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MODE EXTRACTION FROM MULTI-MODES OF LAMB WAVE

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Abstract. Computer simulations revealed that multiple reflections of Lamb waves occur at a delamination and a square notch in plates in our previous work. In this study, a single mode extraction technique was developed to confirm the multiple reflections. Since the Lamb waves scattered at defects consist of many dispersive modes, it is difficult to identify a particular mode and estimate characteristics of defects from such signals. The single mode extraction is base on two-dimensional FFT of received signals in time and space, filtering and 2D inverse FFT. Air-couple transducers were adopted for non-contact fast data acquisition. Using this technique, A0 and S0 modes were clearly separated in preliminary tests of intact plates. Furthermore, the multiple reflections of an A0 mode were observed in reflection tests of plates with a square notch. The reflected waves from the edges of the square notch were identified in the extracted A0 mode as two wave packets. The time of flight gave the widths of notches.

INTRODUCTION

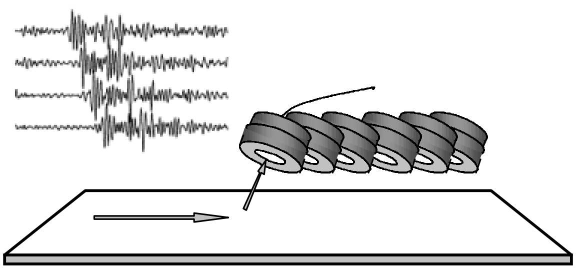
Material properties of plates and cracks in plates have been quantitatively evaluated by a variety of Lamb wave techniques[1,2]. Generally, plate inspections are performed by measurements of Lamb wave velocities, attenuation and mode conversions using single fundamental anti-symmetric and symmetric modes in the low frequency-thickness (*fd*) region. In many cases, however, estimating a propagation path of Lamb wave from the received signals is very difficult due to its dispersivities, mode conversions and the presence of multi-modes, even if incident and receiving angles are adjusted to the appropriate critical angle.

The authors demonstrated in computer simulations that multiple reflections of A0 mode occur at a delamination region of laminated plates[3]. Similarly multiple reflections are recognized for homogeneous plates with a square notch. For the plates with a notch, however, the mode of the reflected waves cannot be identified in received signals due to mode conversions.

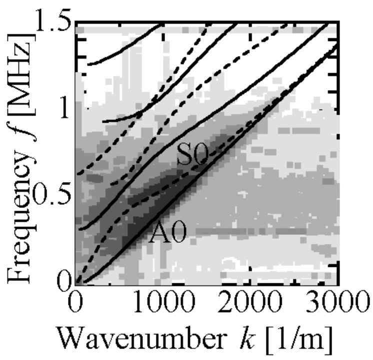
In this paper, a single mode extraction technique is developed to eliminate the effect of the mode conversions and to validate the multiple reflections in the square notch region. The single mode extraction is carried out by detection of Lamb wave at many positions, two-dimensional FFT in the time and space directions, filtering treatments of the resulting *k-f* map and two-dimensional inverse FFT.

EXPERIMENTS

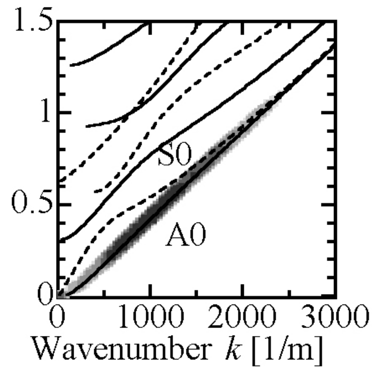
Figure 1 shows a key concept of the single mode extraction. First of all, Lamb waves are recorded in the time domain at many discrete positions in the Lamb wave propagation direction (Figure1 (a)). Applying two-dimensional fast Fourier transform in the time and space direction to the detected signals, a two-dimensional FFT image with respect to wavenumber k and frequency f (k-f map) are obtained (Figure 1 (b)). There are many literatures about plate characterizations using the k-f map[4-6]. Next, a filtering function $F(k, f)$ that retains a mode of interest and eliminates unwanted modes is applied to the k-f map, where the filtering function $F(k, f)$ is determined by the theoretical dispersion curves (Figure 1 (c)). Applying two-dimensional inverse FFT to the filtered k-f map gives extracted waveforms of a single Lamb mode (Figure 1 (d)).



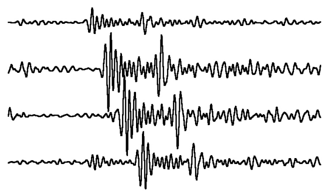
(a) Wave detection at regularly spaced points.



(b) k-f distribution image.



(c) k-f image after filtering.



(d) Filtered waveforms.

FIGURE 1. Key concept of single mode extraction .

