# 3Pa4-1

# Laser Diffraction Caused by Shockwaves from Acoustic Cavitation Bubbles

音響キャビテーションからの衝撃波によって生じるレーザ回折

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## 1. Introduction

Strong ultrasonic waves irradiated into liquid generate tiny bubbles called acoustic cavitation bubbles. Bubbles oscillate and produce physical and chemical effects. In the practical use of the cavitation effects, it is necessary to evaluate the degree of the effects. It is well known that the acoustic cavitation noise (ACN), which is the ultrasound and shockwaves radiated from the bubbles, correlates with the physical effects.[1)] Therefore, acoustic cavitation noise can be used to estimate the physical effects.[1)] However, measuring the ACN by a hydrophone has a risk of breaking the hydrophone and disturbs the sound field. In this study, we propose a method to evaluate shockwaves caused by the acoustic cavitation using laser diffraction without inserting a probe to estimate the cavitation effects.

## 2. Measurement principle

**Figure 1** shows the experimental system. Acoustic cavitation bubbles are generated in water in a vessel by ultrasound from a bolt-clamped Langevin transducer (BLT). Bubbles are generated just below the output surface of the horn of the BLT and form a cone-like structure. A laser beam is cleaned up by a spatial filter and collimated by a lens. The collimated laser beam enters the vessel. The laser beam passed the vessel enters a Fourier transform lens and the light intensity on the focal plane of the lens obtained by an image.

The optical amplitude of the beam $g(x,y)$ is expressed as a Gaussian distribution. The optical amplitude distribution $v(x,y,t)$ just after the vessel becomes the product of transmittance of the sound field $u(x,y,t)$ and $g(x,y)$ as

$$v(x,y,t) = g(x,y)u(x,y,t). \quad (1)$$

The optical amplitude distribution $A(x,y)$ on the focal plane of the lens is proportional to the two-dimensional Fourier transform of $v(x,y,t)$ as

$$A(x,y,t) = V[x/(\lambda f), y/(\lambda f), t], \quad (2)$$

$$V(\nu_x,\nu_y,t) = \mathcal{F}[v(x,y,t)] = \mathcal{F}[g(x,y)] * \mathcal{F}[u(x,y,t)], \quad (3)$$

where $\mathcal{F}$, ($\nu_x$, $\nu_y$), and * represent the two-dimensional Fourier transform, the spatial frequency

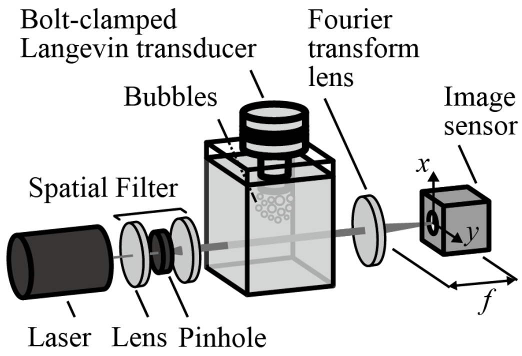


Fig. 1 Laser diffraction measurement system.

in $x$- and $y$-direction, and the convolution integral, respectively. The Fourier transform of $g(x,y)$ have Gaussian amplitude profile with the spot diameter $4\lambda f/\pi w$ where $\lambda$, $f$, and $w$ are the wavelength of the laser, the focal length of the lens, and the diameter of the laser, respectively. Thus, in the absence of ultrasound, this beam sport is formed at the origin.

The optical transmittance $u(x,y,t)$ composed of optical phase delay caused by the incident ultrasound and the shockwaves from the bubbles. The laser beam is sufficiently small compared to the wavelength of the incident ultrasonic waves. Thus, the incident laser deflects and the position of the beam spot fluctuates on the focal plane.[2)] The typical length of the shockwaves caused by bubbles is on the order of 0.1 mm, which is sufficiently small compared to the laser beam diameter. Thus, the laser beam is diffracted and the diffracted light distributes around the beam spot. The shockwaves emitted by bubbles are spherical, and the shockwaves are emitted from many bubbles. Thus, the laser beam is diffracted isotropically, and the diffracted light distribution is axisymmetric. Note that the light intensity of beam spot, which corresponds to the non-diffracted light, is reduced by the diffraction.

