Experimental Study of the Shock Generation at the Collapse of Cavitation Bubble

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Using a photoelastic apparatus or Schlieren interferometer, we experimentally studied the mechanism of the impulsive force generation by a spark-induced cavitation bubble, collapsing near the solid boundary. The experimental results indicate that the cause of the impulsive force is classified by the parameter $l$, where $l=($maximum bubble center distance from the solid boundary$)/($maximum bubble radius$)$. In case of $l \geq 1.36$, the shock waves are dominant and in case of $l < 1.36$, the water microjet impingement is the main cause of the impulsive force. In a special case ($l \leq 1.24$), both the shock waves and the water microjet are supposed to impact against the solid boundary. Even when an asymmetrically collapsing bubble rebounds, the shock waves are observed.

** Key Words: **Cavitation, Mechanism of the Impulsive Force, Photoelastic Method, Schlieren Interferometer, Experiment

1. Introduction

Many studies have been performed to analyze the impulsive pressure accompanying the collapse of the cavitation bubble. Those previous works show that the impulsive pressure results from the shock waves(1)-(4) or the microjet impingement (5)-(8), but the cause of the impulsive pressure is not clearly understood yet. The shock wave is considered to generate when a bubble rebounds, but the state of its generation is not understood in detail. And the instant when the microjet impingement acts on the nearby solid wall is not clearly determined, too. This study is conducted to clarify the cause of the impulsive pressure which acts on the solid wall at the collapsing stage of the cavitation bubble. The photoelastic fringe, resulting from the impulsive pressure at the collapse of a spark-induced bubble, is photoelastically analyzed. From this analysis, it is suggested that the cause of the impulsive pressure varies with the distance between the bubble center and the solid wall. Next by means of the Schlieren interferometer, the shock wave propagation is clarified especially when a bubble collapses asymmetrically. Thus the generation and the impact timing of the shock wave and its maximum impact pressure are determined.

2. Measurement of the Impulsive Pressure

2-1. Experimental Apparatus

In this experiment, a cavitation bubble is induced by an electric spark and the impulsive pressure accompanied by a collapse of the bubble is photoelastically analyzed.

![Experimental Arrangement](image)

Fig.1 Experimental Arrangement

Figure 1 shows the experimental arrangement. 200 photographs are taken successively at time interval of 6μs by use of a high-speed motion camera. Figure 2 shows the water tank in which a spark-induced bubble collapses in the vicinity of the solid wall. Two electrodes are made of stainless steel wire(0.1mm in diameter). The liquid in this tank is tap water, deionized and degassed ultrasonically. And the photoelastic material is

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mounted flush with the solid wall as shown in Figure 3.

Fig.2 Water tank
1. Electrode
2. Photoelastic material

Phosphor Bronze Plate

Photoelastic Material

Fig.3 Solid wall

The photoelastic material is required to possess the following two properties; high photoelastic sensitivity to analyze even the small stress and high propagation speed of the fringe, in order to analyze the impact time in detail, but those two properties tend to contradict each other. Some previous studies\(^\text{(4)}\),\(^\text{(5)}\),\(^\text{(6)}\) were tried to analyze the impulsive pressure by means of the photoelastic method. The photoelastic materials used in their studies were epoxy resin\(^\text{(4)}\), CR-39(allyl carbonate)\(^\text{(5)}\) and polyurethane rubber\(^\text{(6)}\). They treated only two-dimensional fringe resulting from the impulsive pressure. But because the fringe propagation speed decreased gradually, it was difficult to determine the impact time by analyzing the fringe, so that the above-mentioned materials were not suitable for detailed analyses.

In this experiment, we intend to analyze the impulsive pressure; to distinguish the pressure of the impact of the microjet from that of the shock wave, which acts on the solid wall for several scores of micro-seconds before and after the collapse of a cavitation bubble. So we newly make an epoxy resin, possessing both a higher photoelastic sensitivity\((1.08 \times 10^3 \text{ m/N})\) than that of the previously used epoxy resin\(^\text{(4)}\), and a higher propagation speed of the fringe\((811 \times 10^3 \text{ m/s})\) than CR-39\(^\text{(5)}\) as well as polyurethane rubber\(^\text{(6)}\). Other properties of the newly made epoxy resin are \(231 \times 10^3 \text{ MPa}\) in Young's modulus 0.455 \pm 0.03 in Poisson's ratio and 1284 kg/m\(^3\) in density. And we determined the dimensions of photoelastic material such that the fringe propagated at constant speed \((811 \times 10^3 \text{ m/s})\). They are 2.7mm in thickness, 4.0mm in width and 45.0mm in length.

