ACOUSTICAL LETTER

Sensitive tint visualization system for Lamb waves propagation in a glass plate

Yoshito Hosaka[1,*] and Kazuhiko Imano[2,†]

[1]*Department of Electrical and Electronic Engineering, Graduate School of Engineering and Resource Science, Akita University, 1–1 Tegata Gakuen-machi, Akita, 010–8502 Japan*

[2]*Department of Electrical and Electronic Engineering, Graduate School of Engineering Science, Akita University, 1–1 Tegata Gakuen-machi, Akita, 010–8502 Japan*

(*Received 29 November 2016, Accepted for publication 19 December 2016*)

Keywords: Strobe photoelastic method, Sensitive tint method, Lamb waves, Polarity of ultrasonic wave pressure, Subtraction image

PACS number: 43.35.Sx [doi:10.1250/ast.38.165]

1. Introduction

The strobe photoelastic method is one of the representative methods for visualizing an ultrasonic field in a transparent solid material [1,2]. When stresses occur in a solid, birefringence is generated. In the photoelastic method, a solid sample is typically arranged between two linear polarizers (a polarizer and an analyzer) to observe the extraordinary ray produced by birefringence. When two polarizers are arranged in the cross Nicol state, the extraordinary ray is transmitted through the analyzer. The conventional "static" photoelastic method and the sensitive tint method which use a continuous light source, can visualize static stresses in transparent solids [3–5]. If a pulse light source such as a strobe light is used, the time transition of the propagation of ultrasonic waves can be observed because "dynamic" stresses are produced by ultrasonic waves [6–10]. The sensitive tint method is also a useful visualization method for observing the direction of stress in a solid, i.e., the polarities of sound pressure can be visualized. In the sensitive tint method, birefringence is observed via the interference color [11,12]. Therefore, the polarities of the stresses are clearly visualized by this method [13–15]. Figure 1 shows examples of the visualization of longitudinal ultrasonic waves. By combining the strobe photoelastic method and the sensitive tint method, the dynamic properties of the propagation of ultrasonic waves and the polarities of sound pressure can be observed at the same time.

In this paper, a strobe photoelastic visualization system incorporating a sensitive tint method system has been constructed to visualize Lamb waves propagation in a glass plate. Using this system, the time transition of S0-mode Lamb waves propagation and the polarities of the sound pressure are visualized. In the next section, the experimental method will be described in detail.

2. Experimental visualization methods and results

To demonstrate the usefulness of our method, S0-mode Lamb waves propagation is visualized in an experiment. Figure 2 shows the visualization system for ultrasonic waves. The glass sample used to visualize the propagation of Lamb waves was a HOYA® glass plate with thickness, width and length of 4.02 mm, 40 mm and 100 mm, respectively. The longitudinal and shear velocities of the ultrasonic waves were 5,500 m/s and 3,100 m/s, respectively. A transducer was fabricated on the glass plate via a plastic wedge as illustrated in the lower part of Fig. 2. This $PbTiO_3$ transducer (Fuji Ceramics, M-6) had a resonance frequency of 500 kHz, a diameter and a thickness of 10 mm and 4.4 mm, respectively. S0-mode Lamb waves were selected for use in the experiment because S0-mode is not interfered with the other Lamb waves modes. The group velocity and phase velocity of 500 kHz S0-mode Lamb waves are 3,100 m/s and 4,660 m/s, respectively. To maximize the efficiency of Lamb waves generation, 500 kHz longitudinal ultrasonic waves obliquely incident to the glass plate via the plastic wedge were adopted to realize the phase velocity matching condition. The incident angle was determined to be 29°, which satisfied the phase velocity matching condition calculated from Snell's law [16,17].

Light from a strobe device (Sugawara Lab., NP-1A) was expanded by a pinhole and collimated by a concave mirror. This light source was an argon tube that emitted white light. The flashing time and discharge tube input of the light source were 75 ns and 17 mJ/flash, respectively. The collimated light was incident on the glass. Two linear polarizers (a polarizer and an analyzer) were set to the cross Nicol state. When the glass sample exhibited birefringence as a result of stresses, only an extraordinary ray produced by birefringence was transmitted through the analyzer. As shown in Fig. 2, a sensitive tint plate (550 nm) was placed between the glass plate and the analyzer. Using the sensitive tint plate, the retardation of the ordinary ray and the extraordinary ray produces an interference color [18]. Therefore, the polarities of the sound pressure of ultrasonic waves can be observed because the retardation is different for positive and negative sound pressures. The light transmitted through the analyzer was captured by a CMOS camera (Artray, ARTCAM-2000CMV-USB3) and fed to a computer. Image data from the CMOS camera were saved as 24-bit bitmap data.

