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Measurement of Stress in Glass Sample Using Sensitive Tint and Sénarmont Method under the Ultrasonic Standing Field

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Abstract

Visualization and quantification of stress distribution in solids caused by ultrasonic standing waves are described. A strobe photoelastic system was improved for quantitative measurements of the stress associated with ultrasonic wave field. The stress field distribution and its value associated with the ultrasonic standing wave at the frequency from 54.30 kHz to 2.15905 MHz in glass was observed by the sensitive color method and the Sénarmont method. The measured value is shown with the frequency at 54.30 kHz at the center of the sample. As a result, by the sensitive color method, the distribution of stress value and the stress polarity are clearly visualized in red and blue colors, and by the Sénarmont method, the stress of several hundred kPa (603 kPa) can be quantitatively obtained at the center position of the glass sample. As a result, an improved photoelastic system introducing sensitive tint and the Sénarmont method has the possibility of the quantitative measurement of the stress in glass samples.

Keywords

Sensitive tint method
Sénarmont method
Birefringence
Retardation
Standing wave

1. Introduction

Glass is a widely used material in various fields, and evaluating its properties, especially knowing stress at any given location as a material, is important in fields such as material evaluation and lifetime estimation. Quantitatively evaluating stress (hereinafter referred to as "stress") in glass from ultrasound information is one of the crucial challenges in nondestructive testing. However, it can be difficult to establish a well-established method for quantitatively observing stress generated by the propagation of sound pressure in a material through ultrasound [1]. Negishi *et al.* observed the interior of glass using photoelasticity and visualized Lamb waves, including fundamental modes and higherorder modes, and the presence of standing waves in the acoustic field [2]. While this method is effective for observing Lamb waves, being a photoelastic method, it observes stress in the same way regardless of the polarity of stress associated with the propagation of sound waves. Additionally, quantitative measurement of stress has not been performed in this experiment.

The authors have been investigating methods to quantitatively measure acoustic pressure information in water and solid materials using optical techniques. We have primarily focused on measuring the dynamic propagation of ultrasound during transmission [3,4]. Recently, we have elucidated the distribution of Lamb waves in glass through experimental and wave-number analysis, revealing the existence of multiple Lamb waves in positions that are not visualized [5].

In this report, in contrast to the above, we describe the potential for visualizing stress fields generated by static stresses, i.e., standing waves within glass samples, and quantitatively measuring their magnitudes using the methods of sensitive tint and Sénarmont [3]. We discuss the capability of determining the polarity of the stress (compression or tension) within glass samples using this approach and describe the quantitative measurement of acoustic pressure in glass samples using the Sénarmont method [4]. By integrating the results obtained through those two methods, we can non-destructively obtain the sign and magnitude of stress within glass samples, and we discuss the possibilities and challenges of this system as a quantitative measurement system.

2. Sample and measurement system

We conducted experiments using glass as a sample to visualize the stress field induced by the acoustic field, specifically the sound pressure distribution, within solid materials. The shape and dimensions of the glass sample are shown in **Figure 1**. A rectangular piezoelectric ceramic transducer (FujiCeramics, M-6) with dimensions of 30.0 mm long, 5.0 mm wide, and 1.0 mm thick was attached to the surface of synthetic quartz glass (50.0 mm long, 50.0 mm wide, and 16.2 mm thick) using conductive paste (Dotite, D-753, Fujikura Kasei Co.). The resonant frequencies within the glass sample for this configuration were 44.93 kHz, 54.30 kHz, 342.88 kHz, 890.19 kHz, 1.26730 MHz, and 2.15899 MHz. These frequencies correspond to the standing wave states of stress, as mentioned earlier. Although the orders of magnitude of these frequencies differ, they were finely tuned to identify observable frequencies. No standing waves were observed at other frequencies, and no images were obtained.

