad (1)$$

Where Z_1 and Z_2 show acoustical impedances of medium 1 and medium2 respectively.

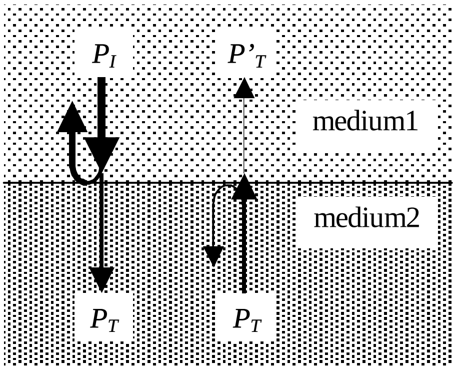


Figure 1: *Schematic drawing of ultrasound's transmission at an interface.*

Table 1: Acoustical properties

	Density r (10^3kg/m^3)	Sound velocity of longitudinal wave C (m/s)	Acoustical impedance $Z = r\ C$ (10^6kg/m^{2}s)
Water	1.0	1480	1.48
Air	0.0013	344	0.00045
Acrylic resin	1.18	2720	3.21
Epoxy resin	1.15～1.3	2500～2800	2.8～3.7

Table 2: Echo transmittance

Medium1 / Medium2	Water	Air
Acrylic resin	0.86	5.6×10^{-4}
Epoxy resin	0.82～0.90	4.7×10^{-4}～6.4×10^{-4}

Table 1 shows the acoustical properties of water, air, acrylic resin and epoxy resin, and Table 2 summarizes echo transmittances. It is clear that the sound energy transmitting in the air is thousands times smaller than that in the water.

As described above, transmission coefficient of air-coupled ultrasonic technique is quite low, it is of great significance to consider frequency of sound, probe property and capability of equipment.

Air-coupled ultrasonic technique described below was investigated by using suitable system.

3. Propagation of Lamb wave

Though composite material constitutes complex structure such as honeycomb, channel and stringer, it is based on plate structure, which is often inspected by ultrasonic testing using reflection technique or through transmission technique. Lamb wave has been used for the case of steel plate.

Lamb waves are a complex vibrational wave that travels through the entire thickness of a material. Propagation of Lamb waves depends on density, elastic, and material properties of a component, and they are influenced remarkably by selected frequency and material thickness. With Lamb waves, there are the two most common modes, symmetrical and asymmetrical, and many higher harmonics of them are produced. The equation 2 and 3 are requirements for existing symmetrical and asymmetrical Lamb wave, respectively.

$$4pq\tan\frac{pfd}{c}q + \left(p^2 - 1\right)^2 \tan\frac{pfd}{c}p = 0 \qquad (2)$$

$$\left(p^2 - 1\right)^2 \tan\frac{pfd}{c}q + 4pq\tan\frac{pfd}{c}p = 0 \qquad (3)$$

Where c, f and d mean phase velocity of Lamb wave, frequency of ultrasound and thickness of material, respectively. Equation 4 and 5 show parameters p and q, and c_D and c_S mean sound velocity of longitudinal and transverse wave, respectively.

$$p^2 = \left(\frac{c}{c_S}\right)^2 - 1 \qquad (4)$$

$$q^2 = \left(\frac{c}{c_D}\right)^2 - 1 \qquad (5)$$

As an example, calculation results of phase velocity of Lamb wave in CFRP, in which sound velocity of longitudinal wave is 3670m/s and that of transverse wave is 1440m/s, is shown in Fig. 2.

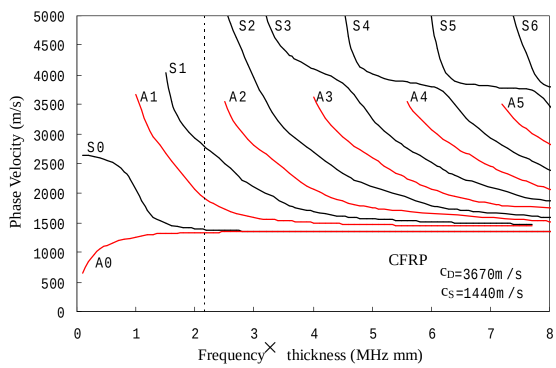


Figure 2: *Calculation results of phase velocity of Lamb wave in CFRP*

The dotted vertical line in the figure, which represents the condition of 5mm in thickness and

430kHz in frequency, predicts that there are symmetrical mode S0 and asymmetrical mode A0 having similar sound velocity as well as higher harmonics.

