VISUALIZATION OF ULTRASONIC WAVES IN A SOLID BY STROBOSCOPIC PHOTOELASTICITY AND IMAGE PROCESSING TECHNIQUES

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INTRODUCTION

Visualization of ultrasonic waves propagating in a solid is very useful for studying the characteristics of the ultrasonic wave generation and propagation. Applications considered are:

1) development of ultrasonic probes,
2) study of basic behavior of ultrasound in a solid,
3) understanding ultrasonic testing of complex shape components,
4) training of ultrasonic testing operators.

For these purposes, some visualization systems have been developed using photoelastic or schlieren method (1-5). Since the visualization system visualizes stresses in the test piece, residual stress induced by machining of the test piece is visualized at the same time, as the ultrasonic waves. This disturbs the analysis of the visualized ultrasonic wave behavior.

We have developed an ultrasonic wave visualization system, based on the synthesized photoelastic method, using a stroboscopic light source and a digital image processing computer (6). The system has high sensitivity for ultrasonic wave visualization and measures the sound pressure distribution from the visualized ultrasonic waves quantitatively.

In order to eliminate the image due to the residual stress and to improve the visualized ultrasonic wave picture, we have applied some image processing techniques. Subsequently, these techniques made ultrasonic wave images very clear and, at the same time, the sensitivity of the ultrasonic visualization increase. In this paper, we describe the visualization system and the effects of image processing, and show various images of visualized ultrasonic waves propagating in a solid.

VISUALIZATION SYSTEM

The diagram of the developed visualization system is shown in Fig. 1.

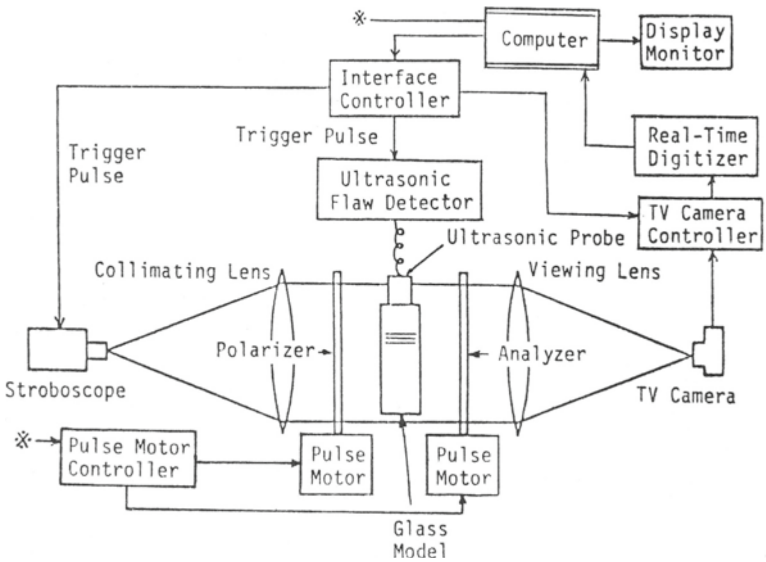
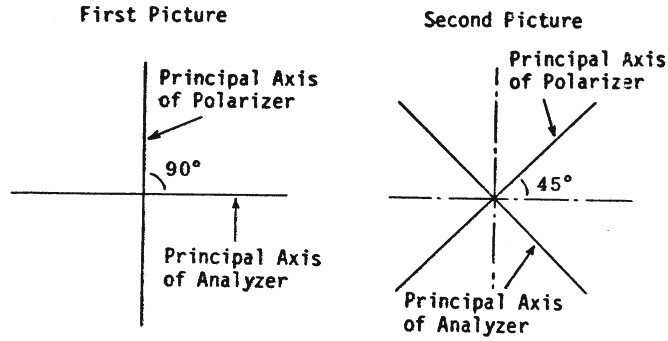


Fig. 1 Diagram of Ultrasonic Wave Visualization System

The optical part of the system has a linear polariscope with a stroboscopic light source, having a flashing time short enough to visualize the ultrasonic waves traveling with very high speed as a still picture. Two pulse motors for rotating polarizer and analyzer axis are needed to perform the synthesized photoelastic method, which enable this visualization system to have high sensitivity and quantity. The trigger pulse actuating the stroboscope has the delay time against that of ultrasonic flaw detector and, by varying the delay time, an observer varies the position at which the ultrasonic wave is stroboscopically frozen and imaged. Pyrex glass, having 20 mm thickness, was used for a visualization medium, because it has a better stress-optical coefficient than most inorganic glasses and the ultrasound velocities of this glass are very similar to that of the steel. This means that conventional ultrasonic flaw detector and probes for practical non-destructive testing can be used for this visualization experiment as a same way.

