Experimental Study on the Mode Conversion of Lamb Wave Using a Metal Plate Having a Notch Type Defect

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Propagation of Lamb wave in an aluminum plate having a notch type defect is observed. Lamb waves passing through the aluminum plate were analyzed by two-dimensional Fourier transform (2D-FFT) to discriminate the modes and their mode conversions. A0-mode Lamb waves which is transmitted into aluminum plate is discriminated using the 2D-FFT charts. The mode conversion from A0 to S0 and A1-mode waves by the notch type defect is clearly detected in the reflected and the transmitted waves. The suggestive result that the ratio of S0 or A1 to A0 indicates the degree of damage has been described. Possibility of a Lamb wave method for detecting defect such as ablation, wear and wall reduction is also referred.

Key Words : Lamb wave, Mode conversion, notch type defect, two-dimensional Fourier transform

1. Introduction

Ultrasonic waves are frequently used in the pulse-echo and pulse transmission methods for the detection of defects in the material. 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 propagation of great distance in the plate or cylindrical structures\(^3,4\). In the Lamb measurement, defects in the material can be quickly detected with one time measurement compared with the point-to-point measurement such as ordinal bulk wave inspection. In the NDE systems employing for a metal plate or pipe structures, Lamb waves or Rayleigh waves have only recently been constructed with a tilted angle polarization type piezoelectric transducer\(^5\) or air-coupled ultrasonic waves in the meghertz range by the authors\(^6,7\).

As is known widely in the Lamb wave studies, the propagation of Lamb waves in a plate is extensively affected by the thickness \(d\) of materials and the frequency \(f\) of the ultrasonic waves. Studies on the propagation behaviors in the plate having varying thicknesses might be useful for obtaining the information about defects.

However, the behaviors of Lamb waves propagation around the defect are very complex\(^8,9\), so that few theoretical research has been conducted. Therefore, only experimental research about Lamb waves propagation in plate of varying thickness has been reported\(^10,11\). To understand the propagation behavior of Lamb waves in a plate of varying thicknesses is very important for the NDE or health monitoring to evaluate the properties such as wear, abrasion and corrosion-induced wall reduction etc.

In this paper, the propagation of Lamb waves in an aluminum plate having a notch type defect is experimentally observed using optical detection method to clarify the propagation characteristics of Lamb waves. The mode conversion of Lamb waves in an aluminum plate and its possibilities of use in NDE will be discussed.

2. Propagation characteristic of Lamb wave

2.1 Generation of Lamb wave

The propagation modes of Lamb wave in plate depends on both the thickness \(d\) of materials and the frequency \(f\) of the ultrasonic waves. The propagation characteristics of Lamb waves can be calculated by the Rayleigh-Lamb equations. Dispersion curves of phase velocity \(c_p\) and group velocity \(c_g\) in aluminum plate (longitudinal wave velocity \(c_l=6410\) m/s, shear wave velocity \(c_s=3040\) m/s) are shown in Figures. 1(a) and (b), respectively. Group velocity \(c_g\) was calculated as,

\[
c_g = \frac{c_p^2}{f \cdot d \cdot \frac{dc_p}{df}}
\]  

(1)

Lamb wave can be efficiently excited when the incident angle \(\theta_i\) satisfies phase matching condition\(^10\). This angle is calculated from the Snell's law as,

\[
\theta_i = \sin^{-1} \frac{c_s}{c_p}
\]  

(2)

Where \(c_s (=2500\) m/s) is the ultrasonic wave velocity in a wedge which exists between a piezoelectric transducer and the plate to insure the oblique incidence of sound wave. Figure 1 shows the dispersion curves of the critical angle \(\theta_i\) in aluminum plate. Thickness \(d=1.0\) mm and frequency \(f=2.0\) MHz are selected to excite the A0 mode Lamb waves because A0 mode Lamb wave has relatively constant group velocity \(c_g\), small velocity dispersion in other word, as shown in Figure 1(b). When \(fd=2.0\) MHz mm, the incidence angle \(\theta_i\) is \(72^\circ\) for the phase matching condition to excite the A0-mode Lamb wave in the aluminum plate.

2.2 Structure of transducer

For effective generation of A0-mode Lamb wave in the aluminum plate, a wedge was inserted between a piezoelectric transducer and a aluminum plate. The wedge was made of epoxy resin \( c_w = 2500 \text{ m/s} \) and the incident angle of wedge was adjusted to 72° as shown in Figure 1(c). The transducer was thickness-mode piezoelectric (PbTiO\(_3\)) 10 mm\( ^2 \) disk and its resonant frequency was 2.0 MHz. The admittance-frequency characteristic of transducer is shown in Figure 2. The transducer and wedge were pasted with silver paint to make the electrical lead.