The excitation voltage signal from the function generator (Keysight Tech., 33600A) in the setup was designed to be 500 kHz with a 30-cycle burst sine wave pulse. This signal

*e-mail: imanoken@ee.akita-u.ac.jp

†e-mail: imano@gipc.akita-u.ac.jp

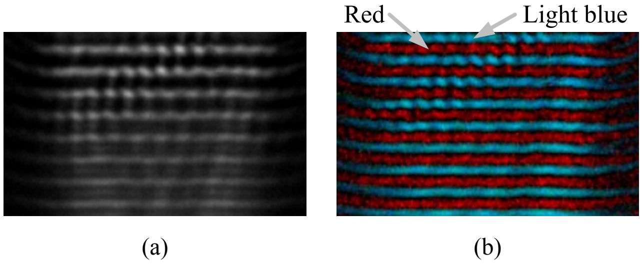

Fig. 1 Examples of visualization. (a) Conventional strobe photoelastic image, (b) sensitive tint image.

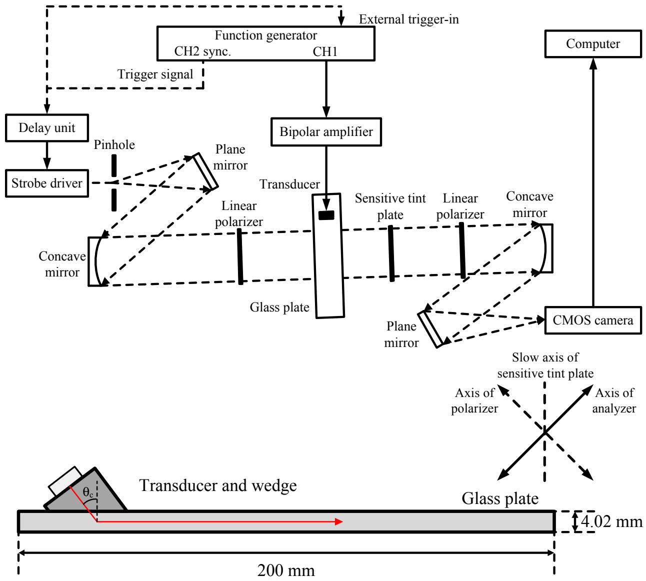

Fig. 2 Lamb waves visualization system using strobe photoelastic method and sensitive tint method. In the lower part of this figure, the transducer, wedge and glass plate are illustrated.

was amplified to $V_{pp} = 100\,V$ by a bipolar amplifier (NF, HSA4101) and applied to the transducer on the glass sample. In this experiment, the transducer was driven by a relatively low voltage to avoid the occurrence of elastic nonlinearity of the transducer and glass sample.

The repetition period of the burst signal was set to 10 ms. The pulsed light was delayed by an arbitrary time using a pulse delay unit (Sugawara Lab., FG-310) with a time resolution of 10 ns. The repetition period (= 10 ms) of the emission of light was synchronized to the acoustic excitation period. Thereby, the time transition of ultrasonic waves propagation can be observed by varying the delay time ΔT of the delay unit. In the imaging process, the differential method [19–21], in which the sound-off image is subtracted from the sound-on image was used to enhance the contrast of the image.

Figures 3(a)–3(d) show ultrasonic waves propagation images of 30-cycle S0-mode burst sine Lamb waves for delay times, ΔT, of 14 µs, 18 µs, 26 µs and 38 µs, respectively. The time transition images show that ultrasonic waves radiated from the transducer and propagated from the left side to the right side of the glass plate. In these images, the areas of red correspond to shear tensile forces and longitudinal compressive forces. The areas of light blue correspond to shear compressive forces and longitudinal tensile forces.