4. Propagation of Lamb wave

In order to confirm the propagation behavior of this Lamb wave experimentally, Lamb wave was tried to emit and propagate into the CFRP with the layout shown in Fig. 3. Probe, which transmits or receives longitudinal wave in the air, has a composite piezo-electricity element with 25mm in diameter and a nominal frequency of 400kHz.

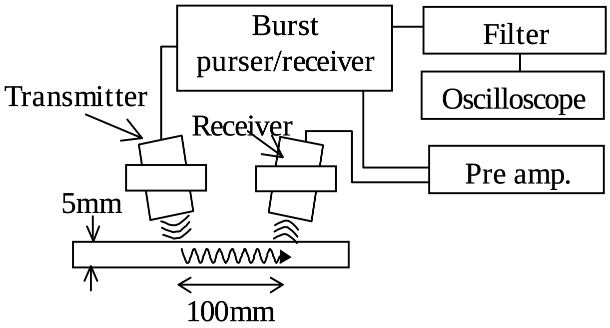


Figure 3: *Block diagram for experiment of Lamb wave propagation.*

Examples of collected waves are shown in Fig.4, and experimental results and theoretical solution are compared in Table 3. Although some differences between the calculation result and the experiment result were shown, waves of the mode of S1, A1, and mixed mode of S0 and A0, which were predicted by calculation, were clearly observed. Moreover, The distance amplitude characteristic curve, which is obtained by scanning the transmitter, is shown in Fig. 5. The figure shows that attenuation of mode of S0+A0 is greater than that of the other modes. Then, it was presumed that this mode had much leakage of ultrasound to the air, and it was not suitable for long-distance propagation because of high attenuation. However, it was easy to detect propagation of the Lamb wave in the air.

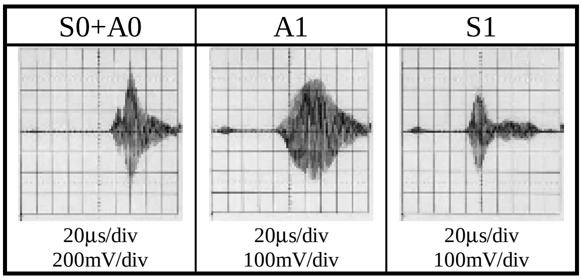


Figure 4 Examples of collected wave

Table 3: Comparison between experiment and theoretical solution

experiment		Theoretical solution	
Estimated mode	Phase velocity	Mode	Phase velocity
S0＋A0	1100m/s	S0	1387.6m/s
		A0	1342.3m/s
A1	1960m/s	A1	1932.8m/s
S1	2460m/s	S1	2806.0m/s

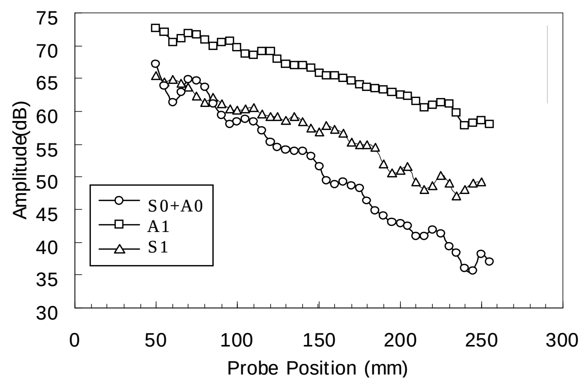


Figure 5: Distance amplitude curves of Lamb wave.

The One Side Access Inspection Method was developed to detect the lamb wave in this mode propagating a testing object. When disbonding etc. exists in the path of propagating Lamb wave, the boundary conditions about propagation of the wave change, therefore the Lamb wave is attenuated and the amplitude of a detected wave decreases as shown in Fig.6. That is why disbonding, impact damage, crack etc. can be detected by this inspection technique from the amplitude change.

