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Evaluation of Disturbance by Light Scattering Particles on Sound Field Measurement Based on Laser Deflection

レーザ偏向法に基づく音場計測における光散乱粒子の影響評価

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1. Introduction

Optical measurement methods of ultrasound filed, such as shadowgraph[1)], and Fresnel phase retrieval method[2)], have been studied actively for the advantages of non-invasiveness. Although the optical methods have above advantage, these methods were only applied to the ultrasound propagating completely transparent media because of the susceptibility to scattered and diffracted light from opaque object. Thus, the optical measurement is not achieved in the sound field containing light scattering particles like acoustic cavitation bubbles.

The authors have been focused on the light deflection method[3, 4)] for measurement of kHz order sound field in water because of the instrumentation simplicity and robustness to vibration and ambient light. In this method, the sound pressure amplitude is obtained from the laser beam displacement proportional to the gradient of projected sound pressure along the light axis. Even if the propagation media contains the light scattering particles, the pressure amplitude may be obtained when the displacement is successively determined. In this paper, the disturbance of light scattering particles on the sound pressure measurement with light deflection method is evaluated.

2. Theory

The schematic of the light deflection method is shown in **Fig. 1**. A Gaussian laser beam with light amplitude, $g(x, y)$, irradiates one-dimensional sinusoidal ultrasound field with pressure, $p(x, t)$. The outgoing beam enters the converging lens with focal length, f. The light amplitude of outgoing beam, $l^+(x, y)$, is expressed as below if the beam displacement in the sound field and multiple light scattering by particles are neglectable.

$$l^+(x,y) = u(x,y)b(x,y)g(x,y), \tag{1}$$

$$g(x,y) = \exp[-4(x^2+y^2)/d^2], \tag{2}$$

$$u(x,y) = \exp[-j2\pi\gamma Sp(x,t)/\lambda], \tag{3}$$

$$b(x,y) = \begin{cases} 0 & \left(\sqrt{(x-x_i)^2+(y-y_i)^2} \le (a/2)\right) \\ 1 & \text{otherwise} \end{cases}, \tag{4}$$

where λ, S, $u(x, y)$ and $b(x, y)$ are the optical wavelength, the width of sound field, the optical transmittance of the ultrasound and the particles, respectively. The diameter and the center position of ith particle are a and (x_i, y_i). The piezo-optic

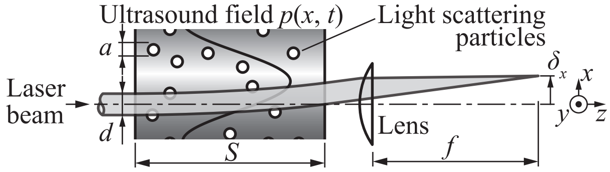

Fig. 1 Schematic of light deflection method.

constant, γ, is 1.47×10^{-10} Pa^{-1} in water. The light amplitude, $L(x, y)$, on the focal plane is given by

$$L(x,y) = C(x,y)L^+\left[x/(\lambda f), y/(\lambda f)\right], \tag{5}$$

where $C(x, y)$, $L^+(v_x, v_y)$, v_x, and v_y are the complex coefficient expressing wavefront curvature, the Fourier transform of $l^+(x, y)$, x- and y-directional spatial frequency, respectively. The light intensity on the focal plane, $I(x, y)$, is $|L(x,y)|^2$. When the laser beam diameter is adequately smaller than the acoustical wavelength, the light intensity without particles (i. e. $b(x, y) = 1$) is shown as[5)]

$$I(x,y) = 4\pi/d^2 \exp\left\{-8\left[(x-\delta_x)^2+y^2\right]/(\rho\lambda f)^2\right\}, \tag{6}$$

The light intensity is Gaussian shape with diameter, $\rho = 4\lambda f/(\pi d)$, and the displacement, δ_x. The diffracted light distributes axisymmetrically about $(x, y) = (\delta_x, 0)$ when the light scattering particles exist. Assuming the pressure is sinusoidal as $p(x, t) = P_a\sin(2\pi x/\Lambda - \omega t)$, the pressure amplitude, P_a, can be determined from the displacement from,

$$\delta_x = fS\gamma\ \partial p(x,t)/\partial x = 2\pi P_a fS\gamma/\Lambda, \tag{7}$$

where Λ is the acoustical wavelength.[3)]

The displacement of the laser beam on the focal plane is determined from center of gravity (CoG), x_c, of the light intensity, $I(x, y)$, with

$$x_c = \frac{\int_{-W}^{W}\int_{-W}^{W} R\left[I(x,y)\right] x\,dx\,dy}{\int_{-W}^{W}\int_{-W}^{W} R\left[I(x,y)\right] dx\,dy}, \tag{8}$$

$$R[I(x,y)] = \begin{cases} I(x,y) - I_t & (I(x,y) \ge I_t) \\ 0 & (I(x,y) < I_t) \end{cases}, \tag{9}$$

where I_t is the intensity threshold. Simple geometric centroid is calculated with $I_t = 0$. The threshold method improving the nonlinearity employs the threshold, I_t, which satisfies next equation[6)].

$$\iint_{I(x,y)>I_t} dx\,dy = \pi\rho^2/4. \tag{10}$$

3. Simulation result

The variance of the determined CoG is simulated to evaluate the measurement accuracy of the sound filed. The light amplitude on the focal

