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Experimental Study on the Mode Conversion of Lamb Waves in a Metal Plate of Stepped Thickness Using Optical Detection

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The optical observation of the propagation of Lamb waves in an aluminum plate with stepped thickness is described. Lamb waves passing through the aluminum plate were analyzed by two-dimensional Fourier transformation to discriminate modes and thus determine mode conversion. S0-mode and A0-mode Lamb waves corresponding to theoretical dispersion curves were experimentally found to propagate in the aluminum plate. Conversion from A0-mode to S0-mode waves at the thickness step was also observed. This mode conversion of Lamb waves is thus a useful index for detecting defects such as ablation, wear and wall reduction.

Key Words : Lamb wave, Mode conversion, Optical detection, Non-destructive evaluation (NDE)

1. Introduction

Ultrasonic waves are frequently used in the pulse-echo and pulse transmission methods for the detection of defects. Recently, plate waves have been employed in the nondestructive evaluation (NDE) of materials[1, 2]. Guided waves such as Lamb waves have the unique feature of propagating a great distance in plates and cylindrical structures[3]. In Lamb wave measurements, defects in a material can be detected with one propagation measurement rather than point-by-point measurements. Novel guided wave measurement systems employing Lamb waves or Rayleigh waves have been constructed; e.g., a tilted angle polarization-type piezoelectric transducer for plate wave generation[4] and a NDE system for a pipe or a plate that uses air-coupled ultrasonic waves in the megahertz range[5,6].

The propagation of Lamb waves in a plate is affected by the thickness d of the material and the wave frequency f. Propagation behavior in a plate having varying thickness, which models abrasion, wear or wall reduction, might be useful to obtain information about defects. However, the behavior of Lamb waves at the plate edge and the defect are considered to be very complex,[7,8] so that the experimental research into Lamb wave propagation in plates of varying thickness has only been reported.[9] However, theoretical study of mode conversion of Lamb waves in plate at defects has not been established. The propagation of Lamb waves in a plate of varying thickness is important for the NDE of properties such as wear, abrasion and corrosion-induced wall reduction.

In this paper, the propagation of Lamb waves in an aluminum plate of varying thickness is experimentally observed using optical system. The mode conversion of Lamb waves in the aluminum plate and its possible use in NDE are discussed.

2. Propagation of Lamb waves

2.1 Generation of Lamb waves

The propagation mode of a Lamb wave in a plate depends on both the thickness d of the material and the frequency f of the ultrasonic waves. The propagation of Lamb waves can be calculated using the Rayleigh-Lamb equations[1]. Lamb wave can be divided into two kinds of mode; one is the symmetrical mode (S mode) and the other is asymmetrical mode (A mode). Vibration of displacement and velocity on the plate surfaces are symmetrical in S mode and asymmetrical in A mode, respectively. Each mode of Lamb wave continues to propagate in the same mode when the plate has the same thickness and uniform properties. Therefore, the mode conversion between different modes would become a measure of the presence of non-uniformity such as effects.