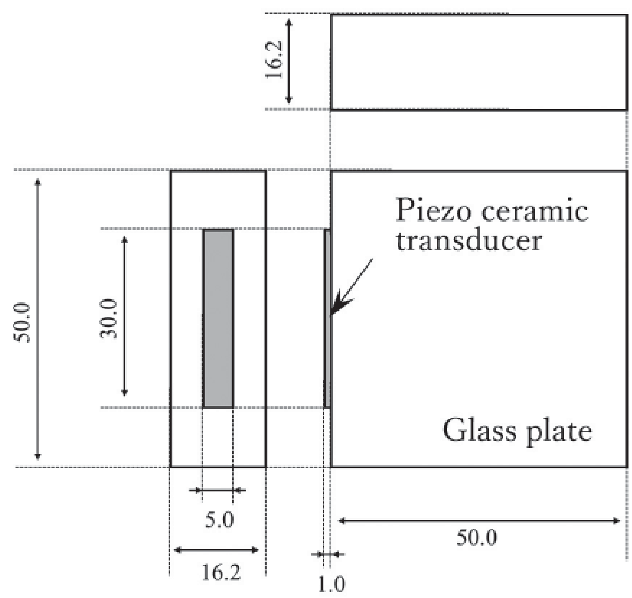


Figure 1. Shape and dimensions of glass plate and piezoelectric ceramic transducer

Figure 2 shows the admittance and phase characteristics of the glass and transducer at this time, indicating sensitivity to standing wave transmission and reception in the range from tens of kHz to approximately 2.3 MHz. While multiple peaks are observed in this figure, the frequency bandwidth Δf between these peaks corresponds to the reciprocal of the round-trip time ΔT of sound waves within the glass sample. This Δf measurement can be used to determine the propagation velocity of sound waves within the sample, denoted as c. However, the accuracy of Δf is low, and c was not determined using this method. In cases where it is necessary to obtain standing waves over a wide frequency range, the above method is not suitable unless the bandwidth of the piezoelectric transducer is broad.

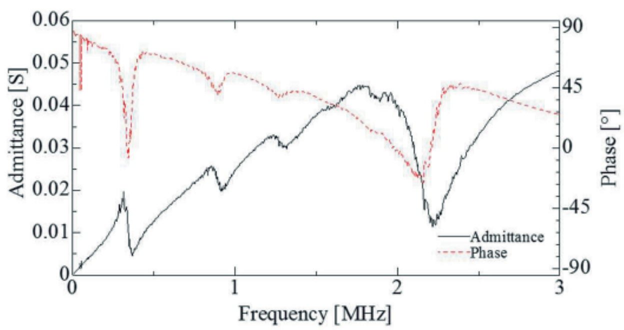


Figure 2. Admittance response and phase characteristic of the transducer with glass plate

Figure 3 illustrates the system for visualizing the stress field within the sample caused by standing wave ultrasound. Initially, two concave mirrors (diameter 80.0 mm, focal length 1,000 mm) were used to place the glass sample. An excitation voltage signal was generated by an oscillator (Keysight Technologies, 33600A) channel 1, amplified to 50 Vpp using a bipolar amplifier (NF Corp., BA4825), and applied to the piezoelectric transducer on the glass sample surface. Pulsed white light with a pulse duration of 70 ns (Sugawara Laboratory, NP-1A) with transformed into a spherical wave through a pinhole, reflected by a flat mirror, and then directed on the right concave mirror. Collimated white light, after passing through a linear polarizer, propagated through the glass sample, causing birefringence due to the stress field and resulting in retardation (R). Subsequently, after passing through a linear analyzer, the light affected by the previously mentioned birefringence was detected by a CMOS camera (ARTRAY, ARTCAM-2000CMV-USB3). At this time, the strobe light's emission period was controlled by an oscillator (channel 2) and set to 50–100 Hz. Moreover, two polarizers (polarizer and analyzer) were set in a crossed Nicol state. When there was no sound, i.e., no stress, the image remained dark as the light was blocked by the two polarizers. When standing wave ultrasound was present within the glass sample, stress distribution occurred, resulting in birefringence and the generation of light that passed through the analyzer, producing images of the standing wave distributions, i.e., stress distributions, as described below. This process is similar to the principles of photoelasticity and sensitive tint method [7,8]. To obtain high-contrast visualizations of the stress field, a λ retarder (Luceo Co., Ltd., one-wavelength plate 550 nm, φ 80.0 mm) was inserted between the analyzer and the glass sample. This allowed obtaining interference colors of red (R) and blue (B) from the RGB color signal at this wavelength, while green (G) was nearly absent. Thus, when there was no stress in the sample (i.e., no standing wave), the entire screen appeared in shades of blue and red, creating a bluish-purple color. As previously mentioned, this is also the principle of conventional sensitive tint methods [6-8]. White stroboscopic illumination at 45° to the X-axis was used, ensuring that the entire RGB color elements were included in the light source. In the experiment, the excitation voltage of the piezoelectric transducer was set to generate a burst sinusoidal wave with a burst interval of 10 ms and 100 cycles, appearing as continuous illumination. The timing of the strobe light was controlled using a pulse delay generator (Sugawara Laboratories, FG-310), allowing continuous changes for observations of wave propagation and dynamic sound waves [6,7]. In this experiment, standing waves were observed with a pulse frequency of 100 Hz. This is similar to continuous light and can be replaced by a continuous white light source as long as it emits white light. This system switches between observing static and dynamic sound waves based on the purpose of the measurement and, therefore, uses a stroboscopic white light instead of continuous light.