2-2. Examination of the Fringe Propagation

We examined experimentally the fringe propagation pattern and the rising property of the fringe when the impulsive shock acted on the photoelastic material, mentioned in Section 2-1, which was hung by two fine threads and was shocked by the impact of a brass piston, whose diameter was 5.0mm or 2.0mm in impact area. That piston was driven by the compressed air and its impact speed was about 10m/s. The fringe propagation and the piston movement were photographed by means of a high-speed motion camera.

(a) Distributed load (b) Concentrated load

Fig.4 Propagation of the photoelastic fringe

Figures 4(a),(b) show two examples of the high-speed photographs. Figure 4(a) illustrates a fringe propagation pattern in case that the impact speed of the piston was 10.1m/s and the impact diameter was 5.0mm; and Fig.4(b) shows one in case of 11.4m/s and 2.0mm, respectively. The impact speed of the piston is calculated as follows, as the piston moves at almost constant speed, we approximate the piston movement as first-order, determine the
impact speed of the piston, and calculate the time \( t_1 \) when the piston contacts with the photoelastic material. The elapsed time from \( t_1 \) is indicated at the right side of each frame in Figs. 4(a),(b).

![Diagram](image)

Fig.5 Fringe traveled distance

Figure 5 shows the fringe traveled distance in time lapse from the time \( t_1 \). In Fig.5, the round symbol and the square symbol denote the experimental results in cases of the diameter of the piston's impact area being 2.0mm and 5.0mm, respectively.

After about 3μs elapse from \( t_1 \), the fringe propagates at constant speed (811±30m/s). But in this experiment, the rising property of the fringe is not understood clearly. So we approximate the time-dependent fringe traveled distance as first-order and the time \( t_2 \) is calculated at the instant when the fringe just begins to propagate. This time \( t_2 \) does not coincide with the time \( t_1 \) and \( t_2 \) is always earlier than \( t_1 \) (\( t_1 > t_2 \)). This time difference (\( t_1 - t_2 \)) is considered to include the rising property. \( (t_1 - t_2) \) is about 7μs when the fringe traveled distance of 6~8mm is measured in a frame in which the fringe is first photographed and \( (t_1 - t_2) \) is about 1μs when about 4mm is measured. Therefore, the shock impact time is estimated by measuring the fringe traveled distance and considered this rising property.


![Frames](image)

(a) \( l=1.57, \) \( da=6.8\text{mm} \)

(b) \( l=1.35, \) \( da=6.9\text{mm} \)

(c) \( l=1.24, \) \( da=7.6\text{mm} \)
Figures 6(a)~(d) show high-speed photographs of the bubble behaviour and the fringe propagation at various distances between the solid wall and the electrodes. The first frames in each series show the instant of an electric spark. The third frames and the 13th frames show the maximum and minimum bubble diameters, respectively. The time indicated in each frame is the elapsed time from the first frame.

The dimensions of a spark-induced bubble are measured from each frame and are shown in Fig.7. The bubble diameter $d$, the normalized wall distance $l$ and Rayleigh's theoretical collapse time are as follows: $d = \left( d_0 / d_1 \right)^{1/3} \left( l/L_{0} - d_{m}/2 / d_1 / 2 \right)$, $l_{th} = 0.91 l_{0.68} \left( d_0 / d_m / L_{0} / \mu \right)^{1/2}$ (the suffix "m" denotes the dimensions at the third frame).

The fringe propagation is photographed under the condition $l<1.67$. The fringe is considered to come from the impulsive pressure at the bubble collapse.

In Fig.6(a),(b), the trailing edge of a bubble (upper bubble wall) is seen to be flatten after 685ms and so a microjet formation is considered, but the microjet impingement against the solid wall is not observed. In these cases, the fringe appears after 13th frame in which the minimum bubble diameter is photographed. In Fig.6(c), the asymmetrical bubble collapse is remarkable and the microjet impingement is observed. Figure 6(d) shows a hemispherical bubble collapse in contact with the solid wall. In Fig.6(c),(d), the fringe generation is considered to come earlier than the bubble collapse. Moreover another fringe generates when the bubble rebounds.

2-4. Impulsive Pressure Impact Timing

In order to trace to the cause of the impulsive pressure, we estimated the collapse time $t_c$ of the bubble and the time $t_i$ when the impulsive pressure acts on the solid wall.