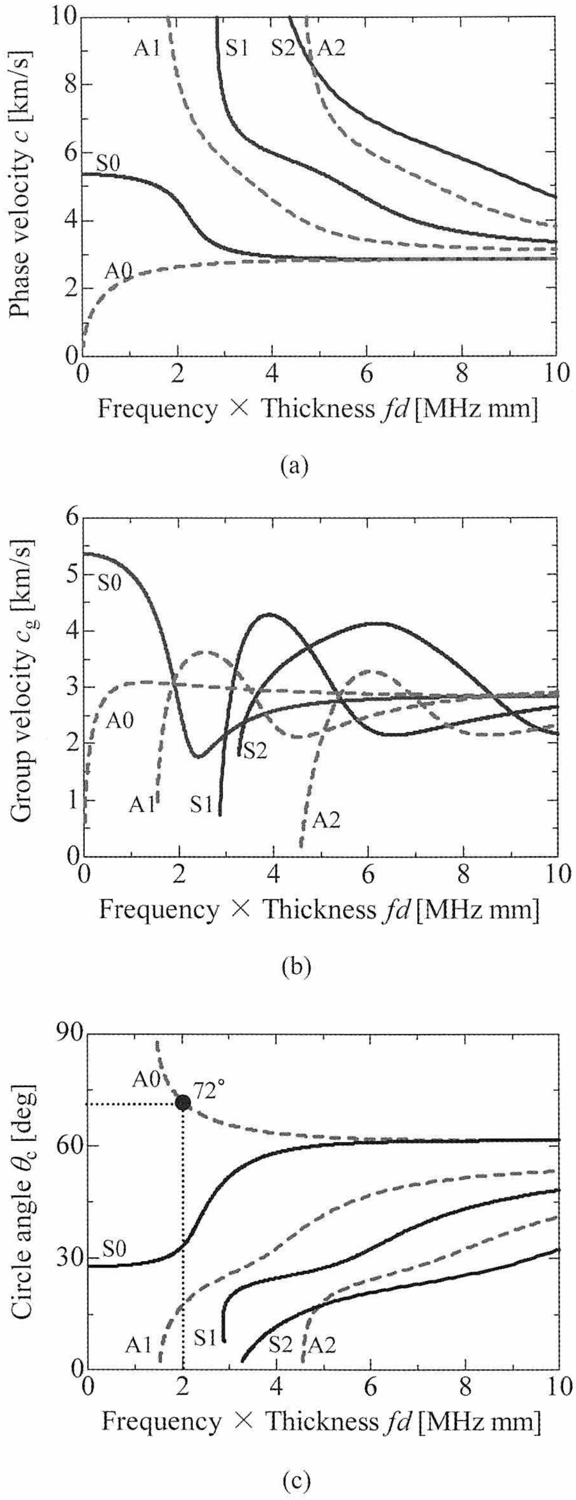
Dispersion curves of the phase velocity c_p and group velocity c_g in an aluminum plate (longitudinal wave velocity $c_L = 6410$ m/s, shear wave velocity $c_T = 3040$ m/s) are shown in Figures 1(a) and (b) respectively. Lamb waves can be effectively excited when the incident angle θ_c satisfies the phase matching condition[3,4]. This angle is calculated from Snell's law as

$$\theta_c = \sin^{-1} \frac{c_w}{c_p}, \qquad (1)$$

where c_w (=2500 m/s) is the ultrasonic wave velocity in the wedge. Dispersion curves of the critical angle in the aluminum plate are easily calculated and are shown in Figure 1(c). The thickness $d = 1.0$mm and frequency $f = 2.0$ MHz are selected to demonstrate the phenomenon of mode conversion of Lamb waves. Only S0 and A0 mode Lamb waves can be existed and propagated in the plate under this condition. When $fd = 2.0$ MHz mm, the incident angle θ_c is calculated using c_p (2630 m/s) and c_w (2500 m/s) as 72° for the effective generation of A0-mode Lamb waves.

2.2 Structure of the transducer

For effective generation of A0-mode Lamb waves in the aluminum plate, a wedge was inserted between the piezoelectric transducer and the aluminum plate. The wedge was made of epoxy resin (c_w=2500 m/s) and the incident angle of the wedge was adjusted to 72° as shown in Figure 1(c). The transducer was a thickness-mode piezoelectric ($PbTiO_3$) disk and its resonance frequency was 2.0 MHz. The frequency admittance of the transducer is shown in Figure 2. The transducer and wedge were pasted with silver paint to make an electrical lead.



(a)

(b)

(c)

Figure 1 Dispersion curves of the phase velocity c_p (a), group velocity c_g (b) and critical angle θ_c (c) of Lamb waves in the aluminum plate.

