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Rapid Communication

Sensitive Tint Visualization of Mode Variation of Lamb wave in the Gently Varying Thickness of Glass Plate

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Propagation of ultrasonic Lamb waves in the glass having gently tapered part is visualized by the strobe photoelastic system introducing sensitive tint method. The time transition of ultrasonic pressure of 1.447 MHz burst sine wave propagation are observed. To enhance the contrast of ultrasonic Lamb wave, subtracted image with the C-MOS camera is adopted. As the results, polarities of ultrasound pressure are clearly visualized. As the Lamb wave propagate, higher mode of S2 mode of Lamb waves in the thick part are appeared and they are gradually varied to S0 mode in the thin part via the tapered part of S1 mode.

Keywords : Strobe photoelastic method, Sensitive tint method, Tapered glass sample, Lamb wave mode, Ultrasonic

1. Introduction

The strobe photoelastic method is the representative visualization method for observing the ultrasonic wave propagation in the transparency solid material. The solid sample is arranged between two linear polarizers (polarizer and analyzer) under orthogonal Nicol state to observe the extraordinary ray of birefringence. When stresses are applied to the solid, the birefringence would be generated. In this state, the extraordinary ray is transmitted through the analyzer. Conventional "static" photoelastic method and sensitive tint method which uses the continuous light source can visualize static stresses in the transparent solids. If the pulse light source such as the strobe light source is used, a time transition of the propagation of ultrasonic waves can be observed. Therefore, the "dynamic" stresses propagation are visualized.[1-3] Sensitive tint method is also the useful visualization method for observing the stress in the solid. In the sensitive tint color method, the changing of birefringence is observed in the interference color. Thus, the polarities of the stresses are clearly visualized by this method.[4-5] By combining the strobe photoelastic method and the sensitive tint method, both dynamic properties of propagation of ultrasonic wave and pressure polarities of ultrasonic wave can be observed.

In this paper, the strobe photoelastic visualization system introducing sensitive tint method system has been constructed to visualize the ultrasonic Lamb wave propagation in the gently varying thickness glass. Using this system, time transition of ultrasonic wave propagation and polarities of the sound pressure is visualized. The pattern of Lamb wave mode variation with the wave propagation against the thickness is also visualized. The usefulness of interpretation of the propagation of Lamb waves in plate samples with different thicknesses will be considered.

2. Experimental visualization methods

Fig. 1 shows geometrical dimensions of the glass sample used to visualize the propagation of ultrasonic Lamb wave. Dimension of sample were determined to excite from three modes to one mode by the prediction of calculation. The glass sample was borosilicate glass. At the left and right side of thick part, $l_1 = l_3 = 30$ mm and thickness $d_1 = 7$ mm and $d_3 = 1.5$ mm, respectively. In the center part, the thickness is tapered from 7 mm to 1.5 mm and the length is $l_2 = 40$ mm. At left side part, higher order Lamb mode wave propagate, while only fundamental mode Lamb wave was appeared in the right side part of sample. In all of parts, the width of glass sample is

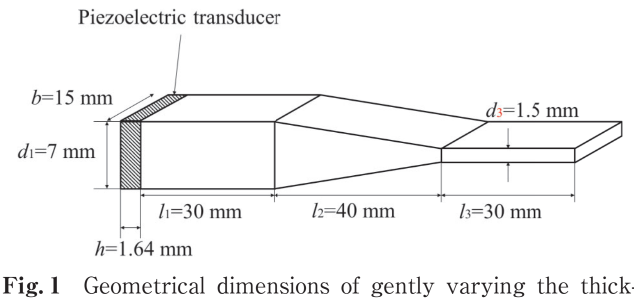

Fig. 1　Geometrical dimensions of gently varying the thickness glass.

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constant at $b = 15$ mm. Transducer was fabricated on the glass surface using silver conducting paste as shown in Fig. 1. Transducer used was a rectangular type $PbTiO_3$ ceramics (Fuji Ceramics, M-6) and have a resonance frequency of 1.447 MHz. Thickness, width and length of the transducer are $h = 1.64$ mm, $d_1 = 7$ mm and $b = 15$ mm, respectively. The transducer and the left end of glass face have the same cross-sectional shape as shown in Fig. 1.

Fig. 2 shows the visualization system of ultrasonic wave.

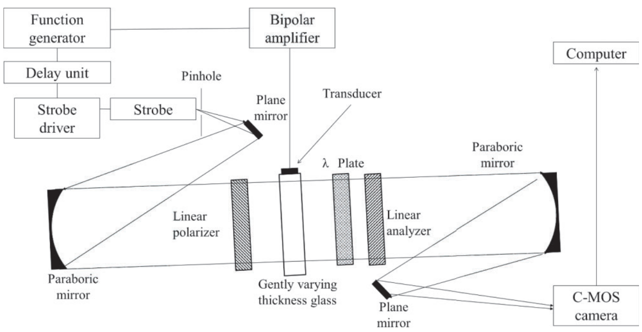

Fig. 2 Ultrasonic wave visualization system using sensitive tint method.