SYNTHESIZED PHOTOELASTIC METHOD

When using linear polarized light, the visualized picture varies according to the change of the direction of polarizer's and analyzer's principal axis because the visualized image contains isoclinic lines. Figure 2 illustrates the brightness at any point when the same stress field is observed in the linearly polarized light. In this figure, I_1 is the intensity of the brightness at any point on the first picture and I_2 is on the second picture. In the case of synthesized picture, the intensity of the brightness at any point corresponds to only the principal stress difference. The relationship between the intensity of the brightness and the principal stress difference is the same as the case of the circular polarization obtained using quarter wave plates. But the sensitivity of the ultrasonic wave visualization using synthesized technique is much higher than that using circular polarized light (6). Since the relationship between principal stress components are well known as shown in Fig. 2, the ultrasonic wave stress (sound pressure) can be calculated from the measurement of the intensity of the brightness on the synthesized



$$I_1 = a^2 \cdot \sin^2 2\theta \cdot \sin^2 \frac{\delta}{2} \qquad I_2 = a^2 \cdot \cos^2 2\theta \cdot \sin^2 \frac{\delta}{2}$$

$\delta = C \cdot d \cdot (\sigma_1 - \sigma_2)$ σ_1, σ_2:Principal Stress Value

C:Photoelastic Constant d:Thickness of Test Piece

θ:Angle Between Direction of σ_1 and Principal Axis of Polarizer in First Picture

Synthesized Picture

$$I = I_1 + I_2 = a^2 \cdot \sin^2 \frac{\delta}{2}$$

Sound Pressure

Longitudinal Wave ······ σ_1 ($\sigma_2 = 0$)

Shear Wave ················ σ_1 ($\sigma_2 = -\sigma_1$)

Fig. 2 Synthesized Photoelastic Method

picture. Synthesization of the first picture and second picture was performed in the computer.

IMAGE PROCESSING TECHNIQUES

Applied image processing techniques included averaging treatment by accumulation of input images, elimination of residual stress pattern by image subtraction, drawing an outline of test piece and probe, and contrast enhancement. Conventional averaging technique and contrast enhancement were done to the visualized images.

Visualized pictures obtained before ultrasonic waves are generated by the probe show the residual stress field induced by machining the test piece. We subtracted the intensity of brightness on the picture without ultrasonic waves from the intensity on the visualized picture containing ultrasonic waves for elimination of the residual stress pattern. In this image subtraction, absolute values of the intensity difference between both images are needed for getting the actual ultrasonic wave image. The reason is that, when longitudinal waves are traveling in the compressional residual stress field, the intensity of the brightness increases in the compressional stress part of the longitudinal wave by adding the compressional stress due to the residual stress field, and in the tensile stress part of the longitudinal wave, the intensity decreases by adding the same compressional stress. In the case of shear wave, similar intensity increases and decreases occur when traveling in the residual stress field.

After elimination of residual stress pattern, contrast enhancement treatment is done to that image. Procedures for drawing outline of the test piece and probe are as follows:

1) slightly break the crossed condition of the polarizer-analyzer's principal axis and then an image without ultrasonic waves is input.
2) perform smoothing treatment to this input original image and make comparative image between the smoothing image and the original image, which is before smoothing treatment.
3) binarize the comparative image and obtain outline of test piece and probe.