A0 and S0 modes were extracted in this study for aluminum plates of 5mm thick. A conventional angled transmitter was used for high power transmission and an air-coupled non-contact receiver was adopted for easy scanning. The angle transmitter consists of a Panametrics V402SB and a polyimide wedge of 60-degree incident angle(c=2520m/s), and adheres to the plate with coupling medium under the weight of 500gf. The air-coupled transducer, MicroAcoustic Model BAT^{TM}-1, was scanned over the plate by a linear stage with auto controller system of LabView. The transmitter used is a broadband transducer with a nominal frequency of 2MHz. Received signals, however, were shift to 0.5MHz due to the high attenuation in air at the high frequency. Thus, incident and receiving angles are adjusted to 60^{o} and 8^{o}, respectively, so as to be a critical angle for the A0 mode. Detected signals were recorded at 100 points in 1mm increments after 256 signal averaging.

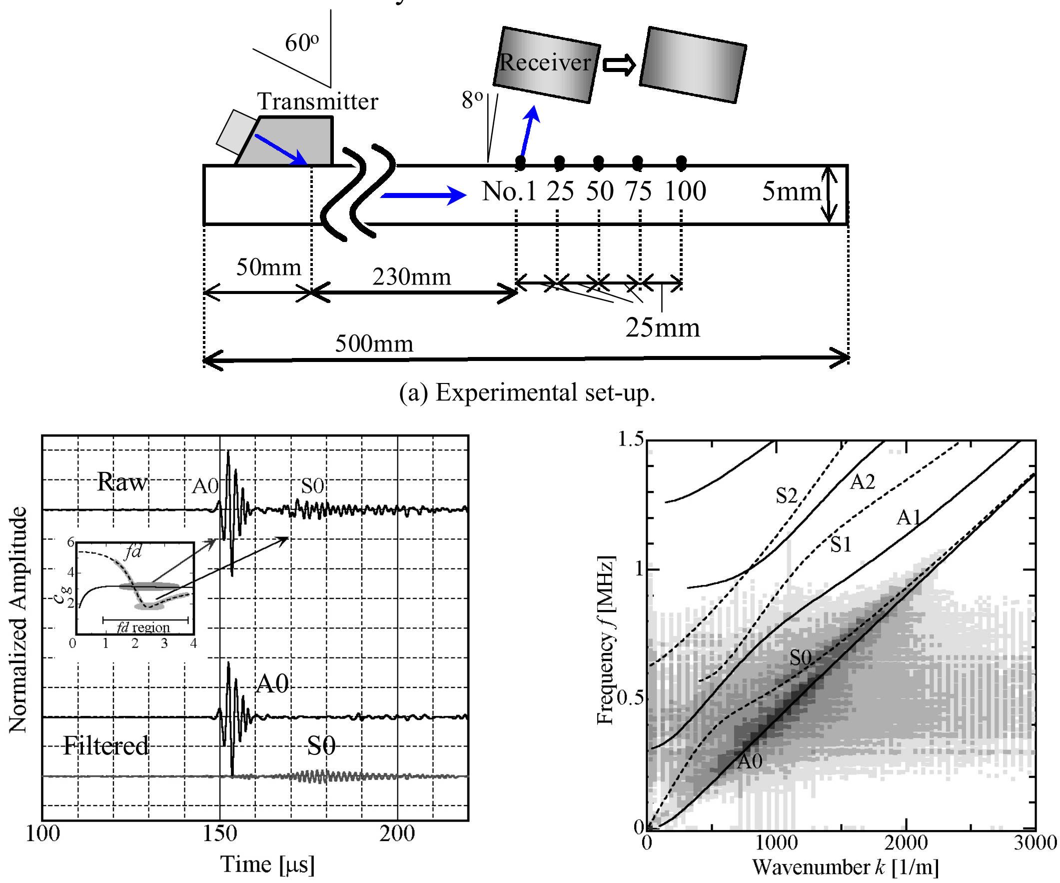
The following Hanning window function was adopted as the filtering function F(k,f),

$$F(k,f)=\begin{cases}0.5+0.5\cos\left\{\dfrac{2\pi(k-k_{\mathrm{X}})}{w}\right\}, & |k-k_{\mathrm{X}}|<\dfrac{w}{2} \\ 0, & |k-k_{\mathrm{X}}|>\dfrac{w}{2}\end{cases}, \tag{1}$$

The center of this Hanning function, the wavenumber k_{X} of mode X (X=A0, S0, ….), is theoretically obtained as a function of frequency f, and the window width w is 200 [m^{-1}] in this paper.

