3P4-21
Proceedings of Symposium on Ultrasonic Electronics, Vol. 34 (2013) pp. 471-472
20-22 November, 2013

On the Intermittent Changes in the Number of Pulsating Bubbles under Ultrasound
超音波照射下におけるキャビテーション気泡数の変動

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1. Introduction

An application of intense ultrasound into a liquid results in the generation of many cavitation bubbles.[1)] These bubbles are responsible for various physical and chemical effects.[2, 3)] The extent of the effects is closely related to the spatial structure of cavitation bubbles. The spatial region of bubbles is confined by the action of primary and secondary Bjerknes forces according to the applied acoustic amplitude.[4)] In a standing wave field, the primary Bjerknes force, which is proportional to pressure gradient, directs a bubble with a radius smaller than a resonant radius towards the pressure antinode, while the force directs a bubble with a radius larger than a resonant radius towards the pressure node. The secondary Bjerknes force, which is inversely proportional to the square of the distance between bubbles and directly proportional to the square of sound pressure, is the attractive force between bubbles pulsating in phase. This is responsible for the coalescence of bubbles leading to the generation of large bubbles when sound pressure becomes high.

Intermittent changes in the formation of bubbles were shown by Mettin *et al.*[5)] and they deduced that the existence of many bubbles causes a decrease in sound pressure amplitude, after which, pressure amplitude is restored by the decrease in the number of bubbles. However, they did not deal with the temporal changes in the number of bubbles in pulsation. Moreover, they did not identify the mechanism underlying the changes in the number of bubbles owing to the coalescence of bubbles.

The present study investigated the spatiotemporal changes in the number of ultrasonic cavitation bubbles in pulsation by capturing sequential images of bubbles and the measurement of scattered light from bubbles illuminated by laser light.[6)]

2. Experiment

A cw sinusoidal signal of 142 kHz generated by a function generator was amplified with a 55 dB power amplifier. A Langevin-type transducer (45 mm diameter) was used. The transducer was fixed to a stainless steel plate. A rectangular glass cell with internal dimensions of 50×50×145 mm^3 was set above the transducer. The thickness of the glass cell was 5 mm. The volume of distilled water in the cell was 250 cm^3 and the temperature was 20 °C. The dissolved air concentration of distilled water was adjusted by bubbling air. The concentration of dissolved oxygen (DO) in distilled water was measured using a DO meter (Horiba D-25) and served as an index of the amount of dissolved air. A diode laser beam (NEOARK 50 mW, 684 nm, 1 mm in beam diameter) modified with a lens to a 0.5-mm- thick sheet light was introduced into cavitation bubbles generated at an antinode of a sound pressure in the cell, where the illuminated area was a tetragonal with dimensions of 25×50 mm^2 and one-half of one antinodal plane whose one side was set close to the central axis. The images of the bubbles were captured with a high-speed video camera (Redlake Imaging PCI 8000S). The exposure time of the camera was 1/60 s, which was the same as the frame rate. The intensity of scattered light from bubbles was measured with a photomultiplier tube (Hamamatsu H7732-10), and the output voltage from a hydrophone (Brüel & Kjær 8103) set at a pressure antinodal plane was also measured. The waveform of scattered light was recorded with a digital oscilloscope (Yokogawa DL1540C). The input ultrasonic power determined calorimetrically was 11 W.

3. Results and Discussion

Figure 1 shows the measured waveforms of scattered light for one ultrasonic cycle at (a) approximately air saturation (initial DO concentration=8.86 mg/L) and under (b) partly degassed condition (5.17 mg/L). In Fig. 2(a), peak-to-trough intensity is defined as the difference between the maximum and minimum intensities.[7)] The waveform measured is the superposition of the waveform of an independent bubble. Peak-to-trough intensity is related to the number of the pulsating bubbles. It is found that the shape of the waveform in Fig. 1(a) is almost symmetrical while that in Fig. 1 (b) is asymmetrical and appears to indicate a single bubble. The former reflects various times of collapse of bubbles with various radii caused by the coalescence of bubbles. In the latter, there are a smaller number of bubbles at a low DO concentration. There is some possibility that bubble-bubble interaction influences the waveforms.[8)]