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plane is simulated by discrete two-dimensional Fourier transform. The focal length of the lens is 300 mm and the laser beam diameter is 0.8 mm. The spatial resolution on the input plane and output plane are set to 2.5 μm and 18 μm, respectively. The particles are randomly distributed. The average transmittance, T, of $b(x,y)$ shown below is varied by changing the number of particles.

$$T = \int_{-W}^{W}\int_{-W}^{W} b(x,y)\,dx\,dy \,/\, (4W^2)\,. \tag{11}$$

The parameters, P_a, Λ, and the time, t, are 200 kPa, 50 mm, and 0 s, respectivery. The displacement of the beam (true value of CoG) is 55.4 μm. The half width of the window to calculate CoG, W, is 2ρ.

Figure 2 shows the simulated light intensities before the lens and on the focal plane. **Figure 3** shows the coefficient of variation (CV) and the mean relative error of the CoG for 1,000 repeats of calculation. The CoG calculated by the simple method has huge error because the CoG is biased by the scattered light. On the other hand, the CoG by the threshold method is successively determined. When the particle diameter is adequately smaller than the beam diameter as shown in Fig. 2 (ii), the laser beam focuses keeping circular shape because the diffracted light caused by the particles is widely spread, and thus, the intensity near the beam spot is relatively low. When the particle diameter closes to the beam diameter, the laser beam is deformed because the scattered light is concentrated near the spot as shown in Fig. 2(iv). Although the beam is deformed, the disturbance to the CoG is small because the light intensity distribution is axi-symmetrical and focuses on vicinity of the spot. The CV has large value in conditions that the particle diameter is near 100 μm and the trans-mittance is under 0.1. It is because the light intensity has large value near the end of the window as shown in Fig. 2(iii). The truncation of high intensity region by the window causes the bias of the CoG and increases the CV. Therefore, the CoG can be determined even in the presence of the particles if the appropriate window size is chosen. Note that, when the width of the ultrasound field is long, the CoG is biased to the origin because the light scattered near the incident point distributes around the incident angle, which is the same as the light axis without ultrasound.

4. Conclusion

In order to evaluate the disturbance, the optical propagation simulation of the light passed ultrasound field containing the light scattering particles and the CoG of the laser beam, which moved proportional to the pressure gradient, is calculated. As a result, it was found that the CoG could be determined if the appropriate window size for calculation of the CoG was chosen.

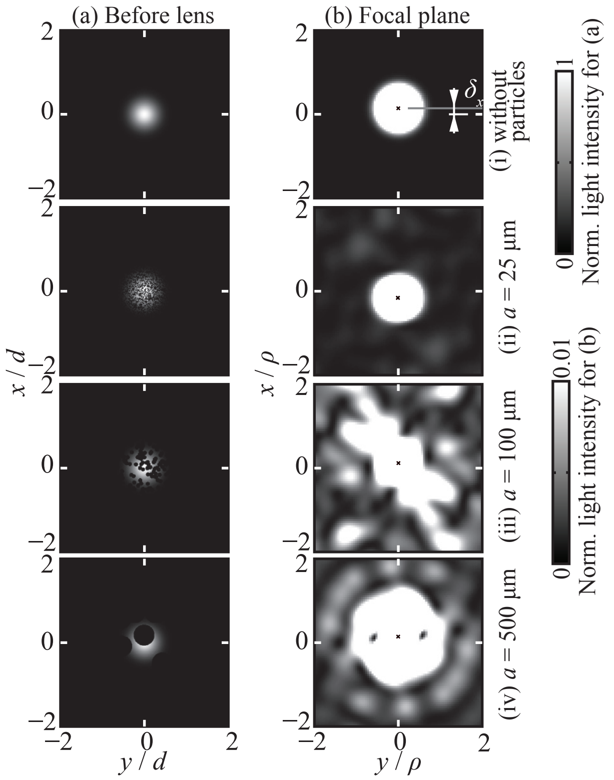

Fig. 2 Simulated light intensity (a) before lens, $|I^{+}(x, y)|^2$ (b) on focal plane, $I(x, y)$.

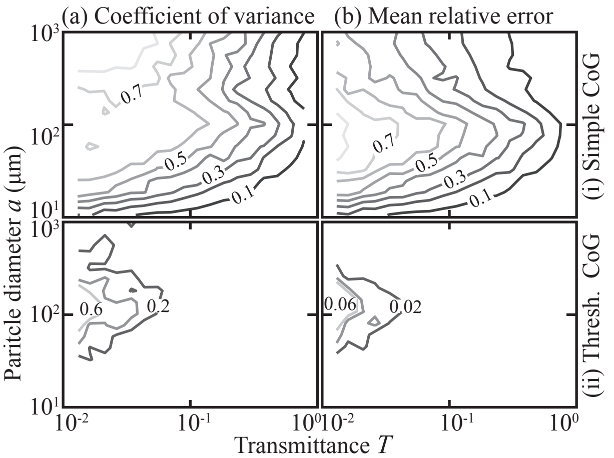

Fig. 3 Relationship between CoG and particle diameter and number of particles.

Acknowledgment

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