Digital sound field image data obtained with a CMOS camera is transferred from the digital camera's memory to the computer. Data transferred to the computer's memory is processed to enhance image contrast. Specifically, normal stress field images are acquired, and 100 images are integrated, averaged, and normalized to eliminate fluctuations in the light source. Subsequently, the same process is applied to acquire background images without sound waves. Finally, the stress field

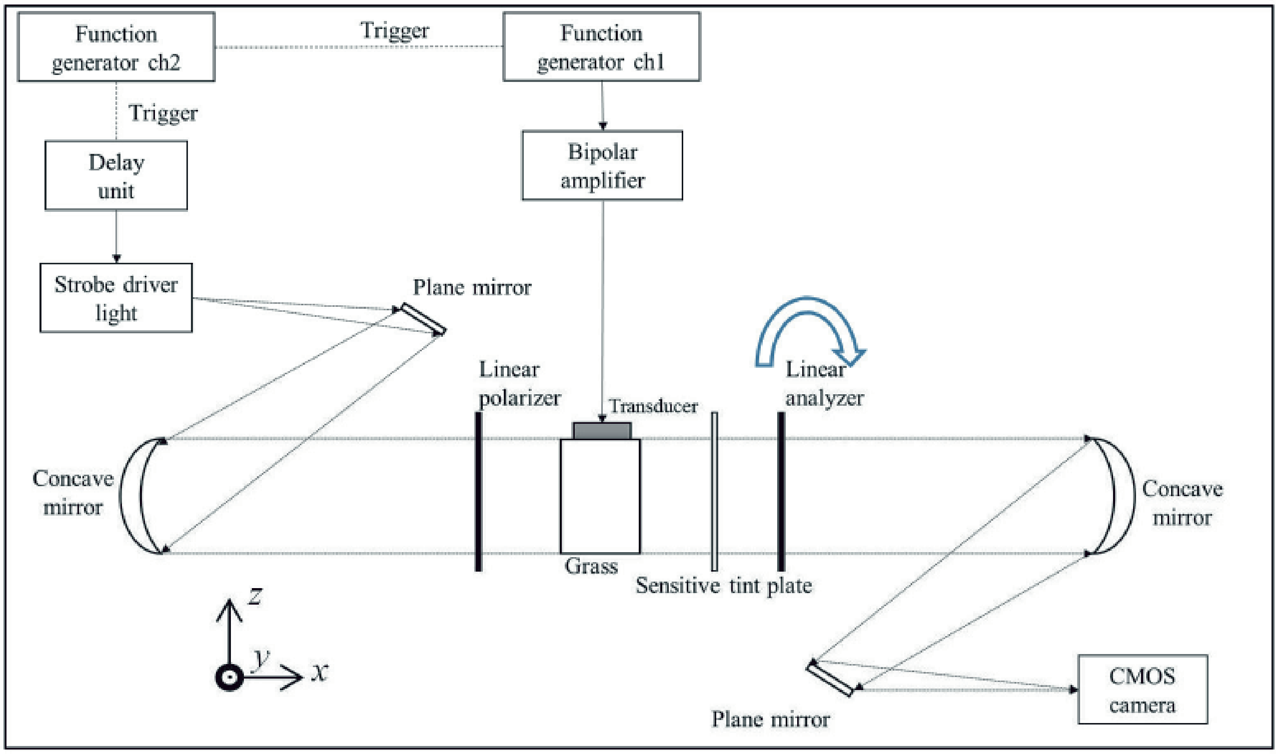


Figure 3. The visualization system of pulsed strobe-sensitive tint imaging system for the stress field of ultrasonic wave in the grass sample. The sensitive tint plate is fixed. The analyzer was rotated to find the light and dark point b 0.1°

images are obtained by subtracting the background image from the acquired stress field image, resulting in a different image. These steps enable the acquisition of high-contrast stress field images [6-8].

In **Figure 3**, by inserting a quarter-wavelength retarder (quarter-wave plate) instead of the λ plate used in the sensitive tint method, the system can be modified to enable experiments using the Sénarmont method [4]. Specifically, in **Figure 3**, if the λ plate is replaced with a 1/4λ plate, the brightness distribution changes when the analyzer is rotated. In this case, we search for points where the brightness increases at any measurement point. In the Sénarmont method, the magnitude of retardation (R) at the measurement point can be determined from the rotation angle θ of the analyzer until the brightness is minimized, and it is proportional to the magnitude of retardation (R) at the measurement point [4,9-12].

