Visualization of Three-Dimensional Ultrasonic Wave Fronts Using Holographic Interferometry

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A new method to visualize wave fronts of a 3-D ultrasonic wave in a transparent medium is proposed. It employs holographic interferometry with phase-modulated reference beam. The wave field is illuminated by a sheet-like light and the light scattered in the medium is recorded in a hologram. The reconstructed image displays wave fronts of the ultrasound on the light sheet. The experiments are carried out for an ultrasonic wave with frequency 200 kHz and 1 MHz, and prove the validity of the method. This method is considered applicable for an ultrasonic wave with frequency up to about 10 MHz.

§1. Introduction

For visualizing wave fronts of ultrasonic waves in a transparent medium, the schlieren technique with a stroboscopic illumination is widely used.[1)] The technique is based on the detection of variation of optical path length caused by refractive index variation induced by the ultrasound. The resultant image depends on the total refractive index along the probing rays. Thus the image corresponds to the wave fronts only when the rays are parallel to the real wave fronts to be measured; we can visualize a wave field only when it is of a 2-D nature.

This paper presents a new method for visualizing wave fronts in a transparent medium even if the field is three-dimensional. This essential feature results from the use of holographic interferometry with a sinusoidal phase-modulated reference beam and sheet-like light formed through a cylindrical lens.

Holographic interferometry with a sinusoidal phase-modulated reference beam has been applied to visualizing amplitude and phase distribution of small vibration on a rough surface of an opaque object.[2)] If this method is applied to a progressive ultrasonic wave, its equi-phase positions appear as bright and dark fringes in the reconstructed image.[3)] Thus wave fronts on a rough surface can be visualized.

To visualize the wave fronts of the ultrasound in the interior of a transparent medium, a substitute for the rough surface is necessary. For this purpose fine particles are suspended in the medium and are illuminated by a sheet-like light. The particles on the illuminated plane scatter light; the plane acts as a rough surface. The scattered light is recorded in a hologram with a phase-modulated reference beam. If the particles vibrate in accordance with ultrasonic vibration, wave fronts on the illuminated plane can be seen in the form of bright and dark fringes in the reconstructed image.[4)]

We should note that in this method the variation of optical path length is not caused by the refractive index variation, but by vibrational displacement of the suspended particles. The optical path length change, therefore, is determined at a local position, not by an integration along a light path. Consequently, we can measure the wave fronts on a 2-D plane, even if the wave field is three-dimensional. In addition, by changing the position of the sheet-like light the whole 3-D wave field can be investigated.

§2. Theory

Figure 1 shows a basic arrangement for this method. An ultrasonic wave with angular frequency Ω is propagated in the glass vessel. The vibrational displacement at a position $\boldsymbol{r}$ and time t is assumed as

$$\boldsymbol{d}_o(\boldsymbol{r}, t) = \boldsymbol{a}_o(\boldsymbol{r}) \cos [\Omega t + \mu_o(\boldsymbol{r})]. \qquad (1)$$

The co-phasal surfaces, which are made up of points of constant $\mu_o(\boldsymbol{r})$, form the wave fronts.

The hologram is recorded with light scattered from illuminating sheet-like light. The reference beam is phase-modulated by a vibrating transducer Td2 with the same frequency Ω as the

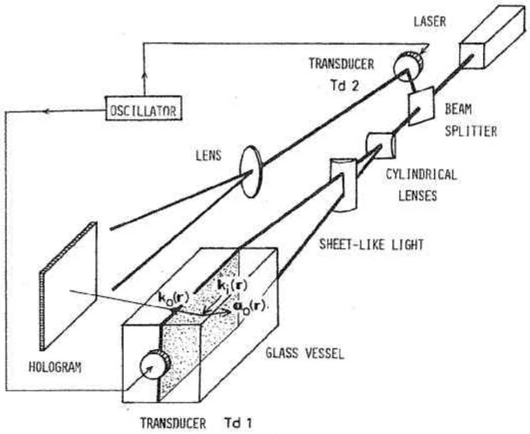

Fig. 1. Optical arrangements to vizualize the ultrasonic wave fronts propagated in the transparent medium.

ultrasonic wave. The phase-modulation of the reference beam is expressed as

$$\phi(t)=p_r \cos \Omega t, \quad (2)$$

where p_r is the amplitude of phase-modulation related to the vibration amplitude of the transducer Td2. (When the directions of illumination and reflection are the same as the vibration direction, $p_r=(4\pi/\lambda)A$, where A is vibration amplitude and λ is light wavelength.)