Though the bubble motion and the fringe propagation are continuous, the high-speed photographs, shown in Fig.6(a)~(d), are discrete in time and noticeable phenomena are possibly included in the 64s time interval between a frame and the next frame. Therefore, the collapse time $t_c$ does not always coincide with the time indicated in the 13th frame. So we determined $t_i$ and $t_c$ as follows: the measured time-dependent bubble diameter and the fringe traveled distance are plotted in Fig.8 in cases of both the bubble contraction and the rebound stages. Four symbols (1)~(4) in Fig.8 correspond with Fig.6(a)~(d).

The time-dependences of the bubble diameter are approximated as two second-order curves, with reference to the bubble
Table 1 Normalized wall distance, the collapse time and shock impact time

<table>
<thead>
<tr>
<th>Corresponding Fig-No.</th>
<th>Normalized wall distance</th>
<th>Collapse time $\mu$s</th>
<th>Impact time $\mu$s</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 - a</td>
<td>1.57</td>
<td>696</td>
<td>702</td>
</tr>
<tr>
<td>6 - b</td>
<td>1.35</td>
<td>726</td>
<td>736</td>
</tr>
<tr>
<td>6 - c</td>
<td>1.24</td>
<td>793</td>
<td>789</td>
</tr>
<tr>
<td>6 - d</td>
<td>0.90</td>
<td>897</td>
<td>890</td>
</tr>
</tbody>
</table>

The contraction stage and the rebound stage respectively. The intersecting point of these two curves is defined as the collapse time $t_c$. And the time-dependence of the fringe traveled distance is approximated as a first-order curve and thus $t_i$ is calculated as described in Section 2-2.

The normalized wall distance $I$, the bubble collapse time $t_c$ and the impulsive pressure impact time $t_i$ are shown in Table 1 in reference to Fig.6(a)×(d).

Using the above-mentioned procedure, $t_c$ and $t_i$ are calculated from the experimental results at various wall distances. Then in order to clarify the impact timing of the impulsive pressure, time difference $(t_i-t_c)$ is estimated.

The normalized wall distance is, the more $(t_i-t_c)$ tends to decrease. These results correspond to the fact that the smaller wall distance hasten the microjet formation because of the more intense asymmetry of the bubble wall. Therefore, the microjet impingement might be the main cause of the impulsive pressure. In a special case of $I \geq 1.24$, the photoelastic fringe tends to generate twice. The first fringe appears before the collapse time and the second fringe does after the collapse time. Therefore, both the microjet impingement and the shock wave might be the causes of the impulsive pressure.

3. Shock Wave Radiated from a Bubble

The shock wave, generated in the bubble rebound process, is observed by means of the Schlieren interferometer. At the same time, the impulsive pressure value of the shock wave is measured.

3-1. Experimental Arrangement

Figure 10 shows the optical arrangement of the experiment, using the Schlieren interferometer. The water tank is similar to the one shown in Fig.2. In this experiment, the impulsive pressure of the shock wave is measured at the time of taking the high-speed photographs of the bubble behaviour and the shock wave propagation. Figure 11 shows the experimental arrangement to measure the impulsive pressure. A pressure pickup (titanium-acid barium oscillator, the resonance frequency being 500kHz in thickness mode, and 300kHz in radial mode, and its diameter 10mm) is mounted flush with the solid wall. Another pressure pickup (resonance frequency are
1MHz and 300kHz, respectively) is also set up right beneath the water surface in the water tank. Low frequency noises, caused by the electric spark and included in the detected impulsive pressure wave, are excluded through a high-pass filter. The impulsive pressure is once stored in the digital memory at the clock rate 1µs/word, and registered on the oscilloscope and on the electromagnetic oscillograph.

3-2. Experimental Results
A spark-induced bubble grows, collapses and rebounds in the vicinity of the solid wall. Figures 11(a, b, c) show some typical examples of the experimental results.

Fig.11 Experimental arrangement

Fig.12 Bubble behaviour, shock wave propagation and impulsive pressure traces
Impact pressure at the solid wall (upper trace)
Impact pressure at water surface (lower trace)
High-speed photographs are taken at a speed of 165,000 frames/s, the time interval of each frame being 6µs. The upper one of the two pressure traces in Figs.12(a) and (c) is that of the impulsive pressure at the solid wall and the lower one is that measured right beneath the water surface. The time shown in Figs.12 (a) and (c) is the elapsed time from the instant of the electric spark. The time indicated in the pressure traces corresponds with the time in each frame of the high-speed photographs.