$$R = \frac{\lambda\rho}{180°}\theta \qquad (1)$$

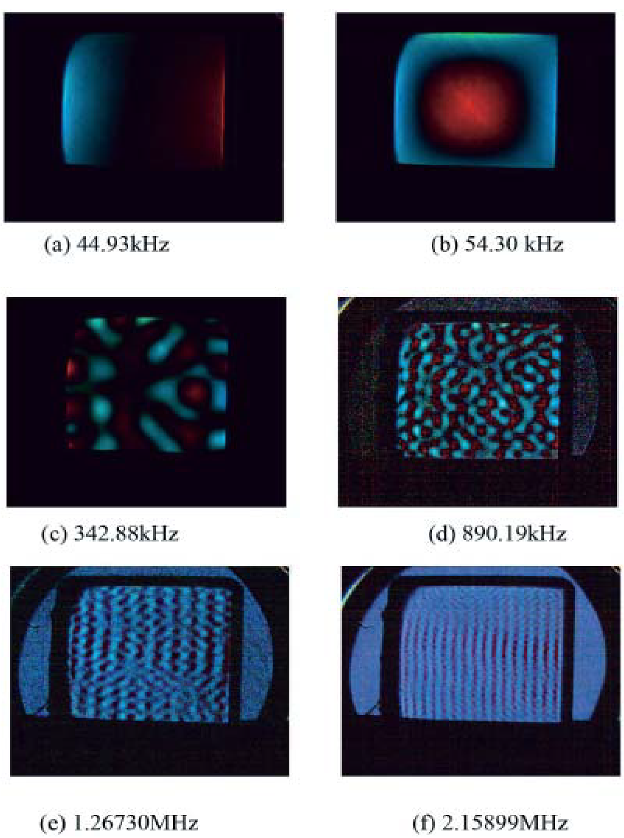
In the above equation, λρ represents the wavelength of light, which in this experiment is 580 nm. The stress σ within the glass sample is as follows:

$$\sigma = \frac{R}{CL} = \frac{\lambda\rho}{180CL}\theta = k\theta \quad (2)$$

Here, C represents the photoelastic coefficient of the glass sample, and L is the thickness of the sample. The constant k is determined as follows [3,4]: it involves using a vise to sandwich a load cell between the glass sample and the vise. Known pressure (f = 203 to 326 N) is applied to the glass sample while measuring the pressure values. Simultaneously, the rotation angle θ of the analyzer is measured. Experimentally, the value of k is determined in this manner. This is because, according to equation (2), the photoelastic coefficient C can vary by approximately 20%–30% depending on the type of glass and its manufacturing process, leading to similar variations in measured values. In this experiment, as mentioned earlier, it is possible to determine stress as described above. By Referencing the measurement positions in the images obtained using the previously mentioned sensitive tint method, it is possible to obtain the magnitude of stress σ at any point within the glass sample, including its polarity.

