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Measurement of Optical Wavefront Deformation Caused by High-Intensity Ultrasonic Standing Wave Using Phase Retrieval

位相回復法による強力定在波音場を通過した光波波面の計測

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1. Introduction

Optical methods for measurement of ultrasound are of interest because of its nondestructive characteristics. The Raman-Nath diffraction, which occurs when the light is wider than the ultrasound wavelength, is often used to measure the 10^6 Hz order ultrasound.[1)] For measurement of less than 10^6 Hz order progressive ultrasound in water, the light deflection, which occurs when the light width is narrower than the ultrasound wavelength, is employed.[2)] The pressure amplitude of ultrasound is calculated from the maximum deflection angle. However, when the light is not adequately narrower than the ultrasound wavelength, the light is not only deflected but also broadened. In addition, in the ultrasonic standing wave, deflection and broadening behavior of the light is varied depending on the incident position of light. Thus, the ultrasound pressure cannot be measured from the maximum deflection angle.

As a measurement method of the relatively low frequency ultrasound, which is difficult to satisfy the condition of the Raman-Nath diffraction, we focus on Fraunhofer iterative phase retrieval (FIPR) [3)]. In this paper, the deflection and broadening of the light caused by the ultrasound is measured in the optical far field (Fraunhofer region). The wavefront of the light, which is shifted proportional to the local pressure in water, is recovered using the FIPR.

2. Measurement theory

Optical Fourier transform system is shown in **Fig. 1**. A plane laser beam, whose cross-sectional intensity is $l(x, y)$, is introduced into the ultrasound. The complex transmittance of one-dimensional ultrasound along x-axis, $t(x, \phi)$, is shown as

$$t(x,\phi)=\exp\left[\mathrm{j}\frac{2\pi}{\lambda}\left(\frac{\partial n}{\partial p}p(x,\phi)\right)S+A\right], \tag{1}$$

where ϕ, j, λ, $\partial n/\partial p$, $p(x, \phi)$, A and S are the phase of ultrasound, the imaginary unit, the wavelength of laser beam, the acousto-optic coefficient, the pressure of ultrasound, the initial optical phase, and the propagation distance of laser beam in water, respectively. The outgoing light from ultrasound, $h(x, y)$, is shown as

$$\begin{aligned} h(x,y)&=t(x,\phi)l(x,y) \\ &=|l(x,y)|\exp\left[\mathrm{j}\frac{2\pi}{\lambda}\left(\frac{\partial n}{\partial p}p(x,\phi)\right)S+A\right]. \end{aligned} \tag{2}$$

The ambient phase shift is neglected because optical phase shift caused by the ultrasound needs to be only considered. The light amplitude on the focal plane of lens, $H(\nu_x, \nu_y)$, becomes

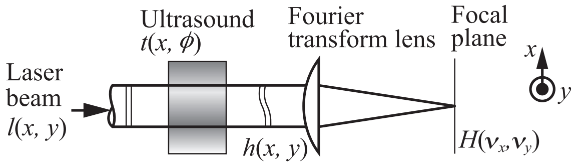

Fig. 1 Optical Fourier transform.

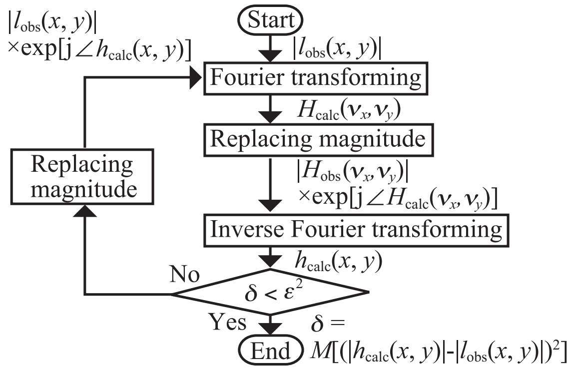

Fig. 2 Fourier iterative phase retrieval.

$$H(\nu_x,\nu_y)=CF[h(x,y)], \tag{3}$$

$$\nu_x=x/(\lambda f), \nu_y=y/(\lambda f), \tag{4}$$

where C, f, and $F[]$ are the complex coefficient, the focal length of lens, and the spatial Fourier transform, respectively.

The phase of $h(x, y)$, which corresponds the optical phase shift caused by the ultrasound, is recovered using the FIPR. The pressure of ultrasound can be calculated from the phase shift as shown in Eq. (1). In the FIPR, the optical phase is calculated from the light magnitude measured on the focal plane of lens and that of laser beam, as shown in **Fig. 2**. Initially, the measured light magnitude of laser beam, $|l_{\mathrm{obs}}(x, y)|$, is Fourier transformed. Then, the magnitude of the transformed amplitude, $|H_{\mathrm{calc}}(\nu_x, \nu_y)|$, is replaced by the measured magnitude of light on the back focal plane, $|H_{\mathrm{obs}}(\nu_x, \nu_y)|$. Next, $|H_{\mathrm{obs}}(\nu_x, \nu_y)|\exp[\mathrm{j}\angle H_{\mathrm{calc}}(\nu_x, \nu_y)]$ is inverse Fourier transformed and $h_{\mathrm{calc}}(x, y)$ is obtained. If the calculated result satisfies the next inequality, the iteration is terminated. Otherwise, $|h_{\mathrm{calc}}(x,y)|$ is replaced by the measured light magnitude of laser beam as $|l_{\mathrm{obs}}(x, y)|\exp[\mathrm{j}\angle h_{\mathrm{calc}}(x, y)]$ and iteration continues.

$$\delta<\varepsilon^2, \delta=M[(|h_{\mathrm{calc}}(x,y)|-|l_{\mathrm{obs}}(x,y)|)^2], \tag{5}$$

$M[]$ and ε are the spatial average and the tolerance, respectively.

