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Sensitive tint visualization of resonance patterns in glass
ガラス共振パターンの鋭敏色可視化

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1. Introduction

Optical visualization of ultrasonic waves is helpful for understanding wave propagation in transparent materials. Stroboscopic ultrasonic visualizations, such as the Schlieren technique[1,2], Fresnel method[3], and photoelastic method[4-6], have been used to find solutions to the problems encountered in ultrasonic non-destructive testing and the evaluation of probe design and performance. Video visualizations of vibrating materials and traveling ultrasonic pulses are also useful educational tools for studying wave behavior and properties.

Photoelastic visualization can be used to clarify the vibrational modes of solid materials which consist of complicated longitudinal and shear strains. However, it is difficult to determine the sign of a stress field. In this paper we describe the color visualization of the plane-strain vibration modes[7] of a glass cylinder using stroboscopic photoelasticity with a sensitive tint plate. This technique allows us to determine the sign of the stress.

2. Experimental methods

The proposed sensitive tint visualization system is based on the photoelastic method described by several authors. **Figure 1** shows a schematic diagram of our visualization system using the stroboscopic photoelastic technique with a sensitive tint plate to observe the plane-strain vibration modes in a cylinder. Light is collimated by a condenser lens L1 and passed through the glass cylinder. Polarizing plates (polarizer P and analyzer A) satisfying the condition of crossed Nicols are used. In order to obtain a color visualization of the resonance stress, a λ retarder (530 nm) is inserted between P and the lens L2. Stroboscopic illumination at 45° linear polarization to the x axis is used. When quarter wavelength retarders producing circularly polarized light are used in photoelastic technique, isotropic sensitivity for resonance modes in the vibrating plane is obtained.

The specimen for visualization was an optical-quality glass cylinder (30 mm in diameter, 50 mm in length). The velocities of longitudinal and transversal waves in the glass (BK-7) are 6000 and 3630 ms^{-1}, respectively. Poisson's ratio is 0.22. A PZT circular disc transducer was placed under the glass cylinder to excite a class of plane-strain vibration modes in the specimen. The transducer is driven by continuous waves in the frequency range of 100 kHz to 1.5 MHz. If a resonance condition of the plane-strain modes of the glass cylinder is satisfied, a characteristic mode pattern is clearly visible. Very close to resonance frequencies, we can see the resonance patterns vibrating slowly. The stroboscopic light source delivers a light pulse as short as 180 ns with a frequency of about 60 flashes per second. The timing of the light flash is synchronized with the CCD camera.

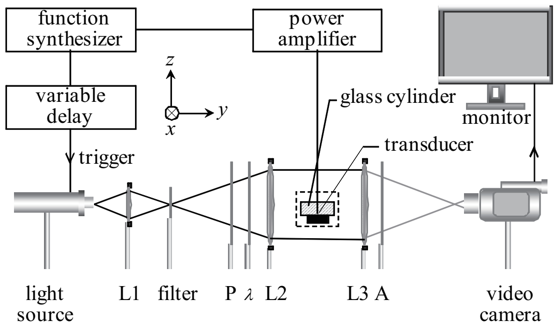


Fig. 1 Experimental setup for the visualization system of the stroboscopic photoelastic technique in sensitive color.

We consider resonance frequencies of the plane-strain vibration mode in a glass cylinder of radius a, transverse wave velocity v_T, and Poisson's ratio σ. We also assume that the cylinder has infinite length; therefore, we can neglect mode coupling via evanescent modes at the ends. The spectrum of resonances is obtained from solutions of

$$\det\left(b_{pq}\right)=0\,, \tag{1}$$

where

$$\begin{aligned}
b_{11} &= \left(n^2-1-y^2/2\right)J_n\left(\alpha y\right),\\
b_{12} &= \left[n\left(n^2-1\right)-y^2/2\right]J_n\left(y\right)-\left(n^2-1\right)yJ_{n+1}\left(y\right),\\
b_{21} &= \left(n-1\right)J_n\left(\alpha y\right)-\alpha yJ_{n+1}\left(\alpha y\right),\\
b_{22} &= \left[n\left(n-1\right)-y^2/2\right]J_n\left(y\right)+yJ_{n+1}\left(y\right).
\end{aligned} \tag{2}$$

In these expressions n is any non-negative integer,

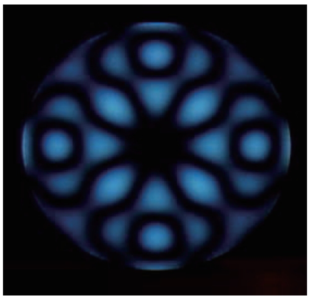
J_n and J_{n+1} are Bessel functions, and $\omega = 2\pi f$ is the angular frequency. The variables y and α are defined by

$$y = a\omega / v_T \, ; \quad \alpha = \left[\left(1-2\sigma\right) / 2\left(1-\sigma\right) \right]^{1/2} . \qquad (3)$$

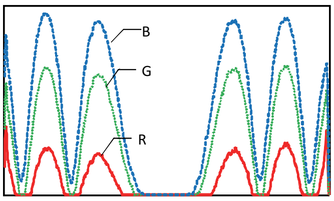
By applying the electric fields to the transducer at the theoretical resonance frequency, resonance vibration may be observed.

3. Experimental results

A typical plane-strain vibration mode pattern in the glass cylinder visualized by the standard photoelastic method is shown in **Fig. 2**(a). We can see that resonance mode of 6-3 at 496.6 kHz has bright spots corresponding to the stress of vibration. The frequency of maximum brightness of the photoelastic image is in good agreement with the theoretical calculation in eq. (1). In the standard photoelastic method both positive and negative stresses are indicated by bright areas. Thus, we cannot determine the sign of stress from the stress birefringence pattern. **Figure 2**(b) shows red, green and blue luminance distributions along the horizontal center line on the cylinder. The three colors have very similar distributions.



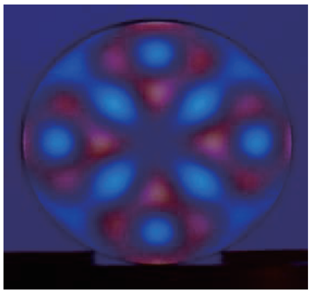
(a) visualized image



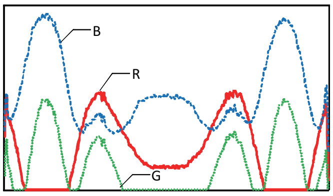
(b) RGB distributions

Fig. 2 Resonant plane-strain vibrating pattern in the glass cylinder visualized using the standard photoelastic method.

The resonance mode of 6-3 visualized using a sensitive tint plate is shown in **Fig. 3**(a). Although Fig. 3(a) is not shown in color, the actual image has red and blue bright spots: red spots correspond to positive stress and blue spots correspond to negative stress. In **Fig. 3**(b) peaks in red and blue luminances appear alternately. Thus several strain-plane vibration modes in the optical glass cylinder can be visualized in color and the sign of stresses can be determined visually.



(a) visualized image



(b) RGB distributions

Fig. 3 Resonant plane-strain vibrating pattern in the glass cylinder visualized in color by the sensitive tint plate method.

4. Conclusion

We have shown that the plane-stain resonance of a cylinder can be adequately described using the theory of such resonances for a cylinder of infinite length, which neglects the influence of the boundary conditions on the end faces. In transparent media, such resonances are readily observed by means of stress birefringence. We have obtained a color visualization of resonance patterns using the photoelastic method with a sensitive tint plate. The sign of stress fields can easily be shown by this method.

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