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Measurement of Instantaneous Laser Diffraction Pattern by Acoustic Cavitation Bubbles Using Two-dimensional Image Sensor

音響キャビテーションにより生じた瞬時レーザ回折パターンのイメージセンサによる計測

Takanobu Kuroyama[1†], Koichi Mizutani[1], Naoto Wakatsuki[1], and Takeshi Ohbuchi[2]
([1]Univ. Tsukuba; [2]National Defense Academy)
黒山喬允 [1†]，水谷孝一 [2]，若槻尚斗 [2]，大淵武史 [3] ([1] 筑波大院・シス情工, [2] 筑波大・シス情, [3] 防衛大・応物)

1. Introduction

The acoustic cavitation is studied actively because of its unique characteristics[1, 2)]. The diameter distribution of the acoustic cavitation is one of the most important parameters because it dominates the temperature and the pressure of the acoustic cavitation[3)]. To measure the periodical change of the diameter distribution, we propose a measurement method using laser diffraction[4)]. In this method, the diameter distribution is calculated from the diffraction pattern of the laser beam caused by the acoustic cavitation.

In the previous study, we employed a high-speed single photodetector and a mechanical stage to measure the diffraction pattern. It was indicated that the diameter distribution of the acoustic cavitation was successfully measured. However, this method takes several minutes of the measurement time to scan the photodetector. The shorter measurement time is required for the practical measurement such as the measurement of the spatial distribution of the diameter distribution. In this paper, we propose a new measurement method of the laser diffraction pattern using a two-dimensional image sensor and an acousto-optic modulator (AOM) to shorten the measurement time.

2. Measurement principle

The diameter distribution is calculated from the laser diffraction pattern caused by the acoustic cavitation. The diffraction pattern (diffracted light intensity distribution) measured by the experimental system shown in **Fig. 1**, $I(r)$, is expressed as,

$$I(r) = C\int_0^\infty v(a)\left(\frac{a}{2}\right)^4\left\{\frac{J_1\left[\pi ar/(\lambda f)\right]}{\pi ar/(\lambda f)}\right\}^2 / \left(\frac{\pi a^3}{6}\right)da\,, \quad (1)$$

$$r = \sqrt{x^2+y^2}\,, \quad (2)$$

where C, a, $v(a)$, f, and λ are the proportional coefficient, the diameter of the acoustic cavitation, the volume-based diameter distribution of the acoustic cavitation, the focal length of the Fourier transform lens, and the wavelength of the laser beam, respectively[4)]. The diameter distribution is calculated by solving the least squares problem. Equation (1) is fitted to the measured diffraction pattern by varying $v(a)$ and C. The parameters $v(a)$ and C are determined so as to minimize the difference between the calculated and measured diffraction patterns.

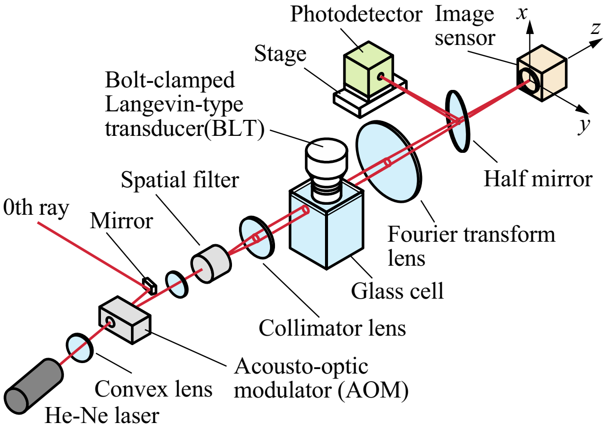

Fig. 1 Schematics of experimental system.

The diffraction pattern changes synchronously with the ultrasound. To measure the diffraction pattern using the image sensor, which has significantly lower sampling frequency than the ultrasound frequency, the acoustic cavitation is irradiated by the pulse laser beam. The pulse laser beam, which has adequately shorter duration than the ultrasound period, is generated from the continuous laser beam by on/off modulation using the AOM. The proposed method only requires several seconds of the measurement time because the one diffraction pattern can be measured in about 100 ms.

3. Experiments

3.1 Experimental setup

Experimental setup is shown in Fig. 1. Ultrasound is irradiated by a bolt-clamped Langevin-type ultrasound transducer (BLT) with a horn. The diameter of the horn is 30 mm. The horn touches the surface of water in a glass cell, whose size is 50 × 50 × 150 (mm^3). The water depth is 145 mm. The BLT is driven by continuous sinusoidal voltage of 19.17 kHz in frequency.

A He-Ne laser beam is introduced into an AOM via a convex lens. The input laser beam is reflected and split to nth order light. The 0th and over 2nd order light are cut by a mirror. The 1st order light is collimated by a convex lens. The collimated beam is spatially filtered and again collimated. This collimated beam irradiates the acoustic cavitation and the passed diffracted light enters a Fourier transform lens of 500 mm in focal length.

