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Second Harmonic Ultrasonic Waves Detection in Glass Plate with Crack
亀裂を有するガラス板からの 2 次高調波検出

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1. Introduction

Ultrasonic waves have been widely used in the non-destructive evaluation (NDE) of various materials. Measurements using plate waves, such as Lamb waves or Rayleigh waves, have recently been applied in NDE. In many NDE methods, bulk ultrasonic waves have been used for point-to-point inspection. Plate waves, on the other hand, can explore a long distance in a one-time measurement. Moreover, much information can be obtained compared with usual inspection methods using a bulk ultrasonic wave.

Infinitely small amplitude ultrasonic pulse waves are used in most conventional NDE methods. Conventional methods can be used for finding open cracks while they cannot detect closed cracks. Recently, nonlinear ultrasonic (second harmonic or subharmonic) pulse waves have been studied for use in NDE.[1-3] The second harmonic frequency component $2f_0$ is generated by nonlinear vibrations of closed cracks, with the finite amplitude ultrasonic waves having a fundamental frequency component f_0; this phenomenon is known as contact acoustic nonlinearity (CAN).[4]

In our previous study, the real-time detection of a second harmonic component from a glass plate with closed crack using a finite amplitude Lamé mode of Lamb wave, was carried out employing the DLPT and pulse-echo method. In this paper, source of the second harmonic component will be discussed.

2. Dispersion Curves of Lame Waves

Dispersion curves of the phase velocity c_p and group velocity c_g in a glass plate (longitudinal wave velocity c_L = 5800 m/s, shear wave velocity c_T = 3300 m/s, and thickness d = 5.4 mm) are shown in **Figs. 1(a)** and **1(b)**, respectively. Lamb waves can be effectively excited when the incident angle θ_c satisfies the phase matching condition. This angle is calculated from Snell's law as

$$\theta = \sin^{-1}\left(c_w / c_p\right), \tag{1}$$

where c_w (= 2500 m/s) is the ultrasonic wave velocity of the coupling medium such as a wedge. Dispersion curves for the critical angle in the glass plate are easily calculated. A frequency of f = 470 kHz is selected to generate S0 mode Lamb waves. The incident angle θ_c can be evaluated from c_p (3800 m/s) and c_w (2500 m/s) as approximately 40 degrees.

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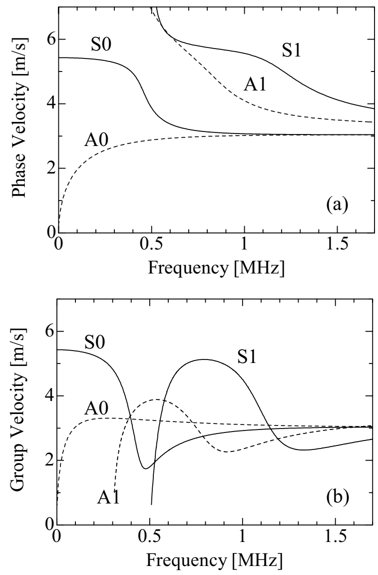

Fig. 1 Dispersion curves.
(a) Phase velocity, (b) Group velocity.

3. Experimental Method

The shape of the glass plate was approximately square (140 mm × 140 mm × 5.4 mm). The center of one side of the glass plate was nicked, and this part was loaded using a gimlet and hammer. A visible crack (open crack) was confirmed, and an invisible closed crack would have grown from the end of the open crack. In this study, the DLPT on the wedge was set 40 mm from the closed crack and 110 mm from the edge of the glass plate.

Experimental set-up is shown in **Fig. 2**. Transmitting signals were generated using an arbitrary waveform generator and their amplitudes were amplified by an amplifier and applied to a double-layered piezoelectric transducer (DLPT)[5]. Ultrasonic pulses of 470 kHz were transmitted through the glass plate via the wedge. Lamb waves were generated as ultrasonic pulse waves propagating through the glass plate. The second harmonic component of the Lamb waves was generated by nonlinear vibrations at the closed crack. The displacement waveform at the edge surface was measured by laser Doppler vibrometer. The waveforms and their spectra were captured by an oscilloscope and second harmonic components could be observed in real time using the fast-Fourier-transform function of the oscilloscope. Finally, the received waveforms were digitized and fed into a personal computer via a general-purpose interface bus.

4. Results and Discussion

Figures 3(a) and **3(b)** show the received waveforms and their spectra without and with pulse inversion averaging (PIA)[5] for the no-crack area and the closed crack area, respectively. In these figures, vertical axes are normalized by the fundamental component of the no-crack area. Fundamental component of closed crack area was smaller than no-crack area because of the reflection and scattering at the crack.

Ratios fundamental to second harmonic components for the no-crack area and the closed crack area were A_1 and A_2, respectively. Relation between the displacement and the difference of A_1 and A_2 are shown in **Fig. 4**. In the case of displacement was approximately 200 nm, second harmonic components were increased by 9 dB compared with smaller displacement. Moreover, when the displacement became over approximately 170 nm, the difference was suddenly increased. It is known that second harmonic components from closed cracks have the threshold. Thus, closed crack is existed in this area.

5. Conclusions

Finite amplitude Lamé mode of Lamb waves were launched into a glass plate having closed cracks using a DLPT. Second harmonic components generated from closed cracks could be detected by laser Doppler vibrometer. In the case of displacement was approximately 200 nm, second harmonic components were increased by approximately 9 dB higher than small displacement. In the future, the locating and imaging of closed cracks will be carried out.

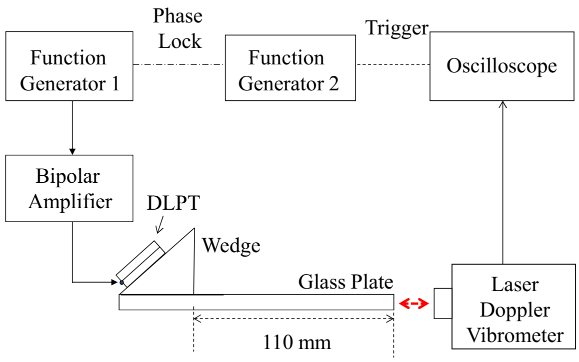

Fig. 2 Experimental set-up.

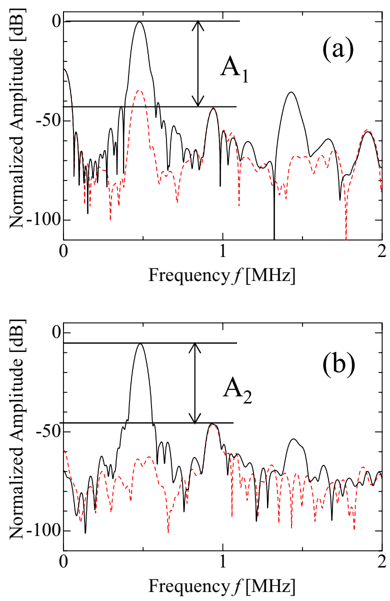

Fig. 3 Spectra of received waveforms (a) in no-crack area and (b) closed crack area, where solid lines are without PIA and dotted lines are with PIA

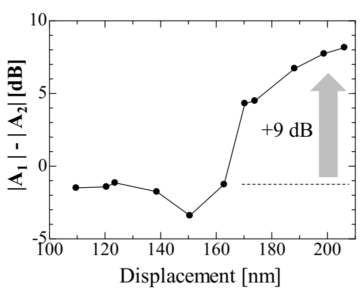

Fig.4 Relation between ultrasonic displacements and second harmonic amplitudes.

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