White light from strobe device (Sugawara Lab., NP-1A) was expanded by the pinhole and collimated by the concave mirror. Collimated light is transmitted through the glass sample. Two linear polarizers (the polarizer and the analyzer) were the orthogonal Nicol state. When the glass sample exhibits birefringence by the stresses, only an extraordinary ray by birefringence was transmitted through the analyzer. In Fig. 2, λ plate (Luceo, RETAX-1λ, $\lambda = 550$ nm) was placed between the glass sample and the analyzer. Using λ plate, the retardation of ordinary ray and extraordinary ray appears as interference color.[6] Therefore, the polarities of sound pressure of ultrasonic wave can be observed because the retardation changes by positive sound pressure and negative one. The light transmitted through the analyzer was captured by the C-MOS camera (Artray, ARTCAM-2000CMV-USB3) connected to the computer. Image data from C-MOS camera were saved as 24-bit bitmap data. Excitation voltage signal from the function generator (KEYSIGHT, 33612A) was designed to be 1.447 MHz 30-cycles sine burst wave pulse. This signal was amplified to 140 Vpp by the bipolar amplifier (NF Corp., HSA4101) and was applied to the transducer on the glass sample. The repetition period of burst signal was set to 14 ms.

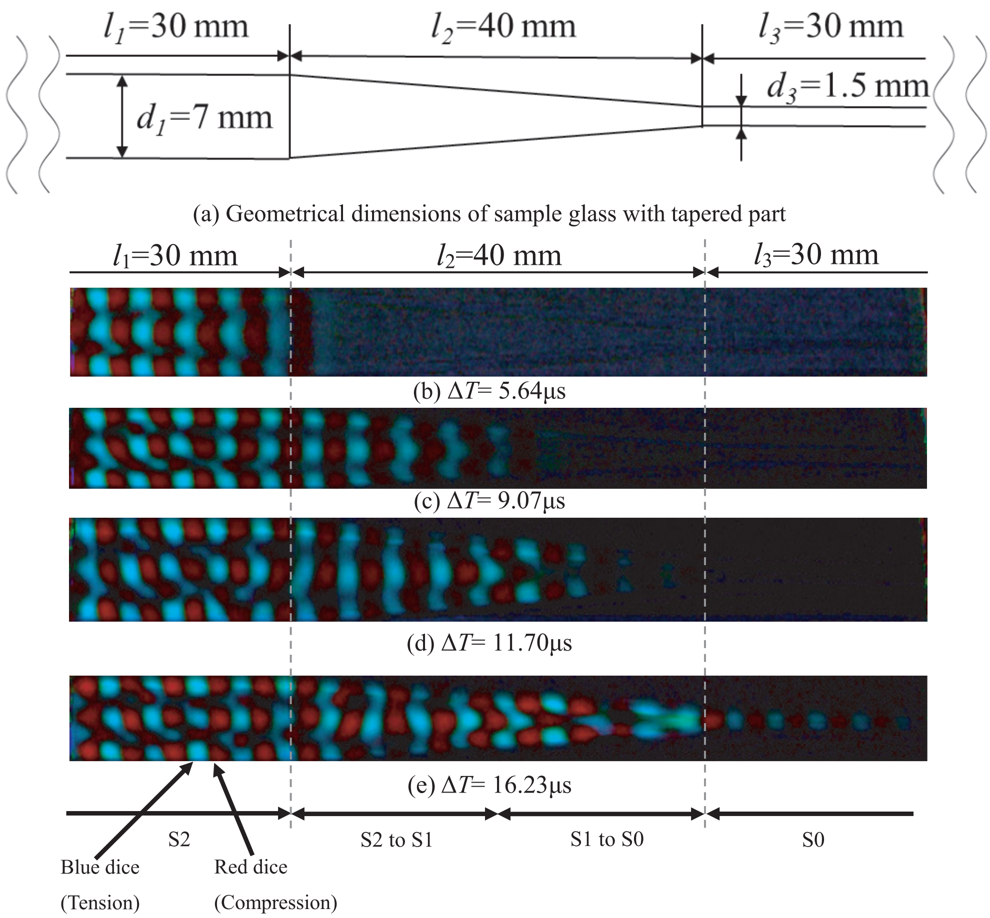

Fig. 3 Visualization images of the gently varying the thickness glass (30-cycle burst sine wave).

Pulsed light with flash time duration of 70 ns can be arbitrary delayed using the pulse delay unit (Sugawara Lab., FG-310) with a time resolution of 10 ns. As the timing of strobe light pulse delayed by the delay unit, the time transition of ultrasonic wave propagation can be observed by varying delay time ΔT of the delay unit. To enhance the contrasts of ultrasonic wave, subtracted image process was adopted.[5,7,8] Light intensity data, RGB color 24 bit map data were then processed at the same time.