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mizutani@esys.tsukuba.ac.jp

The diffracted light passed through the Fourier transform lens is split by a half mirror. One of the split light along the z-axis is measured by a two-dimentional image sensor and the other light reflected by the half mirror is measured by a photodetector. Both the image sensor and the photodetector are placed on the back focal plane of the Fourier transform lens.

3.2 Two-dimensional image sensor

When performing the experiments using the image sensor, the AOM is driven by the sinusoidal burst signal of 80 MHz in center frequency. The period of the burst signal is 2 μs, which corresponds about one twenty-sixth of the ultrasound period. The laser beam is irradiated at several phases of the driving voltage of the BLT, ϕ, and the diffraction pattern is measured at each phases. The size of image is 4,288 × 2,848 (pixels), which corresponds to 23.6 × 15.8 (mm^2). **Figure 2** shows a measured diffraction pattern. The sectorial regions show the ith averaging area, R_i, that is defined by following inequalities,

$$-\pi/18 \leq \tan^{-1}(x/y) < \pi/18, \tag{3}$$

$$r_i \leq \sqrt{x^2+y^2} < r_{i+1}, \tag{4}$$

$$y \geq 0, \tag{5}$$

where, r_i is the edge of the radius interval. The light intensity is averaged in each region to calculate the light intensity distribution in radial direction.

3.3 Scanning single-photodetector

In the previous experiments using the photodetector, the acoustic cavitation is directly irradiated by the continuous He-Ne laser beam. In this paper, the AOM is continuously driven by the sinusoidal signal of 80 MHz in frequency to perform the experiments using the photodetector in the same experimental system as that using the image sensor. The acoustic cavitations irradiated by continuous 1st order light. The photodetector with a pinhole of 0.25 mm in diameter is scanned by a mechanical stage from y = 2 to y = 20 (mm) every 0.325 mm. The output signal of the photodetector is measured by an analog to digital converter, which sampling frequency is 500 kHz. The measured data is transferred to the PC and averaged for 10^4 times synchronously with the driving voltage of the BLT.

3.4 Experimental results

Figures 3(a)-3(d) show the diffraction patterns in radial direction measured by the image sensor and scanning single-photodetector at ϕ = 0, π/4, π/2, and 3π/4 (rad), respectively. The diffraction patterns change with the phase of the driving voltage of the BLT. It implies that the diameter distribution of the acoustic cavitation synchronously changes with the phase of the ultrasound. The diffraction pattern measured by the image sensor is smoother than that measured by the photodetector. This is because the diffraction pattern measured by

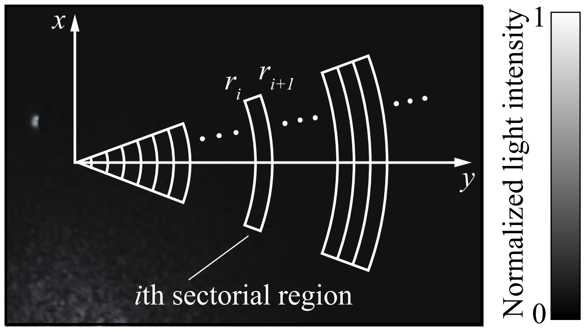

Fig. 2 Diffraction pattern measured by image sensor.

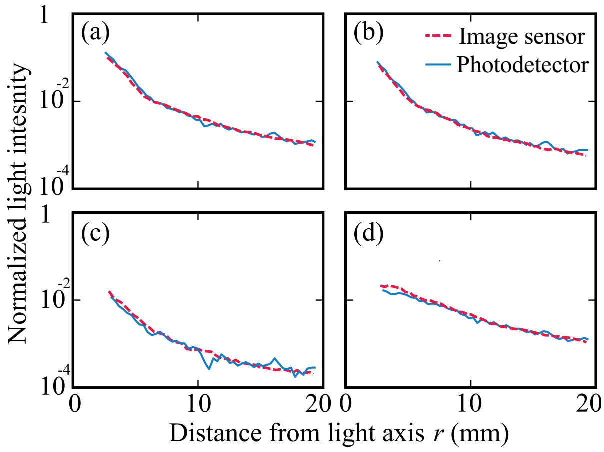

Fig. 3 Diffraction pattern in radial direction.

the image sensor is averaged in the sectorial region, which result in speckle noise reduction. The diffraction patterns measured by the image sensor and the photodetector are similar to each other. The relative errors, e_i, calculated by eq. (6) are within ±5% at the all positions and phases. In eq. (6), I_i, I_i', and n, are the light intensities of the ith region measured by the image sensor and the photodetector, and the number of regions, respectively.

$$e_i = \frac{I_i - I'_i}{\sum_{i=1}^{n} I'_i / n}. \tag{6}$$

4. Conclusions

We proposed a new measurement method of the diffraction pattern for the diameter distribution measurement using the image sensor and the AOM. The diffraction patterns measured by the image sensor and scanning photodetector were compared with each other. As a result, it is confirmed that the diffraction patterns measured by above two methods agree with each other and the relative errors were under 5%. It is confirmed that the instantaneous diffraction pattern can be measured without mechanical scanning, which requires the long time.

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