3. Experiments

Figure 3 shows the experimental system. Ultrasonic standing wave is established in a glass cell whose dimensions are 50 × 50 × 160 mm^3. The water depth is 147 mm. The ultrasound is radiated by a bolt-clamped Langevin type transducer (BLT) attached to the bottom of glass cell. The BLT is driven by sinusoidal voltage of 47.6 kHz in frequency. Input power to the BLT is 18 W. The glass cell and BLT is traversed along *x*-axis using a computer controlled stage.

A laser beam is generated by a He-Ne laser source operating at 632.8 nm at a vacuum wavelength. The laser beam is on/off-modulated by an acousto-optic modulator to expose the ultrasound field synchronously with the ultrasound phase. The modulated beam is spatially filtered and collimated. This collimated beam passes through water in the glass cell. The passed beam enters a Fourier transform lens immediately subsequent to the glass cell. The light intensity distribution on the focal plane of Fourier transform lens is measured by a camera.

4. Results

Figure 4(a) shows the light magnitude distribution of incident laser beam. Figure 4(b) shows the recovered optical phase distributions of laser beam passed the ultrasound at the distance between the water surface and the light axis, *d*.

The water-to-air boundary becomes the pressure node of ultrasound in water, because the boundary is sound soft boundary. The pressure nodes and antinodes are formed alternatively at intervals of one-fourth of ultrasound wavelength. In this experimental condition, the wavelength of ultrasound was 33 mm. In Fig. 4(b), therefore, (i) and (iii) show the optical phase distributions near the pressure antinode and (ii) and (iv) show that near the pressure node. In the case of (ii) and (iv), the gradient of optical phase increases and decreases in an ultrasound period. The gradient of optical phase of (ii) and (iv) are inverted to each other at $\phi = \pi/4$ and $\phi = 2\pi/3$. This is the same manner as the pressure distribution around the pressure node. In the condition of (i) and (iii), the gradients of optical phase do not change significantly but the phases are inflected. It is the same behavior as the pressure distribution around the pressure antinode. These results indicate that the optical phase shift, which is proportional to the pressure in water, can be measured using the FIPR.

5. Conclusion

The FIPR was applied to measure the wavefront of laser beam passed the ultrasonic standing wave in water. It was shown that the optical wavefront deformation has the same manner as the pressure distribution of standing ultrasound. As a result, the viability of pressure distribution measurement in ultrasound field using the FIPR was established.

Acknowledgment

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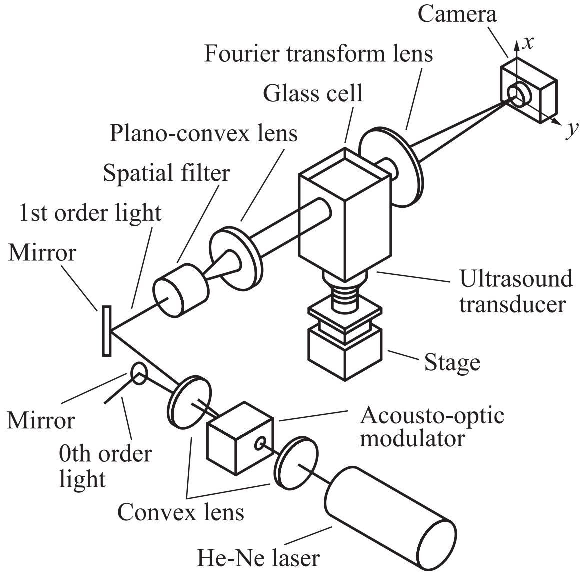

Fig. 3 Experimental system.

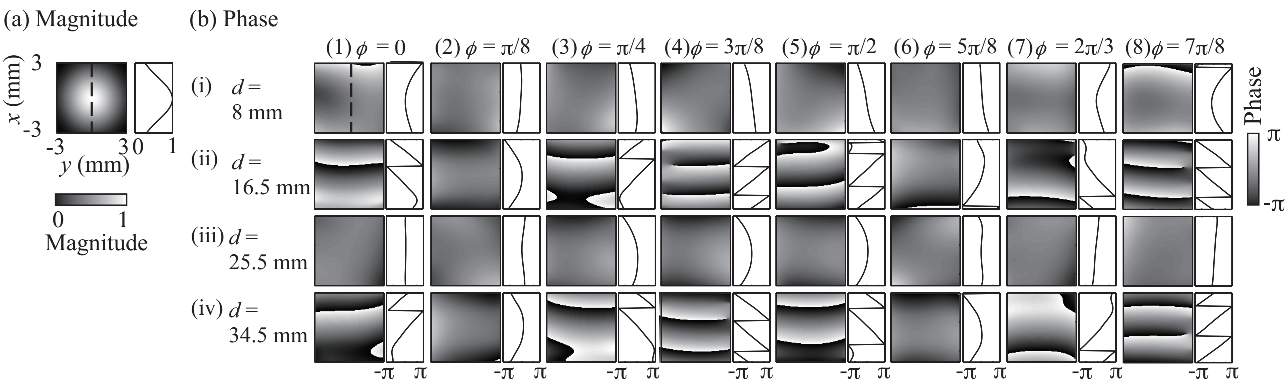

Fig. 4 Experimental result. (a)Square image shows the magnitude of laser beam and line plot shows the amplitude distribution along the dashed line indicated in the square image. (b) Square images show the phase distribution of laser beam passed the ultrasound. The line plots show the phase along the dashed line indicated in the square image.