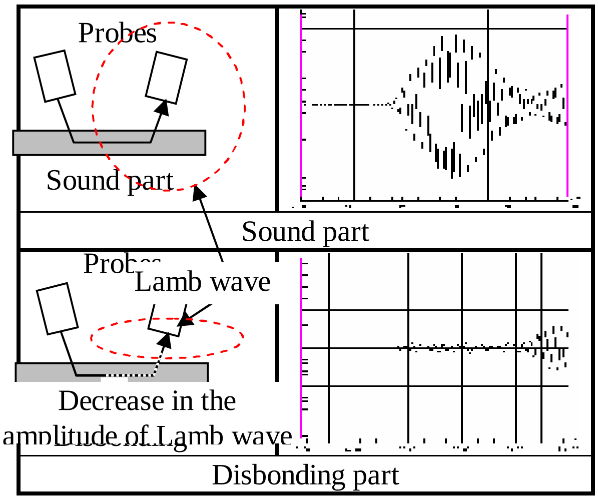


Figure 6: *Example of collected waves at the sound part and disbonding part.*

5. Crack detection of composite material using Lamb wave

The photographs of flap of B747 aircraft are shown in Fig.7. Visual inspection is executed because there is possibility that crack occurs at the fold of skin plate shown by red arrow in the picture. To improve detectability of crack, hereinafter, an investigation of air-coupled ultrasonic inspection was carried out. The testing specimen that simulated the fold in mid flap had artificial crack of 25.4mm and 12.7mm as shown in figure 8.

(a) Triple-slotted flaps

(b) Mid flap

Figure 7: *Photograph of flap of B747*

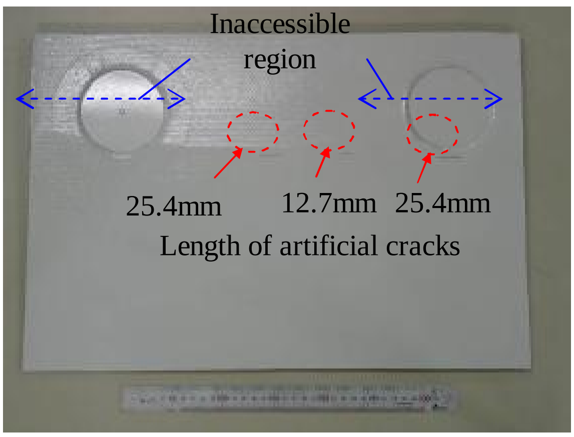


Figure 8: *Photograph of testing specimen simulated the flap of B747.*

To confirm the detectability of crack by Lamb wave technique, the examination of the testing specimen with setting probes shown in Fig.9 was carried out. The typical example of a received wave in a sound part and cracking part are shown in Fig.10. It was confirmed that the Lamb wave that propagates the sound part is detected by receiving probe clearly, and the amplitude decreases in the cracking part. It means that propagation of Lamb wave was interrupted by crack.

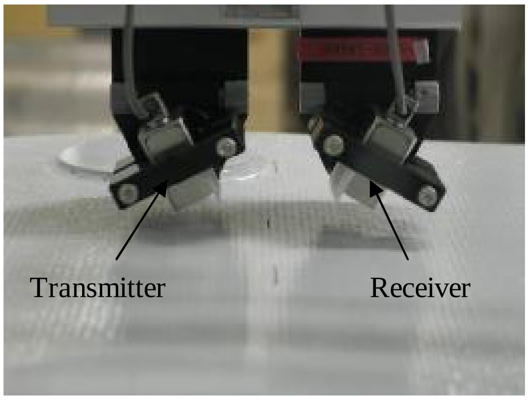
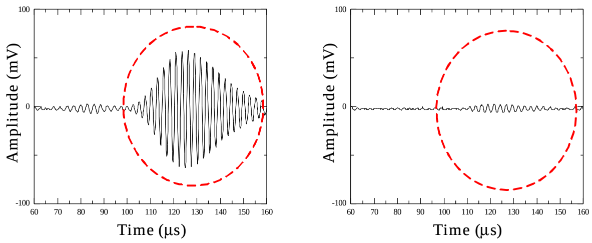