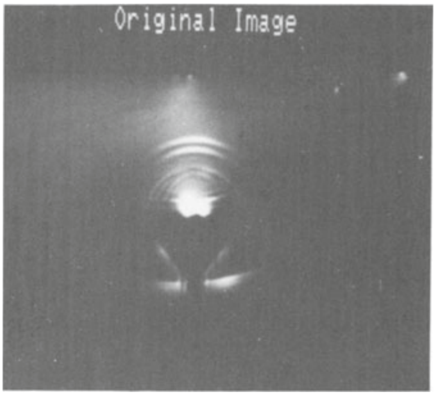
Where, in the first step breaking crossed condition loses stress visualization sensitivity, an outline of the test piece and probe can be observed clearly by increasing the brightness of the visual field. In the second step, an outline can be obtained by making a comparative image, because an abrupt intensity change exists on the outline of the test piece and probe in the original image and then intensity change occurs by smoothing treatment only near the outline. The outline image is added to the ultrasonic wave image after elimination of the residual stress pattern and contrast enhancement.

VISUALIZED ULTRASONIC WAVES

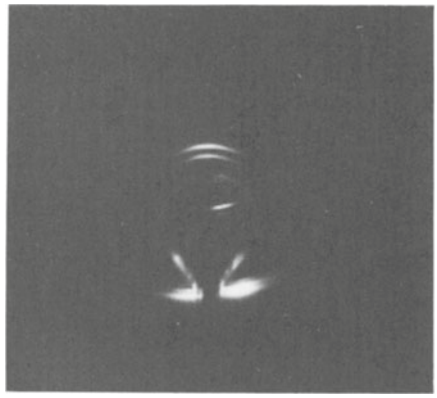
The effect of these image processing procedures are shown in Figs. 3a, 3b, and 3c. These three pictures are obtained from the same ultrasonic waves, showing the reflection of longitudinal wave at the artificial crack-like defect (slit). Incident longitudinal wave (IL) propagating down along the defect surface is emitted from the probe, and cylindrical longitudinal wave (RL) and shear wave (RT) are produced by the reflection of incident longitudinal wave at the defect tip. Part of the incident longitudinal wave propagating along the defect surface converts to the shear wave, which has straight wave front and bridges over between the incident longitudinal wave (IL) and reflected shear wave (RT). This straight shear wave is called a head wave. Hereafter in the visualized image, L is denoted to longitudinal wave, T is shear wave, S is surface wave, I is incident wave and R is the reflected wave.

Figure 4 presents the generation of 10 MHz longitudinal wave. The diameter of the transducer is 6 mm. The cylindrical shear wave, in which the center is the edge of the probe, is emitted accompanied with the generation of longitudinal wave.

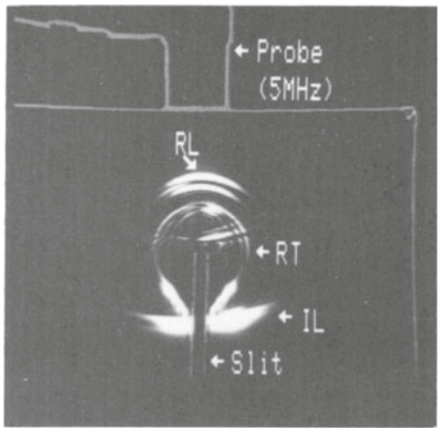
Figure 5 and 6 show the simulation of immersion testing. Figures 5 was obtained using rectangular glass model, and Fig. 6 was from a cylindrical shape glass model. As is similar to the case of direct contact of normal probe shown in Fig. 4, longitudinal wave and shear wave are generated in the normal incident.(Fig. 5(a) and Fig. 6(a)) In oblique incidence, refraction occurs at the water-glass boundary because the wave speeds in the water and glass are different. Normally refracted angle of longitudinal wave is larger than that of shear wave because longitudinal wave propagates faster than shear wave. This refraction law is well known as a Snell's law. In Fig. 5(b), the refraction phenomenon is agreed with the law. But in Fig. 6(b), the refraction angle of the shear wave is larger than that of the longitudinal wave when the longitudinal wave in water is incident to the curved water-glass boundary. Since actual