Usually the amplitude of ultrasonic wave is much smaller than light wavelength. To measure such a small vibration, p_r must be adjusted to value 1.13. In such circumstances, the irradiance of the reconstructed image $I(\boldsymbol{r})$ is calculated as[4)]

$$I(\boldsymbol{r})=\frac{1}{2}I_{st}(\boldsymbol{r})[1+1.35p_o(\boldsymbol{r})\cos\mu_o(\boldsymbol{r})], \quad (3)$$

where

$$p_o(\boldsymbol{r})=[\boldsymbol{k}_o(\boldsymbol{r})-\boldsymbol{k}_i(\boldsymbol{r})]\cdot \boldsymbol{a}_o(\boldsymbol{r}), \quad (4)$$

and $I_{st}(\boldsymbol{r})$ is the reconstructed irradiance without the ultrasonic wave and the reference phase-modulation. As illustrated in Fig. 1, $\boldsymbol{k}_0(\boldsymbol{r})$ and $\boldsymbol{k}_i(\boldsymbol{r})$ are the wave number vectors in the directions of observation and illumination of the sheet-like light, respectively.

For an ultrasonic wave the vibration amplitude varies slowly in space compared with the phase. The reconstructed irradiance, therefore, depends largely on the phase $\mu_o(\boldsymbol{r})$. The local variation of the irradiance is proportional to the quantity cos $\mu_o(\boldsymbol{r})$ which corresponds to the wave form at time $t=0$. Since the ultrasonic field is illuminated only on the light sheet, the reconstructed fringes correspond to the wave fronts on the plane of the sheet-like light.

§3. Experiments

Experiments are performed with the set-up shown in Fig. 1. The sheet-like light is formed through cylindrical lenses and illuminates the transparent medium in the vessel. The vibrating amplitude of the transducer Td2 for phase modulation of the reference beam is adjusted about 60 nm, corresponding to $p_r=1.13$.

The first example is the visualization of an ultrasonic wave propagated in gelatin in the gel state. Impurities naturally contained in gelatin act as light scatterers. In this case exposure time is 15 sec with a 50 mW He-Ne laser as a light source. The ultrasonic frequency is 200 kHz. The reconstructed images are shown in Figs. 2 and 3. In both figures the ultrasonic wave is propagated from right to left.

Figure 2 shows wave fronts of a spherical wave without any obstacles. The positions of the light sheets are illustrated in Fig. 2(a). Figure 2(b) is a reconstructed image on the plane of light sheet A. From this pattern it is found that the ultrasonic wave radiated by the transducer is propagated in the form of a spherical wave. Figure 2(c) is wave fronts on plane B which is perpendicular to plane A. Since a spherical wave is propagated, the resultant pattern on the cross section shows concentric circles.

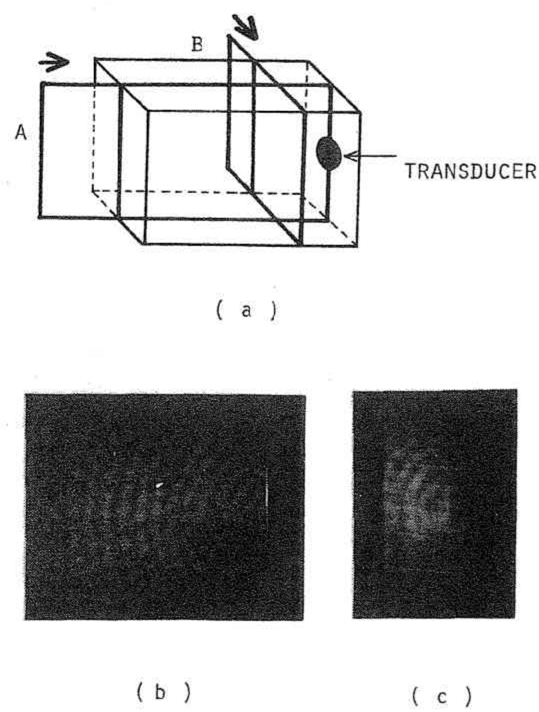

Fig. 2. Reconstructed images in gelatin (ultrasonic frequency: 200 kHz): (a) illuminating positions of light sheets; (b) image on A; (c) image on B.

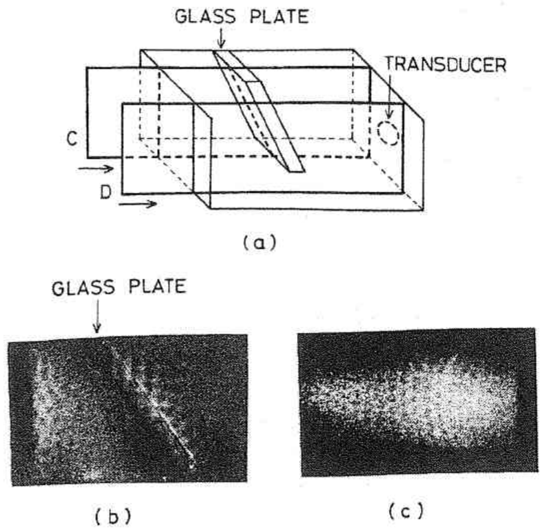

Fig. 3. Reconstructed images in gelatin (ultrasonic frequency: 200 kHz): (a) illuminating positions of light sheets; (b) image on C which intersects with the glass plate; (c) image on D which does not intersect with the glass plate.