RESULTS AND DISCUSSIONS

Lamb waves are observed for aluminum plates without any notches in the experimental set-up as shown in Figure 2 (a). The results of extraction tests are shown in Figure 2 (b) and (c). In the raw signals, A0 and S0 modes appear at the moments that are predicted from the dispersion curves of group velocity. The raw signals in Figure 2 (b) and the k-f map Figure 2 (c) show that A0 mode is detected much larger than S0 mode. This is because incident and receiving angles are adjusted to the critical angle of A0 mode. Filtered waveforms are shown in the lower Figure 2 (b) where black and gray lines indicate the extracted waveforms of A0 and S0 modes, respectively, and both amplitudes are doubled. These extracted waveforms separately show A0 and S0 modes that could be recognized even in raw signals by estimating from group velocities, which means that the mode extraction can be successfully done.



(a) Experimental set-up.

(b) Raw and filtered signals at the No.50.

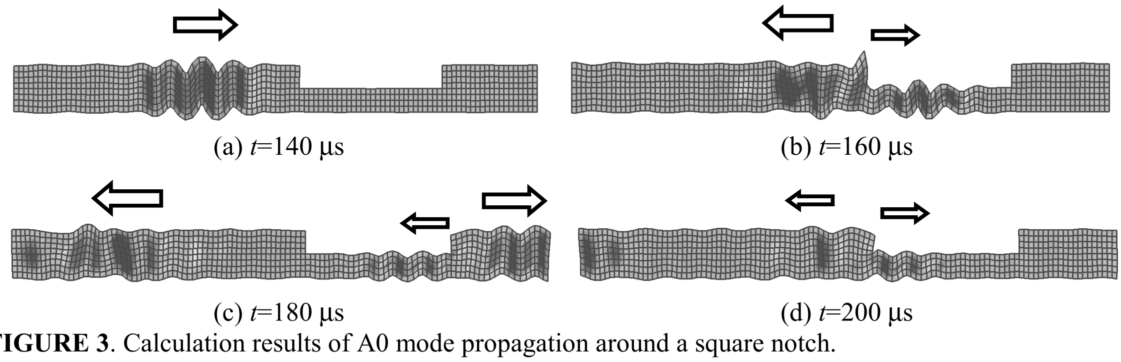
(c) k-f map of raw signals.

FIGURE 2. Experimental results for plates without any notches.

For plates with delaminations, surface corrosions and cracks, however, it is not easy to predict the interaction of Lamb waves with them and to obtain efficient information about the defects because various modes of Lamb wave having propagated in different paths appear in the received signals.

The authors showed that multiple reflections of the Lamb waves occur in a delamination region of laminated plates by computer simulations[3]. Similar phenomena were observed in a square notch region of homogeneous plates as well. Calculation results for the A0 mode propagating in an aluminum plate with a 30mm width - 2.5mm depth (50% of plate thickness) square notch are shown in Figure 3. The A0 mode of Lamb wave that has propagated from the left, is divided at the left edge of the notch into the reflected wave going back to the left region and the transmitted wave propagating to the notch region (Figure 3 (b)). The transmitted wave is separated again into the reflected and transmitted waves at the right edge of the notch (Figure 3 (c)). The reflected wave that has propagated back in the notch region is separated again at the left edge of the notch into the reflected and transmitted waves (Figure 3 (d)). These repetitions cause the multiple reflections. The reflected waves at the edges of the notch, however, are distorted because they consist of not only A0 mode but also the other modes. Thus multiple reflections cannot be clearly seen in the received signals and it is difficult to obtain efficient information about the defects.

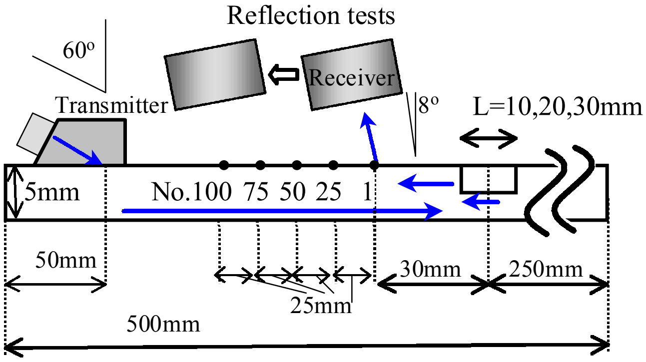
Therefore, A0 mode extraction is applied to such plates with a square notch so as to recognize the reflected waves from the both edges of a notch. Reflected Lamb waves were detected in the configuration as shown in Figure 4 (a). Raw signals (black) and filtered signals (gray) detected at No.25, 50, 75 for the plates with square notches of L=10mm, 20mm and 30mm, are shown in Figure 4 (b), where the amplitudes of filtered signals are doubled. A *k-f* map of raw signals is shown in Figure 4 (c). Many modes other than A0 mode, such as S0, A1 and S1, are clearly observed compared to the *k-f* map for the plates without any notches Figure 2 (c). In detected raw signals (Figure 4 (b) black line), multiple reflections cannot be recognized due to the wave packets appearing in the dotted circles, while in the filtered signals (Figure 4 gray), these wave packets have been eliminated. The first reflected wave from the left edge of the square notch (large arrow) and the second reflected wave from the right edge (small arrow) can be recognized. These time interval corresponds to the notch width, which means that the measurement of Lamb wave gives the information about the width of a notch. Figure 5 shows the time interval of two reflected waves after filtering that is calculated by the cross correlation method. Theoretical time interval obtained from the group velocity (3142m/s) for fd=0.5MHz x 2.5mm; where d=2.5mm is the plate thickness of the notch region, is shown in Figure 5 by the solid line. Very good agreement is obtained and it can be concluded that the measurements of Lamb wave at many points and the extraction of A0 mode gave the approximated width of the notch in plates.