3. Measurement of Lamb wave propagation in the dual-thickness metal plate

3-1. Experimental setup

The measurement system for the Lamb wave is shown in Figure 3. A transmission signal comprising 10 bursts of 2.0 MHz, 1.0 $V_{p\text{-}p}$ sinusoidal voltage from a function generator (Agilent Technologies, 33250A) was amplified to 100 V and applied to the A0-mode transducer (incident angle 72°) via a power amplifier (NF, HSA4101). The A0-mode transducer was attached to an aluminum plate by a coupling gel (Eco-Med Pharmaceutical Inc., EcoGel200). An A0-mode Lamb wave from the transducer and wedge propagates in the aluminum plate and is optically detected by a laser vibrometer (Graphtec, AT0023 and AT3600) via a reflection mirror. Optical detection method has some benefits as; ①noncontact measurement, ②small area ($30\mu m\phi$) information are available, ③real time measurement and ④broad band measurement (~10MHz). These features are very convenient compared to the acoustical contact measurement. The beam of the laser vibrometer scanned the x stage along the direction of Lamb wave propagation from x=0 mm to x=200.0 mm at intervals of 0.2 mm. Surface vibrations of Lamb waves at each point were measured. Vibrating waveforms from the laser vibrometer were digitized using an oscilloscope (Agilent Technologies, 54845A)

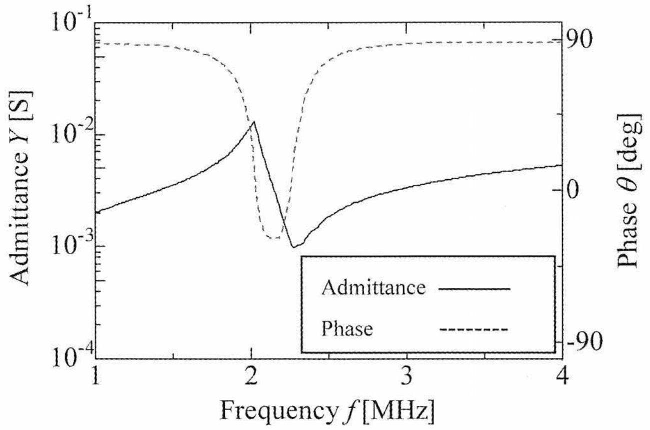


Figure 2 Admittance-frequency characteristics of the transducer.

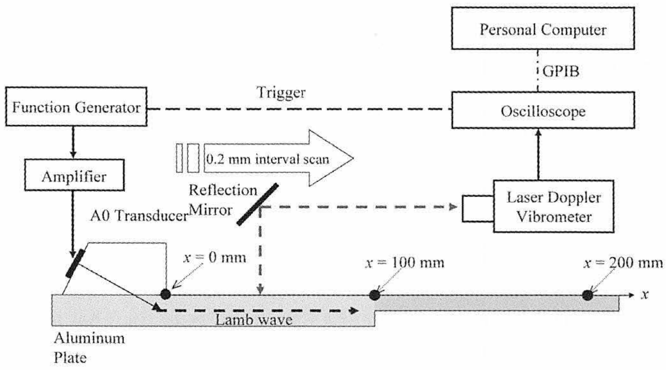


Figure 3 Experiment setup for measuring the surface vibrations of Lamb waves by optical observation.

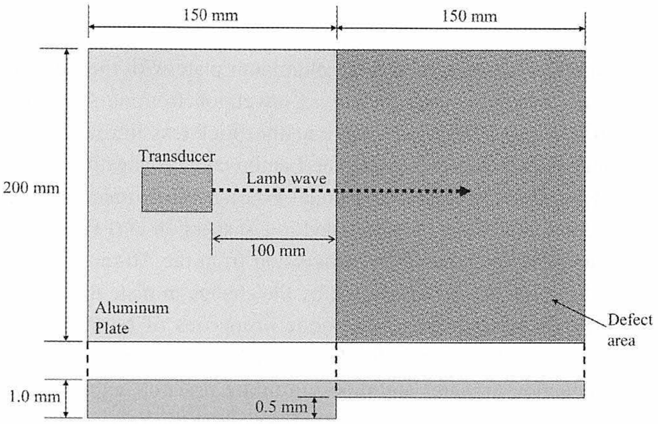


Figure 4 Geometry of the aluminum plate used in the experiment.

and fed into a personal computer via a general purpose interface bus (GPIB).

The dual-thickness aluminum plate, which decreases in thickness by 0.5 mm at its center, is illustrated in Figure 4. The step was located at $x=100$ mm in terms of the propagation of the Lamb waves.