Figure 9: *Layout of probes for Lamb wave technique.*



(a) Sound part (b) Crack part

Figure 10: *Example of waves collected by Lamb wave technique.*

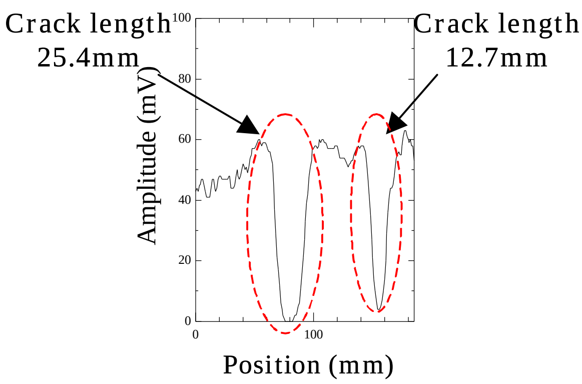


Figure 11: *Amplitude profile by Lamb wave technique.*

Fig.11 shows the amplitude profile of detected wave in the center part of testing specimen shown in Fig.8. The amplitude remarkably decreased at the point of cracks. Therefore it was clear the change in amplitude of Lamb wave could indicate the existence of crack. To investigate the detectability of crack by using this technique, testing specimen shown in Fig.12 with smaller cracks was examined. The Amplitude profile was obtained as shown in Fig.13 and the decrease in the amplitude at the crack of 5mm in length was clearly observed. It is confirmed that the crack of 5mm in length can be detected by this technique.

The region near the support is so difficult to be accessed that it cannot be examined, therefore the transmitter and receiver have to be placed on each side of fold in flap by this technique. The dotted arrow in Fig.8 shows the inaccessible region of the testing specimen.

As crack might occur near a support due to stress condition, it is meaningful to decrease the inaccessible region.

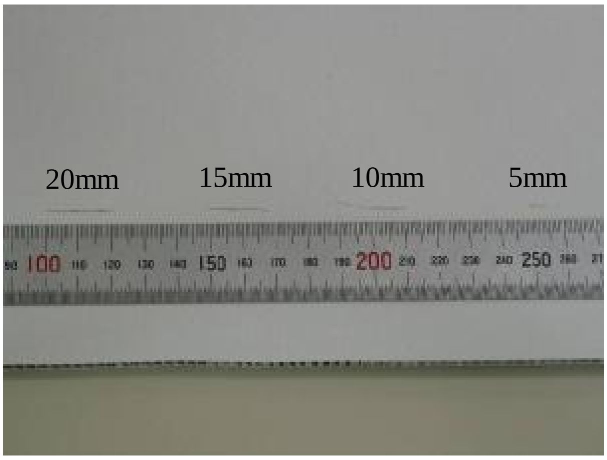


Figure 12: *Smaller cracks.*

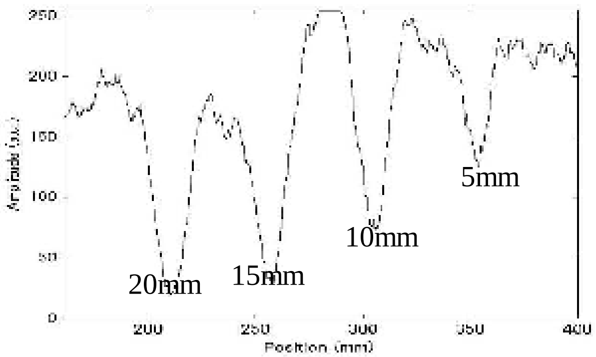


Figure 13: *Amplitude profile of smaller cracks by Lamb wave technique.*

6. Improved Lamb wave technique

The accessibility of probe should be improved to apply this technique for examination of cracks in FRP at maintenance fields of airplane, because in general some obstacles such as supports are located on its test surface. In this study, the probe layout shown in Fig.14 was arranged to examine whole test area. Fig.15 shows the schematic drawing of principal of this technique and example of collected waves. This figure indicates that reflected Lamb wave can be detected at the cracking part by this technique and the amplitude profile is expected to be the reverse.