Figure 2 shows the time course of the peak-to-trough

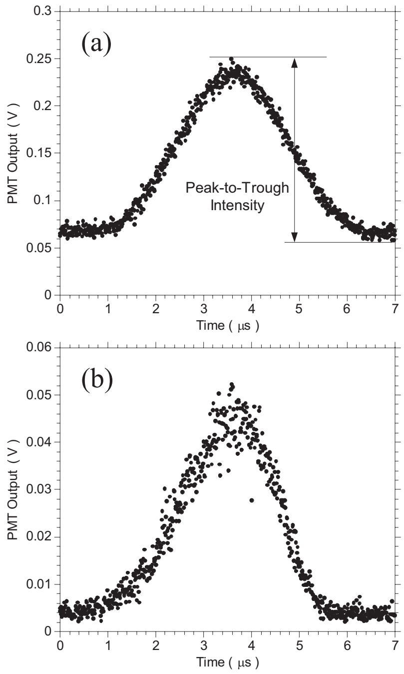

Figure 1. Waveforms of scattered light intensity at different initial dissolved oxygen concentrations: (a) 8.86 mg/L together with definition of peak-to-trough intensity and (b) 5.17 mg/L. (from Ref. 6 © 2012 The Japan Society of Applied Physics)

intensity of scattered light and that of hydrophone output voltage together with captured images of cavitation bubbles. The vertical fluctuations of light intensity indicate the relative changes in the number of pulsating bubbles. It is consistent that, from 11.3 to 13.1 s, the brightness of the illuminated bubbles between the images decreases with light intensity. From 13.1 to 14.9 s, both the brightness and the light intensity increase. The change in peak-to-trough intensity was random in the present experiment since the specific peak of the frequency component did not appear under Fast Fourier transform (FFT) operation on it.

In the graph, it seems that the rise and fall of light intensity appears opposite to that of sound pressure amplitude. The illuminated bubbles in the images show a zigzag formation. It is interpreted that the pressure amplitude on the left side (close to the central axis) of the formation is higher than that on the right side. The pressure gradient isolates bubbles from the region of high pressure amplitude on the left side. It is remarkable that the number of bubbles may change while the formation of bubbles is almost maintained.

The change in the number of bubbles may be due to the fact that in the bright region in the images, which means a high density of tiny bubbles, bubbles coalesce resulting in the generation of large degassing bubbles that are away from the region and move upward. The changes in the number and size of bubbles influence the sound pressure amplitude.

The present study clarified that the number of pulsating bubbles changes intermittently, as determined by capturing the images of bubbles and the measurements of peak-to-trough scattered light intensity. The present method of examining light scattering is promising for various studies of physical and chemical effects of cavitation bubbles.

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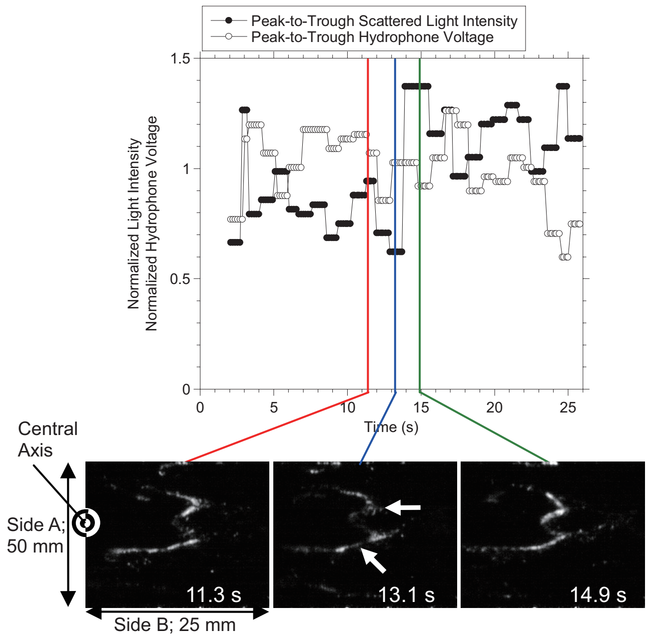

Figure 2. Time course of peak-to-trough scattered light intensity and that of hydrophone-output voltage together with captured images of cavitation bubbles at approximately air saturation. Note that the aspect ratio of each image is not the same for the vertical and horizontal sides (A: 50 and B: 25 mm). This is because each image has been captured from an inclined angle to obtain a brighter scattered light. Arrows in the middle image indicate illuminated bubbles with a lower brightness than those in both the left and right images. (from Ref. 6 © 2012 The Japan Society of Applied Physics)