Figure 12(a) shows the result in case of I=2.05. In this figure, the bubble contracts from its maximum diameter (261µs) and rebounds after 521µs, when the shock wave has already radiated. A microjet is observed in the contraction stage of the rebound bubble. The impulsive pressure at the collapse of the bubble is detected by both pressure pickups set at the solid wall and the water surface as above-mentioned. The time difference between the instant of the peak pressure generation at the solid wall and that at the water surface is considered to be nearly equal to the necessary time for the shock wave to propagate between two pressure pickups, and the impulsive pressure, resulting from the impingement of the microjet, acts only against the solid wall. Therefore, the impulsive pressure measured here is considered to be the cause of the shock wave.

Figure 12(b) shows the results in case of I=1.37. This case is similar to that shown in Fig.12(a). In Fig.12(b), which shows that rebound bubble collapses asymmetrically and rebounds again in contact with the solid wall, the shock wave generates three times.

Figure 12(c) shows a phenomenon similar to the second collapse shown in Fig.12(b). In this case (I=1.08), a bubble collapses asymmetrically in contact with the solid wall and the shock wave generates twice. The impulsive pressure in Fig.12(b), (c) is also considered to result from the shock wave of the same cause as shown in Fig.12(a).

The experimental results indicate for various wall distances that the shock wave always generates without reference to the asymmetry of the bubble collapse.

Figure 13(a) and (c) show the time-dependent bubble diameter, the bubble-center location, the locations of the shock wave front and the reflected wave front. Figure 13(a) and (c) correspond to Fig.12(a) and (c), respectively.

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3-3. Shock Wave Impact Timing

By analyzing the experimental results we clarify the time when the shock wave generates and impacts against the solid wall. The collapse time t_c is determined by the same procedure in Section 2-4. The shock wave generation time t_s and the shock wave impact time t_i are calculated as follows; since the shock wave front propagates at nearly constant speed as shown in Fig.12(a) and (c), its time-dependent traveled distance is approximated by a first-order equation. The propagation speed of the shock wave is easily obtained by this equation (this speed is nearly equal to the sound speed in water). Next, we measure the shock wave front traveled distance from the bubble center, and by dividing it by its propagation speed, we calculate the elapsed time for the shock wave to propagate that distance. This procedure is repeated for each frame in which the shock wave is photographed. Then t_s is defined by taking the elapsed time from the time shown in each frame. We also calculate the elapsed time for the shock wave to propagate from the bubble center to the solid wall. Then t_i is defined by adding this elapsed time to t_s.

In order to determine the timing of the shock wave impact, the time difference (t_i - t_c) at various wall distances are shown in Fig.14. Here, the value of (t_i - t_c) is always positive and t_i is delayed from t_c in accordance with an increase of the wall distance. This fact shows that
the impulsive pressure of the shock wave always acts on the solid wall in the bubble rebound stage.

Fig.14 Time difference ($t_{si} - t_c$)

3-4. Impact Pressure Value of Shock wave

As mentioned in Section 3-2, the impulsive pressure shown in Figs.12(a)-12(c) is considered to result from the shock wave. Then the peak pressures are measured from the pressure traces at the solid wall as shown in Figure 15.

Fig.15 Impulsive pressure value

It is well known that the impact pressure of the shock wave attenuates in proportion with an increase of the shock wave traveled distance. Figure 15 shows the same tendency as this fact does. Experimental results show that maximum impact pressure occurs at $l=1.0$ and its value is 1.5MPa. This value of 1-1.5MPa is less than the value $10^3-10^4$MPa of the previous report(3).

4. Conclusions

This study is performed to determine the cause of the impulsive pressure accompanying a bubble collapse. Figure 16 shows the experimental results in Section 2 and Section 3. From Fig.16, it is seen that experimental results obtained by means of the photoelastic method coincide with those by using the Schlieren interferometer. Consequently we reach the following conclusions.

(1) The cause of the impulsive pressure differs with a bubble location in vicinity of the solid wall, but in general both the shock wave and the microjet impingement cause the impulsive pressure.

(2) In case of $l<1.35$, as the impulsive pressure acts on the solid wall in the bubble rebound stage, the shock wave is dominant.

(3) In case of $l>1.35$, as the asymmetry of a bubble collapse is remarkable and the impulsive pressure acts on the solid wall in the bubble contraction stage, the microjet impingement might be the main cause of the impulsive pressure.

(4) In a special case of $l<1.24$, as the impulsive pressure acts on the solid wall twice clearly before and after the bubble collapse, the microjet impingement is considered to be equivalent to the shock wave in the effects.

Fig.16 Experimental results in Section 2,3

References