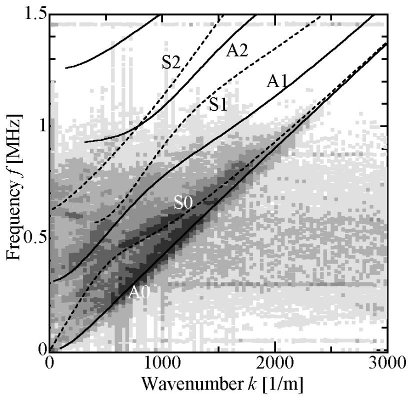
(a) t=140 μs (b) t=160 μs

(c) t=180 μs (d) t=200 μs

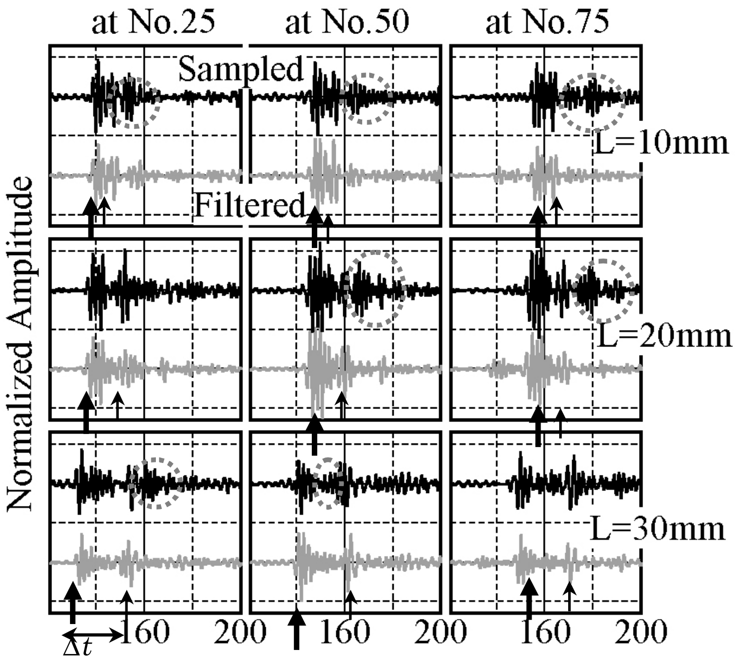
FIGURE 3. Calculation results of A0 mode propagation around a square notch.



(a) Experimental set-up.



(c) k-f map of raw signals



(b) Raw and filtered signals for different notch widths and different observation points.
(Large arrow indicates the reflected wave from the left edge of notch, and small arrow from the right edge.)

FIGURE 4. Experimental results for aluminum plates with square notches.

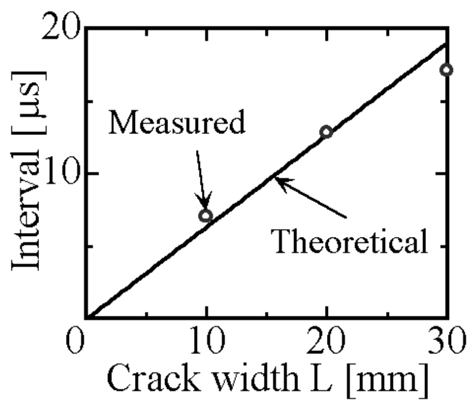


FIGURE 5 Intervals of reflected waves for different notch widths.

CONCLUSIONS

A single mode extraction technique was developed to improve analysis of Lamb wave that is often superimposed by multi-modes. In this technique, the non-contact air coupled transducers enabled to perform easy and fast measurements of Lamb wave at many positions. This extraction technique was validated in the tests for intact plates and for plates with a square notch. For plates without any notches, A0 and S0 modes were clearly separated. In the tests for plates with a square notch, reflected waves from the both edges of the notch could be recognized and the approximate width of the notch was measured.

ACKNOWLEDGEMENTS

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