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Classification of Radial Oscillation Characteristics of Acoustic Cavitation Bubbles Measured by Laser Scattering Method

レーザ散乱法により計測した音響キャビテーション気泡半径振動態様の分類

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1. Introduction

High-intensity ultrasound in liquids generates fine bubbles called acoustic cavitation bubbles. The bubbles radially oscillate with the pressure fluctuation of the ultrasound. The nature of the radial oscillation is well known in single-bubble condition. However, in multi-bubble condition, the bubbles interact with each other with these acoustic radiations. Thus, the oscillation behavior in the multi-bubble system is more complex than that in the single bubble condition and not clarified. In this paper, to investigate the oscillation characteristics of the bubbles in the multi-bubble condition, the bubble oscillation is measured employing the laser scattering method[1)] proposed by the author. The oscillation waveform is measured for several ultrasonic pressure amplitude and waveforms are classified employing K-means method[2)]. The ultrasonic pressure amplitude dependence of the radial oscillation waveforms is discussed.

2. Experimental Method

Figure 1 shows the schematic diagram of the experimental system. The bubble radial oscillation is observed employing laser scattering by the bubble. To detect only the scattered light from a single bubble in the acoustic cavitation bubble cloud, a Gaussian laser beam and a lens system, which is placed perpendicularly to the laser axis, are employed. The scattered light is detected by a photodetector via a pinhole. The photodetector can only detect the scattered light from the conjugate position of the pinhole aperture, which is set to the inside of the laser beam. Therefore, the measurement volume is limited by the pinhole aperture in the direction perpendicular to the lens axis and the laser beam diameter in the lens axis direction. In the experiment, the laser beam diameter is 0.8 mm and the pinhole aperture diameter is 1.5 mm. The magnification of the lens system is 3. Thus, this system detects the scattered light from the bubble within the cylinder like measurement volume, which has the height of 0.8 mm and the diameter of 0.5 mm. The photodetector output is recorded by an analog to digital converter with the sampling frequency of 50 MHz.

The acoustic cavitation bubbles as measuring objects are generated by driving the bolt-clamped Langevin-type ultrasound transducer (BLT). The horn of the BLT, whose diameter is 30 mm, is immersed in purified water and the bubbles distribute near the horn output surface. The BLT is driven by a sinusoidal voltage with frequency, f_0, of 19.3 kHz. The BLT driving voltage and current are monitored and the driving power of the BLT is calculated. The driving power is varied by changing the driving voltage.

A typical waveform of the photodetector output is shown in **Fig. 2**. The photodetector output has high value during a bubble passes through the measurement volume. The scattered light intensity is almost proportional to the square of the bubble radius. Thus, the photodetector output signal fluctuates with the bubble radial oscillation and the oscillation can be observed with this system. To investigate the radial oscillation of a bubble in multi-bubble cloud, oscillation waveforms are classified employing the cluster analysis. When the photodetector output exceeds the threshold level, which is set as adequately higher than the noise level, subsequent waveform with the duration of six ultrasonic period ($6/f_0$) is extracted. Start position of the waveform is matched to the zero-crossing point

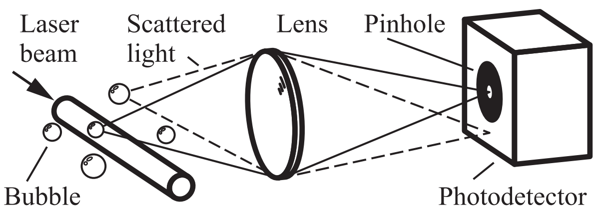

Fig. 1 Schematic diagram of measurement system.

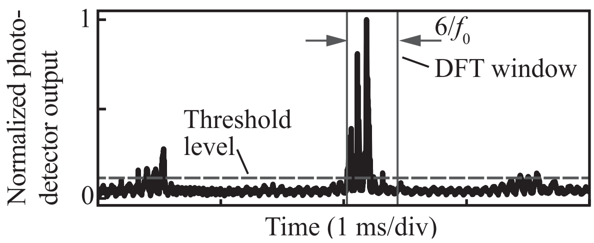

Fig. 2 Typical waveform of scattered light signal.

