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Lifetime measurement of cavitation cloud bubbles using long exposure shadowgraphy

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1. Introduction

Cavitation phenomenon is known to play an important role in biological effects required for therapeutic medical applications[1]. Nevertheless, it is difficult to evaluate the characteristics of cavitation behavior due to its chaotic nature and ultrafast dynamics[2]. And also, bubble behavior such as maximum radius or collapse time is affected by the medium condition and applied pressure waveform types. An optical visualization method is proposed as a useful tool for cavitation evaluation[3] and Kang et al.[4] demonstrated the feasibility of estimating a negative pressure field of shock wave device using accumulated cavitation image.

In the present study, we attempted to measure the lifetime of bubbles induced by shock wave pulse using long exposure shadowgraphy image. The lifetime of a Rayleigh-like bubble is generally proportional to the maximum bubble size[5]. Therefore, we compared the diameter of the bubble with the grayscale intensity of the bubble.

2. Materials and methods

An experimental setup used in this study is shown in Fig 1. A clinical extracorporeal shock wave system (Electromagnetic Type, ShineWave-sonic, HnT Medical, Korea) was taken to generate inertial cavitation bubbles. Three identical capacitors of 0.15 μF connected in parallel were installed and electrically charged up to 19.75 kV. The capacitors are discharged through a shock wave transducer to generate a cylindrical wave that is reflected by parabolic reflector and focused at the geometric focal point.

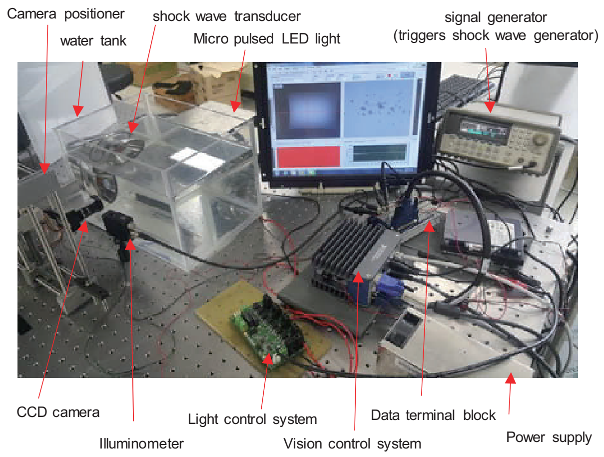

Fig. 1 The experimental setup of long exposure vision system for visualizing cavitation bubbles.

The shock wave pressure was measured using a fiber-optic probe hydrophone (FOPH2000, RP Acoustics, Germany) which has a wide frequency bandwidth up to 150 MHz and strong resistance to violent cavitation activities. The peak positive and negative pressure applied in this study are +112 MPa and -19 MPa, respectively.

The cavitation visualization system was composed of a CCD camera (CM3-U3-50S5M, PointGrey, Canada) with macro-lens, the Micro-pulsed LED light (MPLL-a, KISTech, Korea), water tank (200 x 200 x 200 mm, optically transparent) and the compact vision system (40 MHz FPGA, NI CVS-1459, National Instruments, USA). The water tank was filled with tap water used as the shock wave propagation medium. The water was filtered using a 5 μm filtering system for 10 h (AIMS water conditioning system, NTR Systems, USA) to remove impurities that act as possible unexpected cavitation nuclei. The water was then left at room temperature(20°C) overnight for natural degassing before use.

When the shockwave device was triggered by the compact vision system, the image sensor of the CCD camera began to acquire the light. After 60 μs,

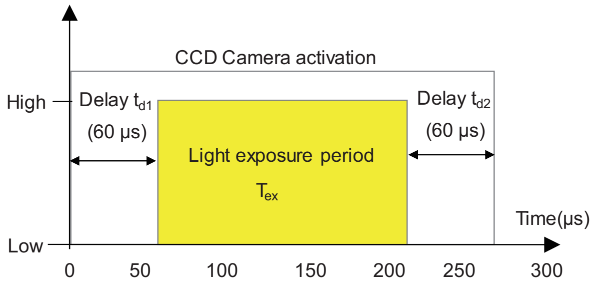

Fig. 2 Sequential image acquisition procedure to synchronize a CCD camera with micro-pulsed LED light.