3-2. Results and Discussion

Figure 5 shows the vibration waveforms of the A0-mode Lamb waves as detected by the measurement system at propagation distances of $x=0$, 50, 100, 150 and 200 mm. The two-dimensional distribution of the propagation distance x and time t of the

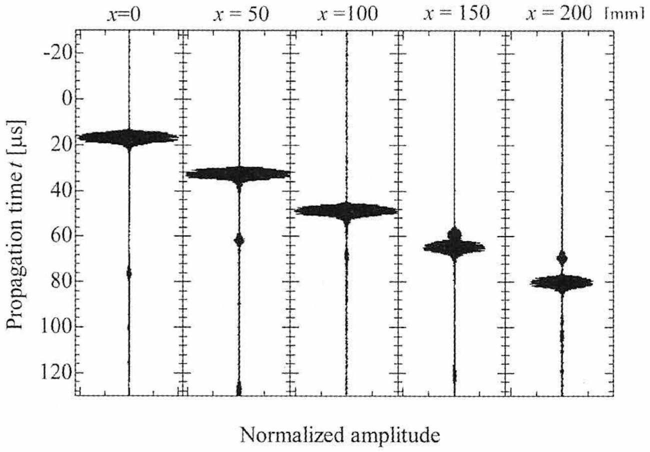


Figure 5 Waveforms of the A0-mode Lamb wave at propagation distances of $x=0$, 50, 100, 150 and 200 mm. Waveforms of each position were normalized by peak amplitude (18 $\mathrm{mV_{peak\text{-}peak}}$) of A0 mode Lamb wave at $x=50$ mm.

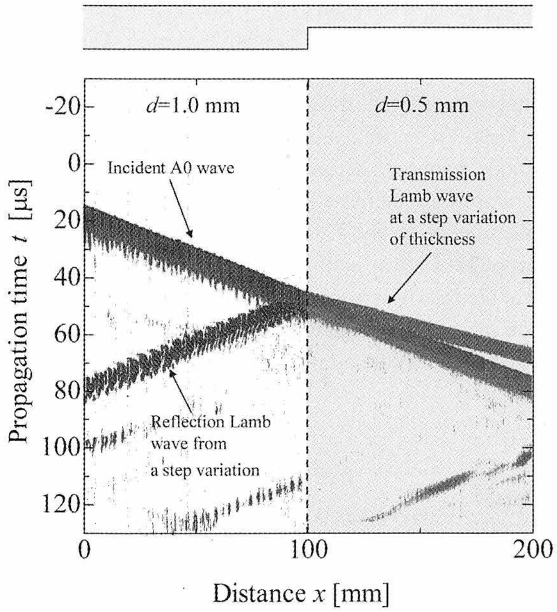
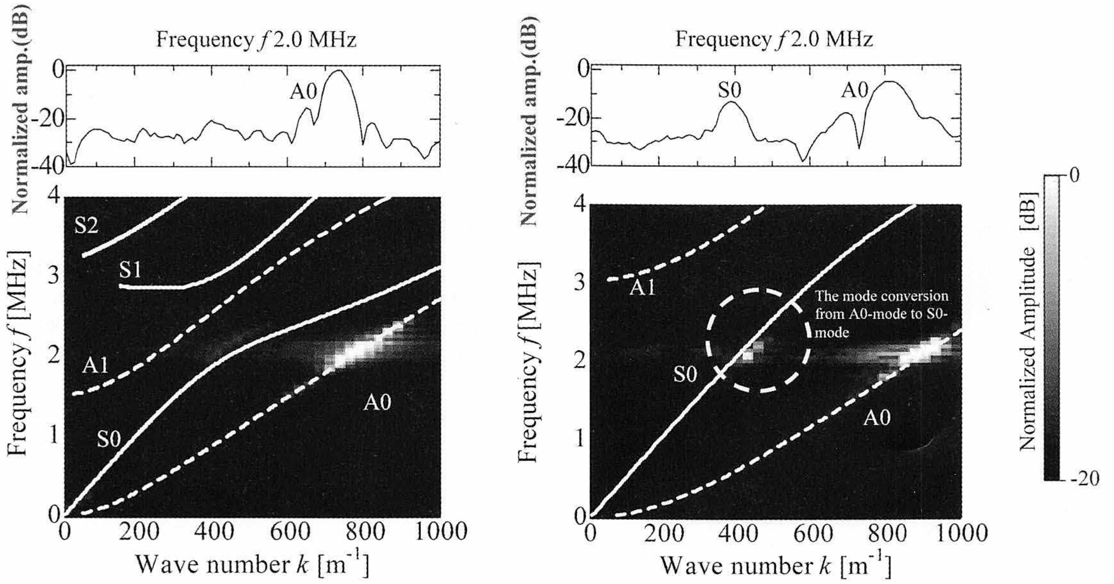