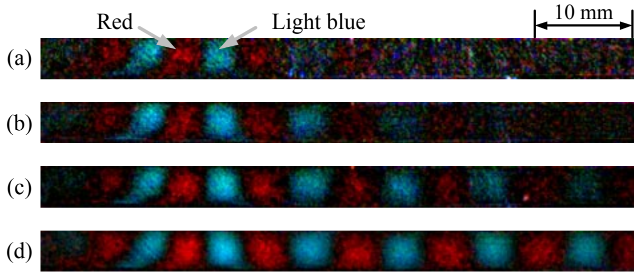

Fig. 3 Visualization images of S0-mode Lamb waves in the glass plate sample (30-cycle burst wave). (a) $\Delta T = 14\,\mu s$, (b) $\Delta T = 18\,\mu s$, (c) $\Delta T = 26\,\mu s$, (d) $\Delta T = 38\,\mu s$.

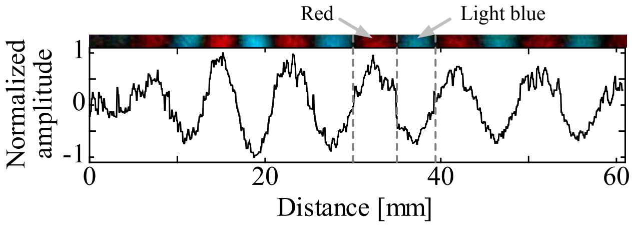

Fig. 4 Waveform obtained from Fig. 3(d).

From the mosaic pattern in Fig. 3(d), the waveform for the distance was obtained as shown in Fig. 4. In this graph, the areas of red correspond to normalized positive sound pressures. Moreover, the areas of light blue correspond to normalized negative sound pressures. The period of the waveform can be observed to be 9.2 mm. If this value is equal to the wavelength λ, the phase velocity can be calculated from the product of the frequency f and λ to be 4,600 m/s. This value agrees with the phase velocity of S0-mode Lamb waves of 4,660 m/s.

Figure 5(a) is an enlarged view of the S0-mode Lamb waves pattern shown in Fig. 3(d). Figure 5(b) shows the displacement vector distribution of S0-mode Lamb waves analyzed by the finite element method (FEM) [22] carried out under the same experimental conditions. The length of each vector corresponds to the magnitude of the displacement. It is clear that red and light blue correspond to shear tension and compression, respectively. Therefore, our strobe photoelastic system incorporating the sensitive tint method is expected to be an effective means of understanding or interpreting Lamb waves propagation and stress distribution.

3. Conclusions

The propagation of ultrasonic Lamb waves in a glass plate was visualized by using a strobe photoelastic visualization system incorporating the sensitive tint method and image processing. The time transition images of the propagation of ultrasonic waves in the glass were obtained. The polarities of

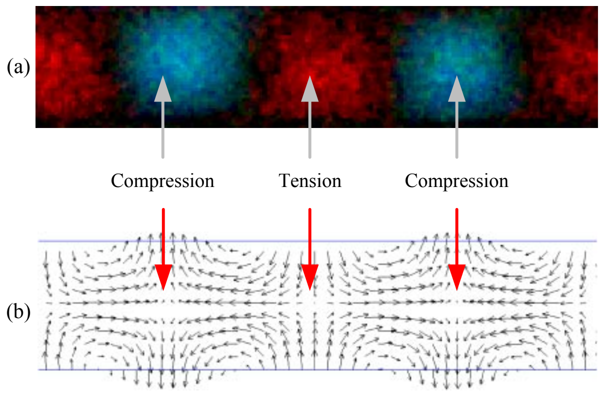

Fig. 5 Partial enlarged view (a) of S0-mode Lamb waves in Fig. 3(d) and displacement vector distribution (b) analyzed by FEM.

the sound pressure of ultrasonic waves could easily be determined by incorporating the sensitive tint method. Furthermore, FEM analysis was performed for comparison with the experimental results. The experimental visualization results were in good agreement with the results of the analysis. In future work, a quantitative measurement system for measuring the internal stress or sound pressure will be developed.

Acknowledgement

This work was supported by JSPS KAKENHI Grant Number JP16K06376.

References

[1] T. Mihara, S. Washimori, T. Hamashima and H. Tashiro, "Development of photoelastic ultrasonic visualization system using pulse laser for the evaluation of high frequency phased array system," *Proc. 30th Symp. Ultrason. Electron.*, pp. 55–56 (2009).

[2] K. Yamamoto, "Optical visualization of ultrasonic waves — The Schlieren technique, the Fresnel method, the photoelastic method and the sensitive tint visualization method applied to see acoustic fields—," *IEICE Tech. Rep.*, US2012-25, 29 (2012) (in Japanese).