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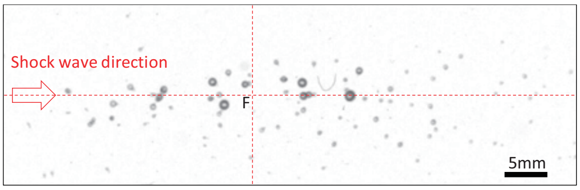

Fig. 3 Typical long exposure shadowgraphy of cavitation bubble cloud obtained under the light exposure time of 150 µs.

the MPLL-a emitted light for 150 µs. And another 60 µs later, the camera operation stopped, and the image was stored and acquisition completed (Fig. 2). The shadow of cavitation bubbles was accumulated on a single image during its entire lifetime. The image size is 2448 x 2048, and the resolution is 40 µm / pixel. Then, the bubbles were detected, and the inverted pixel intensity of the bubble, $P_{i(x,y)}$ was calculated using MATLAB (R2018b, MathWorks, USA).

$$P_{i(x,y)} = \frac{g(x,y)}{n}\sum_{i=1}^{x}\sum_{j=1}^{y}(255 - B(i,j)) \qquad \dots\dots\dots\dots(1)$$

$$g(x,y) = \begin{cases} 1, & if\ B(x,y) \geq threshold \\ 0, & otherwise \end{cases} \qquad \dots\dots\dots(2)$$

Here, B(i,j) is a single bubble image, x and y is the size of a bubble image, n is the total pixel number of B(i,j) within the bubble diameter. The threshold to calculate the inverted pixel intensity of the bubble is 50% of the inverted peak intensity of B(i,j).

3. Results and Discussion

Shadows of bubble behavior were recorded under the long light exposure duration (T_{ex} = 150 µs) which was set to cover the entire bubble lifetime measured in our previous work [2] (Fig. 3). Red dot line passes through the focal point indicated ‘F’ in the vertical and horizontal directions.

Bubble’s shape in the image remains circular, with different sizes and grayscale intensity. No significant displacement of the bubble position was observed, and water jet formation was found on all bubbles. Therefore, we assume that the cavitation bubble induced by the shock wave collapsed in the same position as it was created under the present experimental conditions. Larger and darker bubbles were observed near the focal point, and smaller and fainter bubbles were around them sparsely. Bubbles formed in the outside of the focal plane of the optical lens were excluded due to the out-of-focus blur of the image.

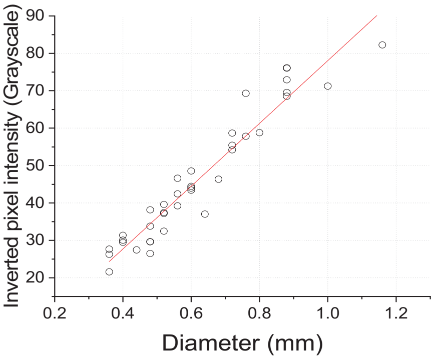

Fig. 4 Correlation analysis between bubble size and the inverted grayscale level of the cavitation bubble image (Adj. $R^2 = 0.92$).

Fig. 4 shows the linear relationship between the bubble size and the inverted grayscale level of the cavitation bubble image. The inverted grayscale level of the cavitation bubble rises as the bubble diameter increases (Adj. $R^2 = 0.92$).

The timing of the bubble's occurrence is different along the axis of the shock wave beam because the shock wave propagates from the left to the right of the image. However, the total amount of light recorded in the image sensor is affected by the absolute duration of the bubbles presence rather than by the occurrence time, so the effects due to the bubble occurrence timing are not significant.

4. Conclusion

This paper proposes a simple method to estimate the lifetime of bubbles induced by a single shock wave pulse visualized in the image by measuring the pixel intensity of the bubble. The size of the cavitation bubble was highly correlated with its pixel intensity of the bubble image. It is expected that the proposed method can estimate the lifetime of the individual bubbles spatially distributed in the image.

References

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