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in rising curve of the driving current of the BLT. The amplitude spectrum of the extracted waveform is determined using discrete Fourier transform (DFT). The amplitude spectra are calculated for all the bubble passing events within the measurement time and the classified employing K-means method. The amplitude spectrum for the K-means analysis is limited under the frequency of $20f_0$ to reduce the influence of high-frequency noise. In addition, the extracted waveform for DFT is normalized by the maximum value in each waveform because the light intensity of the laser beam is not uniform, and thus, the scattered light intensity is affected by the bubble position. Note that the frequency resolution of the amplitude spectrum is f_0 / 6. The number of clusters is set to 5 and the measurement time is 400 ms.

3. Results and Discussion

The result of cluster analysis is shown in **Table 1**. The cluster analysis is performed for the extracted waveform for four driving power conditions. The total number of detected bubble passing events increases with increasing the BLT driving power. It is because the number of bubbles increases with the ultrasonic pressure amplitude. The cluster number is ordered as the larger number of events for the BLT driving power of 13.2 W has larger cluster number. The number of bubbles in clusters #1 and #2 decrease with increasing the BLT driving power. On the other hand, the number of bubbles in clusters #4 and #5 increases with increasing the BLT driving power. It suggests that the bubble radial oscillation characteristics transition from the cluster #1 to the cluster #5 with increasing the BLT driving power.

Figure 3 shows the representative extracted waveform of each cluster, which means extracted waveform nearest the mass center of each cluster. The representative waveform of the cluster #1 shown in Fig. 3(a) resemble to that of typical bubble in the single-bubble sonoluminescence system. The rebounds subsequent to rapid contraction is observed. The waveform repeats the oscillation with fundamental frequency, f_0. The redound is no longer observed for the cases of the clusters #2 and #3 shown in Figs. 3(b) and 3(c). This waveform is observed in relatively high ultrasonic pressure amplitude[3)]. The periodicity of the oscillation is decayed in higher BLT driving power condition as shown in Fig. 3(d) and 3(e). The waveforms with high maximum value and low maximum value are alternatively observed. It may be caused by the interaction between the bubbles[4)]. The waveforms shown in Figs. 3(d) and 3(e) are frequently observed in relatively high input power condition, namely, the high bubble number density condition. The increase of the bubble number density may enhance the bubble-bubble interaction.

Table 1 Number of events classified in *n*th cluster.

Input power (W)		8.54	10.1	11.4	13.2
Cluster	#1	97	571	512	10
	#2	0	41	548	13
	#3	126	161	615	305
	#4	0	0	76	1,286
	#5	0	28	448	1,358
	Total	223	811	2,199	2,972

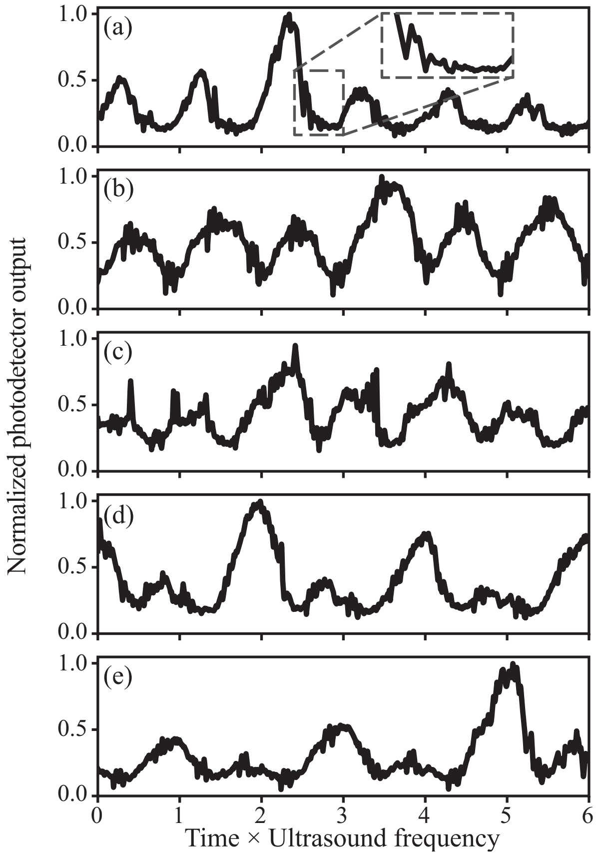

Fig. 3 Representative waveform of clusters. (a) – (e) correspond to cluster #1 - #5, respectively.

4. Conclusion

Input power dependence of the oscillation of a bubble in the bubble cluster is observed employing the laser light scattering. The bubble oscillates similarly to the sonoluminescing bubble in relatively low input power condition but the bubble oscillation becomes aperiodic with increasing the input power.

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