Figure 6 x-t distribution of received waveforms. The vertical axis shows propagation time t and the horizontal axis shows position x.



(a) (b)

Figure 7 k-f images obtained by two-dimensional Fourier transform with the theoretical dispersion curves for $d=1.0$ mm (a) and $d=0.5$ mm (b), respectively. Amplitude spectrum of upper side figures are normalized by amplitude of A0 mode.

waveforms determined by the measurement system is shown in Figure 6, and thus the relationship between time and distance of the Lamb waves is visually presented. A0-mode Lamb waves reach the thin region between 45 and 50 μs as shown in Figure 6.

A two-dimensional Fourier transform method was used to determine the Lamb wave mode.[3,5,10] The *k*-*f* distribution determined from the two-dimensional Fourier transform of the *x*-*t* distribution is shown in Figures 7(a) and (b). The frame length of 2D-FFT were 150 μs and 200 mm for time *t* and distance *x*, respectively. Optical signal were converted to the electrical one and were truncated by the rectangular window. The *k*-*f* distribution peak at d=1.0 mm (thick region) corresponds to the dispersion curve of the A0-mode Lamb waves. Peaks at d=0.5 mm (thin region) correspond to dispersion curves of both the A0-mode and S0-mode waves. These results imply that A0-mode waves were converted to S0-mode waves at the border region. The upper side figures of Figures 7(a) and (b) also indicates the occurrence of mode conversion at the steeped area.

Figure 8 shows the peak values from the spectra for each mode. The A0-mode amplitude decreased by approximately 5 dB and the S0-mode amplitude increased by approximately 12 dB between 47 and 50 μs, respectively. This region corresponds to the location of the stepped thickness of the plate. The mode conversion thus occurred at the thickness border of the aluminum plate; thus, mode conversion can be useful sign to detect at the sites of ablation, wear and wall reduction in structural materials.

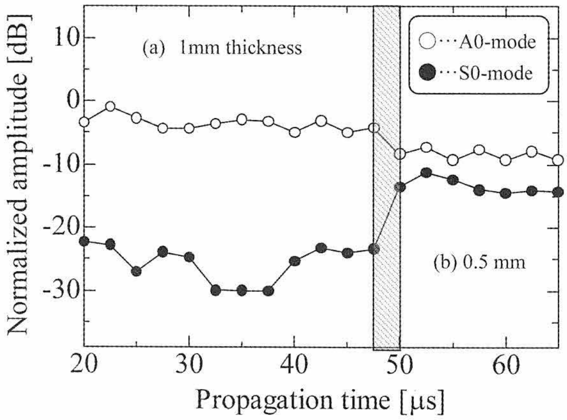


Figure 8 Amplitude-time characteristics in the cases of 1 mm thickness (a) and 0.5 mm thickness (b). The shaded area is the time in which the A0 mode Lamb waves reached the step variation in thickness.

4. Conclusions

Lamb wave propagation in an aluminum plate with the stepped thickness was measured optically. Conversion from an A0-mode Lamb wave to a S0-mode wave at the thickness border in the aluminum plate was observed. The Lamb wave propagation mode was determined by two-dimensional Fourier transformation. The A0-mode Lamb wave corresponded to a dispersion curve for both the thick and thin areas. This conversion from the A0-mode wave to the S0-mode wave was caused by the change in plate thickness. Therefore, observation of the mode properties of Lamb waves would be useful in probing for defects such as abrasions, wear, and wall reduction in plates and pipes. In future research, experiments will be conducted to determine the effect of the thickness ratio at a step and the results will be applied to the detection of defects.

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