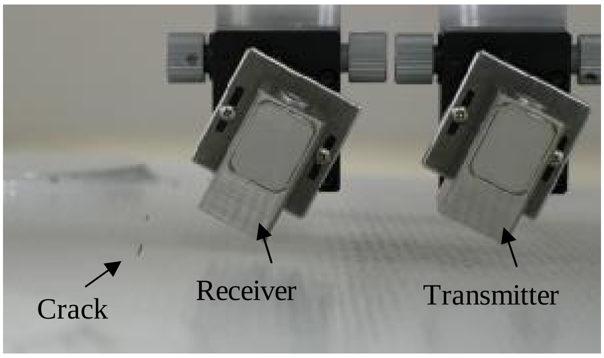


Figure 14: *Probe layout for improved Lamb wave technique.*

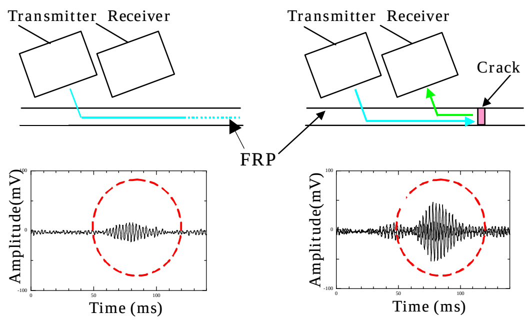


Figure 15: *Principal of improved Lamb wave technique and example of collected waves.*

The testing specimen shown in Fig.16 is the same as the sample shown in Fig.8 except the invisible cracks that are the artificial cracks under the paint. Profile of signal amplitude of it by improved Lamb wave technique is shown in Fig.17. As a result of this examination, it is clear that the crack close to the support can be detected as well as the cracks detected by the previous experiment, and cracks under the paint can also be detected. Therefore it can be said from the above-mentioned results that the whole test area of flap of B747 including fold close to supports can be inspected by this technique.

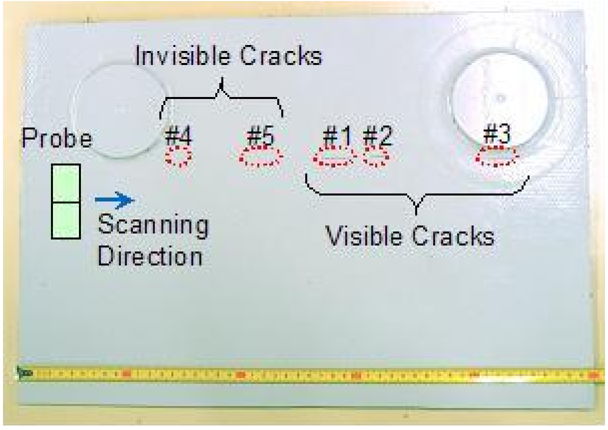


Figure 16: *principal of improved Lamb wave technique and example of collected waves.*

Table 4: Artificial visible and invisible cracks in the testing specimen.

Crack No.	Clack Length
#1 (visible)	25.4mm
#2 (visible)	12.7mm
#3 (visible)	25.4mm
#4 (invisible)	12.7mm
#5 (invisible)	25.4mm

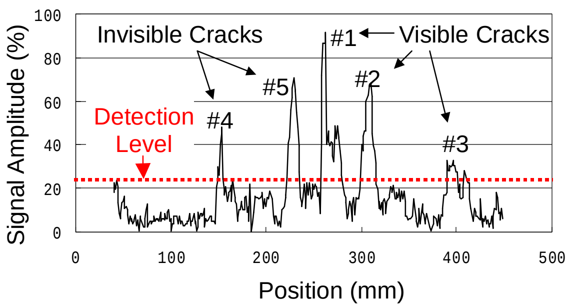


Figure 17: *Amplitude profile of visible and invisible cracks by improved Lamb wave technique.*

7. Conclusions

An investigation of the air-coupled ultrasonic technique, which could be done from one side of a testing material, was carried out in order to detect cracks in Fiber Reinforced Plastics (FRP) by non-contacting. As a result, it was confirmed that small cracks of 5mm in length can be detected and that the air-coupled ultrasonic technique can be used to detect invisible cracks. Moreover it was clear that inaccessible area can be decreased by using improved Lamb wave technique and whole test area can be examined.

Detection of cracks and disbondings in the composite material are so easy and speedy by using this technique that it will be applied in the many fields.

8. Acknowledge

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9. References

[1] S. Matsubara, T. Nagai, T. Yoshiara, M. Shirai and H. Miyamoto, ‘Air-Coupled Ultrasonic Inspection Method for CFRP’, Key Engineering Materials Vols. 270-273 (2004), pp188