3. Experimental results

Fig. 3 show the ultrasonic Lamb wave propagation images of 30-cycle burst sine wave by varying delay times of $\Delta T = 5.64$ μs, 9.07 μs, 11.70 μs, and 16.23 μs, respectively. From the time transition images, Lamb waves are propagated from left side to right side in the glass. On the left side, Odd number of red and blue "dices" are line up in the thickness direction. Therefore, the S mode dominates in this region.[9] S mode propagates symmetrically by repeating stretch and bend motion. In the case of one column, mode is S0 mode. In the case of three column, mode is S1 mode. Thus the number of columns increase with odd number. Since there are five "dices" in the thickness direction, this mode is considered as S2 mode.[9] Similarly, right side "dices" is 1 column, so that S0 mode would be propagated in this region.[9] Center part is transition region, S2 mode generated in the left thick part gradually varies to S0 mode via S1 mode. **Fig. 4** (a) and (b) show the mode dispersion curves at the thick and thin parts respectively. This graph is calculated by analysis software, those are Vallen dispersion attached vallen wavelet (Vallen Systeme GmbH) and code the original program with MATLAB (MathWorks).[10),11] Dispersion curve is calculated by Rayleigh-Lamb equation.[12]

$$\frac{\tan \frac{k_1 d}{2}}{\tan \frac{k_2 d}{2}} = -\frac{(k_0^2 - k_2^2)^2}{4k_0^2 k_1 k_2} \qquad (1)$$

Here, $\omega = 2\pi f$, $c_p = \omega / k_0$, $k_1 = \sqrt{(\omega/c_L)^2 - k_0{}^2}$, $k_2 = \sqrt{(\omega/c_T)^2 - k_0{}^2}$, c_L is longitudinal wave velocity, c_T is transverse wave velocity and k_0 is propagation factor, respectively.[12] Originally, X axis is fd product, but thickness is fixed and calculated. X axis is frequency and Y axis is phase velocity, respectively. Fig. 4 (a) shows dispersion curve of left side part, Fig. 4 (b) shows dispersion curve of right side part respectively. Looking at 1.447 MHz, S0, S1, S2 mode were propagated in the left side part, while only S0 mode was propagated in the right side part, respectively. Therefore, three mode varied to one mode at tapered part. This results agree with the experimental results. In theory, only a mode with constant thickness was obtained, but this method enables how the mode changes. It was demonstrated that it is an effective means to help clarify how

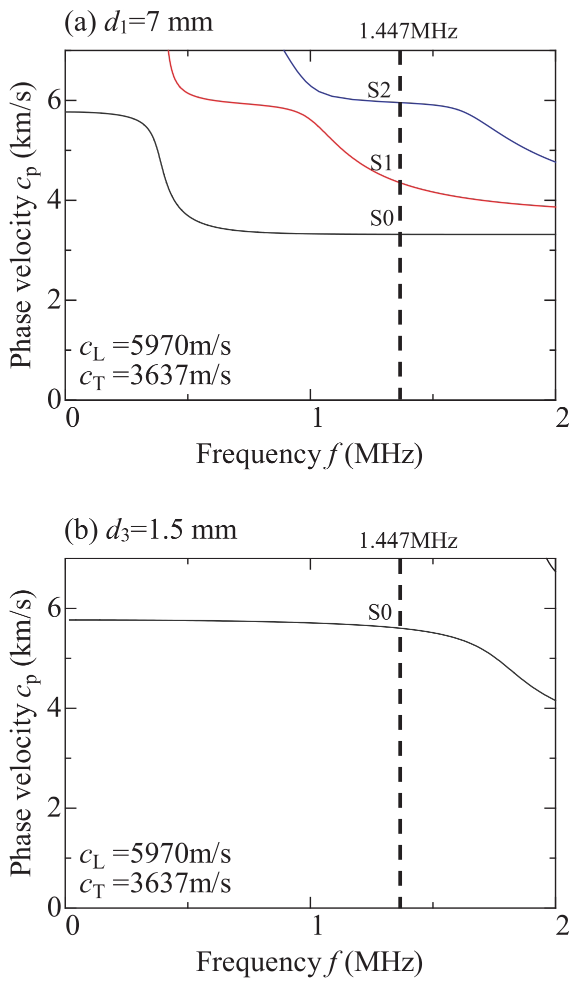

Fig. 4 Dispersion curve of borosilicate glass.

the modes change in varying thickness object. Moreover, in the tapered part, dispersion curves like (a) and (b) cannot drawn because the thickness is not constant. Further examination should be needed to perform the numerical analysis method such as FEM analysis.

4. Conclusion

The propagation of ultrasonic Lamb wave in the gently varying thickness glass was visualized by using the strobe photoelastic visualization system introducing the sensitive tint method. Time transition images of the propagation of ultrasonic Lamb waves in the tapered glass were obtained. Polarities of sound pressure of ultrasonic wave could be easily discriminated by introducing sensitive tint method. Additionally, only dynamic stresses by the propagation of ultrasonic waves could be observed by the image subtraction processing. The behavior of the S2 mode Lamb wave varies to S0 mode via the S1 mode was clearly visualized. It is useful for the interpretation of the propagation of Lamb waves in plate samples with different thicknesses. Next work of this study will be addressed in the examination of analysis such as FEM.

Moreover, the quantitative mode discrimination using image processing will be investigated.

5. Acknowledgement

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