(a) Original visualized image



(b) After subtraction



(c) After image processing

Figs. 3 Effect of image processing

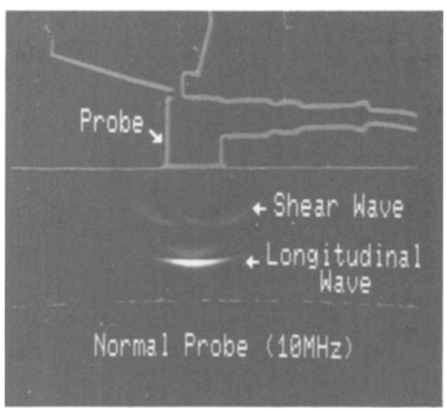
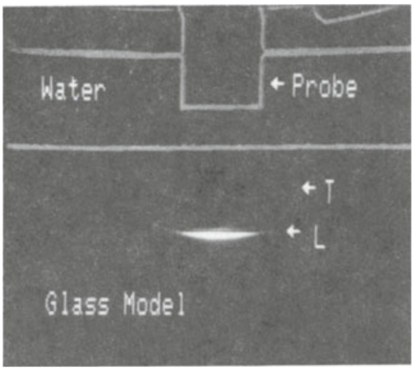
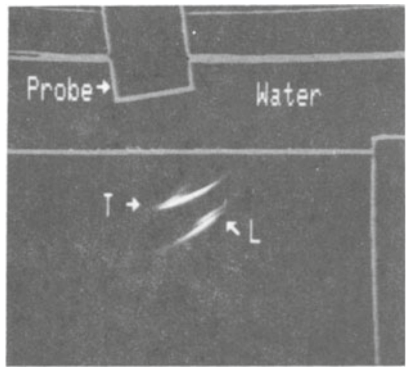


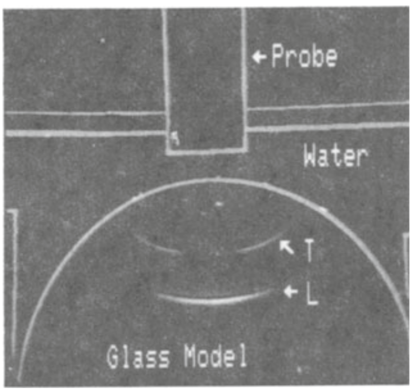
Fig. 4 Generation of longitudinal wave and shear wave from a 10 MHz normal probe

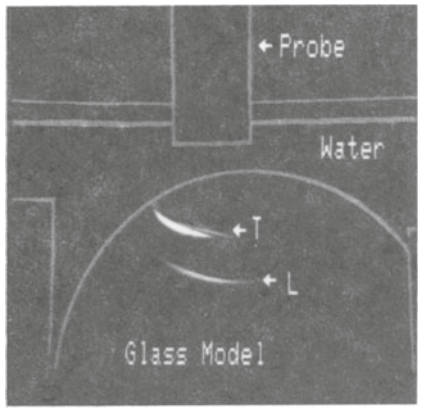




(a) Normal incidence (b) Oblique incidence

Figs. 5 Simulation of immersion testing (rectangular shape)





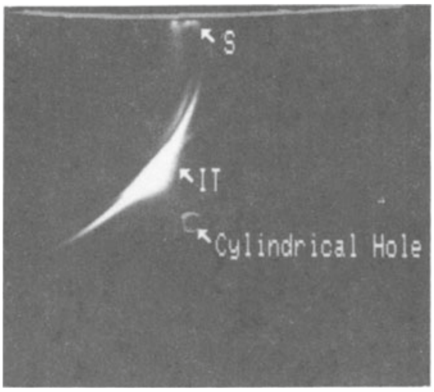
(a) normal incidence (b) Oblique incidence

Figs. 6 Cylindrical shape test piece in immersion testing

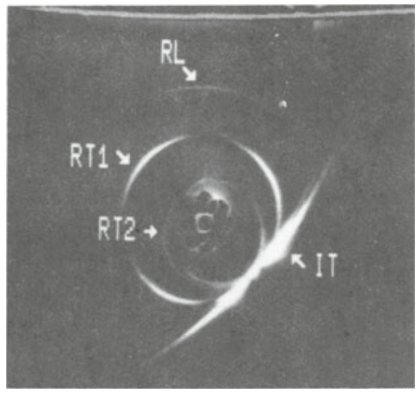
components for non-destructive testing have complex curved shape, the disagreement of the refraction law is very important for practical immersion non-destructive testing.