3. Experimental results and discussion

Figure 4 shows the stress fields induced by resonance due to acoustic waves within the glass sample at frequencies of 44.93 kHz, 54.30 kHz, 342.88 kHz, 890.19 kHz, 1.26730 MHz, and 2.15899 MHz, as observed using the sensitive tint method. The ultrasound propagates from left to right within the sample. In **Figure 4**, bright red and blue points are visible, with red points (tensile stress in the X-direction) corresponding to positive stress and blue points corresponding to negative (compressive stress in the X-direction) stress. Taking the example of the standing wave at the glass's resonance frequency of 54.30 kHz (**Figure 4(b)**), the magnitude of stress σ at the center of the glass sample is 603 kPa, and at this moment, the stress is of positive polarity.



(a) 44.93kHz (b) 54.30 kHz (c) 342.88kHz (d) 890.19kHz (e) 1.26730MHz (f) 2.15899MHz

Figure 4. The stress field caused by standing waves is visualized in color by the sensitive tint method

Figure 5 displays the calculated proportionality constant k between the rotation angle θ of the analyzer and the stress σ. From **Figure 5**, it is determined that the proportionality constant k in Equation (2) is k = 67 kPa/°, using the average value of k at the measurement points shown in **Figure 5**. **Figure 6** illustrates the brightness when changing the rotational angle of the analyzer at a resonance frequency of 54.30 kHz. The measurement point is at the center of the glass. As a result of the measurement, the rotation angle θ of the analyzer was determined to be 9 ± 0.1°, and the magnitude of the stress due to the standing wave can be calculated as follows from Equation (2):

$$\sigma = k\theta = 603 \pm 20kPa \qquad (3)$$

As mentioned above, the stress induced by the standing wave at the resonant frequency of 54.30 kHz in the glass sample used in the experiment is approximately 603 kPa at the center of the sample and is determined to be positive stress.

In this method, there is a significant variation in the value of k, as shown in **Figure 5**, leading to variability in the calculated stress values. One contributing factor to this variation is the visual judgment of brightness when reading the rotation angle of the analyzer. It is necessary to quantitatively measure these factors using light sensors or similar devices. Furthermore, the reading precision of the analyzer's rotation angle θ is 0.1°, which can be improved, leading to increased accuracy. If we calculate stress σ under conditions similar to this experiment, considering the vibration velocity u of the piezoelectric transducer's vibrating surface as described [4], along with the impedance ρ of the sample and the speed of sound c within the sample, we obtained a stress value of 595 kPa. While this value does not match precisely with the experimental result, it falls within the range of variation in k shown in **Figure 5**. In the future, we would like to investigate the precision of these measurements and explore other methods for determining k.

4. Conclusion

We have demonstrated the that stress field induced by

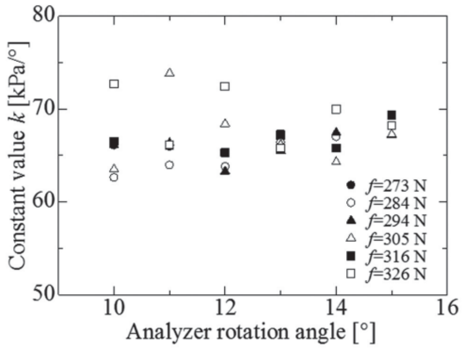


Figure 5. Proofreading of the relationship between analyzer rotation angle and magnitude of stress