Figure 3 shows the results when a glass plate is put in the medium to reflect the ultrasonic wave. The relative positions of the glass plate and illuminating light sheets are illustrated in Fig. 3(a). Figure 3(b) shows the wave fronts on plane C. Part of the wave is reflected by the glass plate and the rest is transmitted. Figure 3(c) shows the wave fronts on plane D, which does not intersect with the glass plate. There is no influence of the glass plate.

The next example is a wave of frequency 1 MHz propagated in glycerine. The result is shown in Fig. 4. Alumina particles are suspended in glycerine in relatively high concentration. The exposure time is 10 msec with an 800 mW Ar laser. The wave is propagated from right to left. Since the frequency is high, the wave radiated from the transducer seems plane.

§4. Discussion on Affecting Factors

4.1 *Thickness of the light sheet*

In this method a reconstructed image displays wave fronts on a light sheet. Its thickness must be sufficiently smaller than the wavelength Λ of the ultrasonic wave. The thickness, however, cannot be made arbitrarily small. The light sheet is thinnest along the focused line, but it becomes thicker according to the distance from it. The maximum width Z of the light sheet on which its thickness does not exceed Λ is determined by the expression[4)]

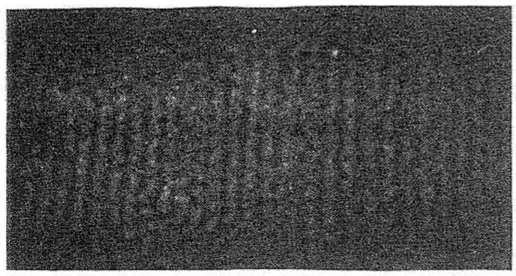

Fig. 4. Reconstructed image in glycerine (ultrasonic frequency: 1 MHz).

$$Z=\frac{\Lambda^2}{\lambda}, \tag{5}$$

where λ is the wavelength of light. This relation is shown in Fig. 5. The measurable combinations of Z and Λ fall on the right side of the lines in Fig. 5. For instance, if $\lambda=0.5$ μm and $Z=50$ mm, then the minimum wavelength is about 0.16 mm, corresponding to the wave with frequency 10 MHZ in water.

4.2 *Influence of flow*

For an ultrasonic wave propagated in liquid, flow is caused by radiation pressure. The flow modulates the reconstructed irradiance. The degree of modulation is determined by the displacement of the particle during the exposure time T. The influence of flow with flow velocity v is not serious under the condition[4)]

$$vT<2.32\lambda. \tag{6}$$

On the other hand, we cannot make the exposure time arbitrarily short. Assume that the exposure time contains at least ten periods of vibration:

$$T>10\cdot\frac{2\pi}{\Omega}. \tag{7}$$

Thus, if frequency is 10 MHz, T must be longer than 1 μ sec. Then Eq. (6) tells us that the flow velocity must be smaller than 0.1 m/sec for $\lambda=0.5$ μm.

4.3 *Amplitude limit of ultrasonic wave*

Using holographic interferometry with the phase-modulated reference beam, the vibration amplitude $\lambda/100$ can be detected.[3)] The ultrasonic power is proportional to the square of the product of vibration amplitude and frequency. Thus, as frequency increases, the amplitude becomes smaller for a constant power. Consequently, the limit of applicable frequency is

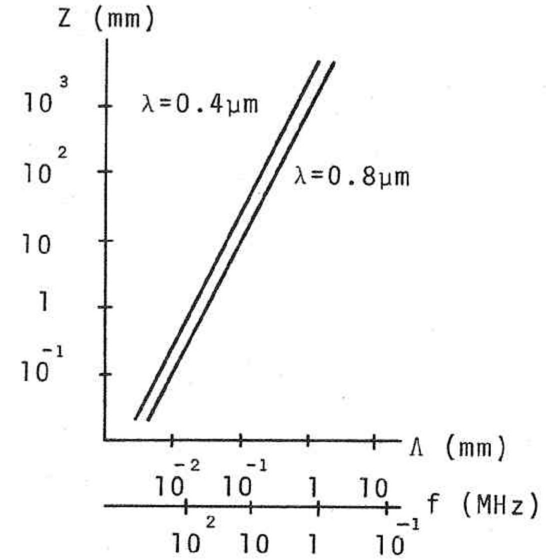

Fig. 5. Maximum width Z of a light sheet obtainable for the ultrasonic wavelength Λ and frequency f in water.

determined by the ultrasonic power. For example, if the ultrasonic power is a value 10 W/cm^2 and the ultrasonic wave is propagated in water, frequency must be lower than the value 11.6 MHz.

§5. Conclusion

The proposed holographic technique employs a light sheet, which enables us to visualize wave fronts of a 3-D ultrasonic wave field. This unique feature is demonstrated by experiments which visualize the ultrasonic field with 200 kHz and 1 MHz. This technique is useful to visualize the 3-D ultrasonic wave with frequency up to about 10 MHz.

This research was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education of Japan.

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