In addition, the laser beam is also affected by diffraction by bubbles. Since the bubble size is on the order of 10 μm and bubbles have high spatial frequency,[3)] the diffracted light distributes over a wide spatial frequency range and its intensity is significantly smaller than that of non-diffracted light and light diffracted by ultrasound [4)]. Therefore, by removing the non-diffracted light considering the

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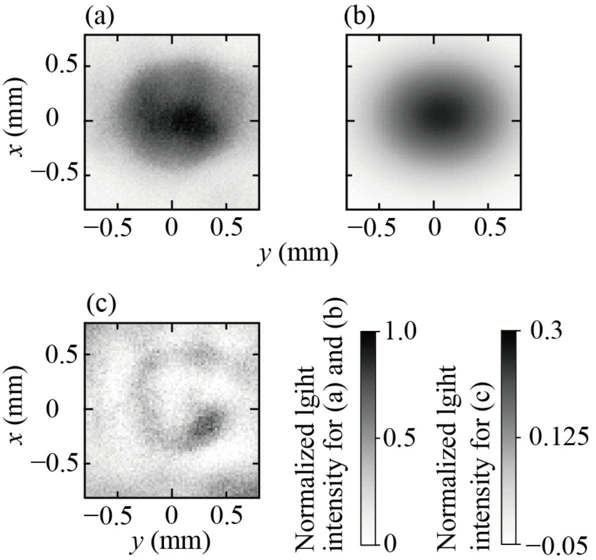


Fig.2 Light intensity distribution on focal plane. (a) Measured light intensity distribution $I$. (b) Gaussian fitting result of (a) $I_G$. (c) Difference between (a) and (b).

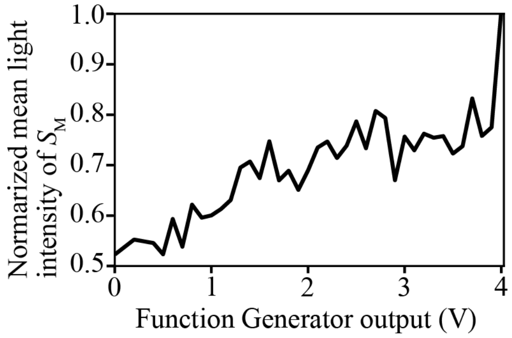


Fig. 3 Power of light diffracted by shockwaves.

movement of the beam spot due to deflection, we can obtain the diffracted light intensity by shockwaves.

The light intensity $I$ on the focal plane, which is measured by the image sensor, is given as the square of the amplitude as

$$I(x, y, t) = |A(x, y, t)|^2. \quad (4)$$

Assuming that the beam spot maintains the Gaussian profile, the beam spot area is fitted with a Gaussian distribution to obtain the regression light intensity, $I_G(x, y)$. The difference between $I_G(x, y)$ and $I(x, y)$ is considered to be the intensity of light diffracted by the shockwaves. Thus, the power of the light diffracted by the shockwaves is evaluated as

$$S(t) = \iint I(x, y) - I_G(x, y) dxdy. \quad (5)$$

## 3. Experimental results and Discussion

An experiment was conducted to validate the measurement principle using the same system shown in Fig. 1. Acoustic cavitation bubbles are generated under the horn of the BLT. The horn diameter is 30 mm. The BLT is driven by a sinusoidal voltage of 46.1 kHz in frequency generated by a function generator (FG). The wavelength and diameter of the collimated laser beam is 640 nm and 4 mm, respectively. The laser beam passes far from the output surface of the horn avoiding region with high bubble number density. The focal length of the Fourier transform lens is 500 mm. The beam spot diameter is 127 $\mu$m.

The laser is emitted in a pulsed manner synchronized with the ultrasonic phase. The duration of the pulsed laser is 100 ns. The ultrasonic phase irradiating the laser is varied by $1/4\pi$ from 0 to $7/4\pi$. The light intensity distribution at each phase is acquired by the image sensor synchronized with the laser emission. The output voltage of the FG was varied by 100 mV from 0 mV to 4,000 mV.

**Figure 2(a)** shows the light intensity distribution of the beam spot, $I$, for FG output of 700 mV. This result was obtained in the laser emitting phase, when the light intensity around the beam spot was the highest. Figure 2(b) shows the regression light intensity, $I_G$, obtained by Gaussian fitting of Fig. 2(a). The difference between $I$ and $I_G$ is shown in Fig. 2(c). In Fig. 2(c), a circular region of high light intensity is seen around the beam spot. This is thought to be caused by diffraction by the shock-waves.

**Figure 3** shows the transition of the power $S_M$ of the light diffracted by the shockwaves for each voltage. Here, $S_M$ refers to $S(t)$ at the phase of maximum. Since the laser has inhomogeneity and its profile is not perfectly Gaussian, $S_M$ has a positive value even at 0V. It can be seen that $S_M$ tends to increase as the output voltage increases. The increase in the output voltage of the FG caused an increase in the number of bubbles and the violence of the bubble oscillation, which causes increasing the intensity and number of shockwaves. As a result, the diffraction by the shockwaves increased with the increase in the output voltage of FG, and the value of $S_M$ also increased.

## 4. Conclusion

In this study, we proposed a measurement method of shockwaves caused by the acoustic cavitation using laser diffraction. The experimental results showed that the diffracted light, which may have been caused by shockwaves, was detected during the onset of acoustic cavitation. The diffracted light intensity increases with increasing the intensity of the ultrasound to generate bubbles. The intensity of this diffracted light can be used to evaluate physical effects of the acoustic cavitation.

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