3. Measurement of Lamb wave propagation in metal plate having a notch type defect

3.1 Experimental Setup

The measurement system for the Lamb wave is shown in Figure 3. A transmitting signal comprising 10 bursts of 2.0 MHz, 130 Vp-p sinusoidal voltage was applied to the A0-mode transducer described in Figure 2 (incident angle 72°). Aluminum plate used here was just rolling and pressed by manufacturer and their surface was not polished. The A0-mode transducer was attached to an aluminum plate by the coupling vacuum grease (Dow Corning silicon grease). An A0-mode Lamb wave from transducer propagates in the aluminum plate and is optically detected by a laser Doppler vibrometer (GRAPHTEC, AT0023 and AT3600) via a reflection mirror to observe the velocity or displacement. Laser Doppler detection method has some benefits as; 1) noncontact measurement, 2) small area (10\( \mu \)m) information are available, 4) real time measurement and 4) broad band measurement. These features are more convenient compared to the acoustic contact method.
measurement. The beam of laser Doppler vibrometer scanned along the direction of Lamb wave propagation from \( x = 0 \) mm to \( x = 60 \) mm at each interval of 0.5 mm. Vibrations on the surface of Lamb waves at each point were measured. Vibrating waveforms from the laser Doppler vibrometer were digitized by oscilloscope (Agilent Technologies, 54845A) and fed into a personal computer via a general purpose interface bus (GPIB).

The aluminum plate has the notch type "slot" which simulates the defect as illustrated in Figure 4. The slot having width of 3 mm and the depth of 0.5 mm was located at \( x = 30 \) mm.

### 3.2 Experimental Results and Discussion

The two-dimensional distribution of each propagation distance \( x \) and time \( t \) of the waveforms determined by the measurement system is shown in Figure 5, and thus the relationship between time and distance of the Lamb waves is visually presented. A0-mode Lamb wave reach the slot region and is observed around 20\( \mu \)s and 25\( \mu \)s as shown in Figure 5. From this chart, position of defect can be observed. To reveal in more detail the nature of defect and the propagation mode of Lamb wave\(^{3,5,10} \), two-dimensional Fourier transform (2D-FFT) was introduced. The \( k-f \) distribution determined from the two-dimensional Fourier transform of the \( x-t \) distribution is shown in Figures. 6(a), (b) and (c).

The frame length of 2D-FFT were 120\( \mu \)s and 60 mm for time \( t \) and distance \( x \), respectively. Optical signals were converted to the electrical one and were truncated by rectangular window.

The \( k-f \) distribution peak at the incident wave region (Figure 6(a)) corresponds to the dispersion curve of the A0-mode Lamb wave. In the figure, two components S0 and A1 are slightly
observed because of short burst excitation. Peaks at the reflected wave region (Figure 6(b)) and the transmitted wave region (Figure 6(c)) correspond to the dispersion curves of the A0-mode, the S0-mode, and the A1-mode Lamb waves. The ratio S0/A0 becomes larger as the depth of defect becomes deeper in our previous research (11). These results imply that the A0-mode Lamb waves were converted to the S0-mode, and the A1-mode Lamb waves at the defect border region. In our previous work (11), the same mode conversion has occurred in the stepped thickness type aluminum plate, so that the main source of mode conversion will occur at the part of the steep change of thickness. Moreover, amplitude ratio of S0 and A0 (S0/A0), which can be obtained from amplitude charts upper side of each Figure 6, would become a useful measure to evaluate the degree of damage. These comprehensive results would allow us to obtain the anomalous information such as wear, abrasion and corrosion-induced wall reduction in the pipe structures.

4. Conclusions

Lamb wave propagation in an aluminum plate with notch type defect was measured optically to exploit the effect of thickness change of plate. Mode conversion from an A0-mode Lamb wave to a S0-mode and A1-mode wave at the defect border in aluminum plate was observed. These mode conversions were occurred by thickness change in notch type defect. Therefore, observation of the mode properties of Lamb waves would be useful in identified the varying thickness in plates. In future research, the experiments will be conducted to determine the effect of the thickness ratio and width at a notch type defect and the results will be applied to the detection of defects. Experimental results for gradually varying thickness type plate are important and the results will be published elsewhere in near future.

References