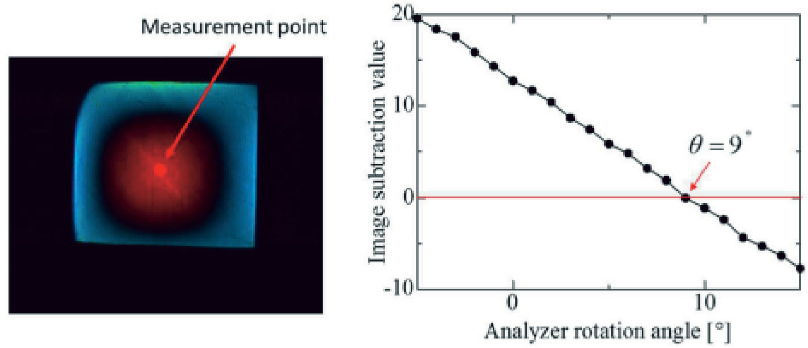


Figure 6. Brightness at the center of the glass sample when changing the analyzer rotation angle (f = 54.30 kHz)

standing waves can be visualized using the sharp color method, and the magnitude of the stress can be measured using the Sénarmont method. By combining these two methods, there is potential to create a system capable of measuring stress at any point within the sample. In the future, we aim to improve the precision of stress magnitude measurements by enhancing the reading accuracy of the analyzer's rotation angle. This method has been developed as a means to measure the polarity and magnitude of stress induced by standing waves, complementing systems that observe the temporal variations of dynamic stress caused by the propagation of dynamic sound waves. We want to develop a system that capitalizes on the advantages of both approaches.

It is worth noting that this method is currently applicable only to transparent materials. However, we would like to explore the development and applicability of a "reflective-type Sénarmont method" for opaque materials, which would rely on reflected light components.

Disclosure statement

The author declares no conflict of interest.

References

[1] Japan Society for the Promotion of Science and Technology, Steelmaking Committee No. 19. Supersonic Detection Method, 1974, Nikkan Kogyo Shimbun, p. 6.

[2] Negishi K, Li HU, 1994, Visualization of Lamb Waves Mode Pattern in a Glass Plate. Ultrasonics, 32(4): 243–248.

[3] Imano K, 2015, Ultrasonic Sound Field Observation using a Laser Beam as a Probe. Japanese Journal of Optics, 44(12): 488–493.

[4] Imano K, 2018, Sound Pressure Measurement of Ultrasonic Waves Using Sénarmont Method. IEICE Transactions on Electronics, Information and Communication Engineers, J101-A(10): 265–267.

[5] Suzuki K, Imano K, 2020, Experimental Study on the Thickness Distribution of Lamb Waves in Glass Plates Using the Sensitive Color Method. Journal of the Acoustical Society of Japan, 76(4): 203–206.

[6] Hosaka Y, Imano K, 2015, Visualization of Ultrasonic Wave Propagation in Solids by Sensitive Tint Method. Journal of Imaging Society of Japan, 54(5): 416–420.

[7] Hosaka Y, Imano K, 2017, Visualization of Lamb Waves in A2 Mode by the Sensitive Tint Method. Journal of the Society of Materials Engineering for Resources of Japan, 28(1/2): 19–24.

[8] Hosaka Y, Imano K, 2016, Visualization of Ultrasonic Waves Propagating in Cracks and Residual Stresses in Solids by Stroboscopic Photoelasticity. Journal of the Society of Materials Engineering for Resources of Japan, 27(1/2): 20–24.

[9] Kuroda Y, Suwa K. [Polarized Light Microscopy and Rock Minerals]. 1968, Kyoritsu Shuppan Co., Ltd., Tokyo, p. 38–41 + 43–44.

[10] Kishii, 1991, Application Technique of Strain Tester IV: Principle and Application of Theoretical Sénarmont Method. The Glass, 1991(20): 26–33.

[11] Tsuboi. Polarizing Microscopy, 1959, Iwanami Shoten, Tokyo, p. 147–158 + 163.

[12] Yamamoto K, Izuno K, Aoyanagi M, 2011, Sensitive Tint Visualization of Resonance Pattern in Glass. AIP Conference Proceedings, 1433: 114–120.

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