Figures 7 and 8 present typical examples of scattering of ultrasonic waves at artificial defects. Shear wave (IT) incident to a 3 mm diameter hole produces three reflected waves: RL is mode-converted from IT at the reflection of the hole, RT1 is direct reflected wave of IT from the hole and RT2 is re-mode-converted from the surface wave, mode-converted from IT and traveling along the hole surface. Therefore, the interval between RT1 and RT2 corresponds to the distance along the hole surface.(Figs. 7)

Figure 8 shows the reflection of longitudinal waves at the crack-like defect. Two series of reflected waves were produced: one is generated at the defect tip (RT1 and S) and the other is at the defect surface (RL and RT2). The reason of the generation of RT2 is oblique incidence of IL to defect surface because of the curvature of the wave front of IL.

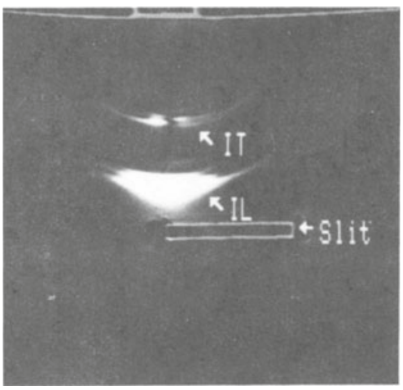


(a) Before reflection

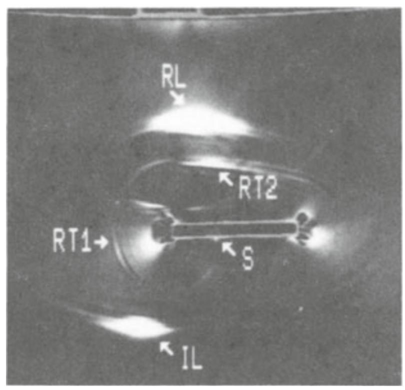


(b) After reflection

Figs. 7 Reflection of shear wave at cylindrical hole



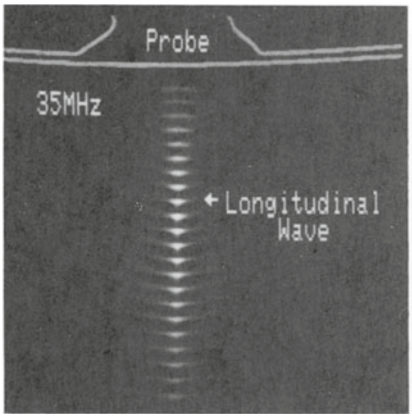
(a) Before reflection



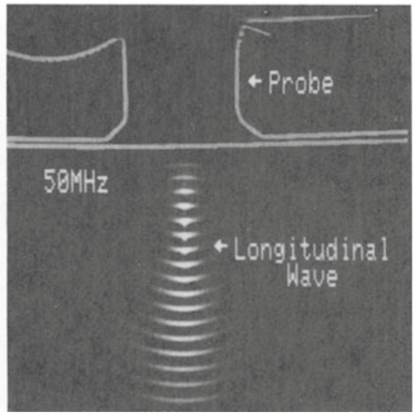
(b) After reflection

Figs. 8 Reflection of longitudinal wave at crack-like defect

Figure 9 shows visualization of high frequency ultrasonic wave propagation: 35 MHz and 50 MHz. These focusing probes, made of piezoeletric polymer, were designed for detection of very small defects in a ceramics or thin material. In order to obtain the change of sound pressure distribution due to the propagation, we changed the delay time for stroboscope flashing every 0.2 micro-second after the generation of longitudinal wave from the probes, and then each longitudinal wave was visualized and recorded using our method. Furthermore, we have synthesized all visualized longitudinal waves obtained from different delay time to make the figures as shown in Figs. 9. From these figures, we can see and evaluate the beam focusing process of the probes very clearly.



(a) Focusing distance 50 mm (water)



(b) Focusing distance 25 mm (water)

Figs. 9 Visualization of high frequency longitudinal wave

CONCLUSION

This paper presents a developed ultrasonic wave visualization system and various images of visualized ultrasonic wave propagating in a solid. The images of the visualized ultrasonic waves do not include the images of residual stress, visualized at the same time in the test piece, so that we can observe ultrasonic waves very clearly. The system consists of a regular linear polariscope with a stroboscopic light source and a digital image-processing system. Typical examples of generation of longitudinal waves, refraction at water-glass boundary, and scattering of ultrasonic waves from artificial defects are shown. High frequency ultrasonic wave such as 50MHz longitudinal wave propagation can be visualized using this system.

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