[3] R. Yamazaki and M. Miura, *Koudanseijikken Kouzoukaiseki* (Nikkan Kogyo Shinbunsha, Tokyo, 1997), pp. 38–42 (in Japanese).

[4] G. Noselli, F. Dal Corso and D. Bigoni, "The stress intensity near a stiffener disclosed by photoelasticity," *Int. J. Fracture*, **166**, pp. 91–103 (2010).

[5] M. R. Ayatollahi and M. Nejati, "Experimental evaluation of stress field around the sharp notches using photoelasticity," *Mater. Des.*, **32**, 561–569 (2011).

[6] K. G. Hall, "Observing ultrasonic wave propagation by stroboscopic visualization methods," *Ultrasonics*, **20**, 159–167 (1982).

[7] K. Date, Y. Tabata and H. Shimada, "A quantitative evaluation of ultrasonic wave in solid by the photoelastic visualization method," *Proc. IEEE 1987 Ultrason. Symp.*, pp. 1093–1097 (1987).

[8] K. Nishimiya, K. Mizutani, N. Wakatsuki, T. Ebihara and K. Yamamoto, "Visualization of mode conversion of Lamb-type waves in glass plates using pulsed light source," *Jpn. J. Appl. Phys.*, **48**(7S), 07GC06 (2009).

[9] K. Yamamoto, K. Nishimiya, N. Wakatsuki and K. Mizutani, "Optical visualization of coupling modes of leaky Lamb waves with negative group velocity in the solid/fluid/solid trilayer," *Acoust. Sci. & Tech.*, **31**, 185–187 (2010).

[10] S. Washimori, T. Mihara and H. Tashiro, "Investigation of the sound field of phased array using the photoelastic visualization technique and the accurate FEM," *Mater. Trans.*, **53**, 631–635 (2012).

[11] G. Teramoto, T. Oda, H. Saito, H. Sano and Y. Fujita, "Morphology control of polypropylene by crystallization under carbon dioxide," *J. Polym. Sci. B*, **42**, 2738–2746 (2004).

[12] J. H. Yun, K. Kuboyama and T. Ougizawa, "High birefringence of poly(trimethylene terephthalate) spherulite," *Polymer*, **47**, 1715–1721 (2006).

[13] K. Izuno and K. Yamamoto, "Sensitive tint visualization of resonance patterns in glass," *Proc. 31th Symp. Ultrason. Electron.*, 3J-3, pp. 449–450 (2010).

[14] Y. Hosaka and K. Imano, "Visualization of ultrasonic wave propagation in solids by sensitive tint method," *J. ISJ*, **54**, 416–420 (2015) (in Japanese).

[15] Y. Hosaka and K. Imano, "Sensitive tint visualization of ultrasonic propagation in the glass with a crack," *Proc. 36th Symp. Ultrason. Electron.*, 3P2-10, 2 pages (2015).

[16] K. Imano, "A tilted angle polarization type piezoelectric transducer for plate wave generation," *IEICE ELEX*, **4**, 340–343 (2007).

[17] K. Imano, "Experimental study on the mode conversion of Lamb waves in a metal plate of stepped thickness using optical detection," *Int. J. Soc. Mater. Eng. Resour.*, **17**, 201–204 (2010).

[18] Y. Kuroda and K. Suwa, *Henkoukenbikyou to Gansekikoubutsu* (Kyoritsu Shuppan, Tokyo, 1983), pp. 38–43 (in Japanese).

[19] N. Kudo, H. Ouchi, K. Yamamoto and H. Sekimizu, "A simple Schlieren system for visualizing a sound field of pulsed ultrasound," *J. Phys.: Conf. Ser. 1*, pp. 146–149 (2004).

[20] K. Imano, "Optical observation method for ultrasonic field using the shadowgraph introducing pulse inversion averaging," *IEICE ELEX*, **11**(17), pp. 1–6 (2014).

[21] Y. Hosaka and K. Imano, "Strobe photo-elastic visualization of ultrasound propagation in the residual stress field of the solid," *J. Soc. Mater. Eng. Resour. Jpn.*, **27**(1/2), pp. 20–24 (2016) (in Japanese).

[22] ITOCHU Techno-Solutions Corp., "ComWAVE," http://www.engineering-eye.com/ComWAVE/ (Accessed 26 November 2016) (in Japanese).