A Study on Impulsive Pressure of a Collapsing Cavitation Bubble*

(Evaluation of the Effect of a Water Microjet)

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The motion of a spark-induced cavitation bubble is examined near a solid boundary by high-speed photography and the impulsive pressure generated at its collapse-reexpansion stage is detected by a local pressure sensor with four small sensor elements. As a result, the impulsive pressures of a shock wave and of a water microjet are separately measured by the local pressure sensor. The result is ascertained by high-speed photographs of the cavitation bubble, which indicate that a microjet is generated at the top surface of the collapsing bubble and collides against one of the pressure sensor elements through the interior of the bubble at its collapsing stage. Moreover, the diameter of the generated microjet tip and its travelling velocity through the interior of the bubble are evaluated to be about 0.5mm and 100~110 m/s, respectively.

Key Words: Cavitation, Impulsive Pressure, Microjet, Shock Wave, Local Pressure Sensor, High-speed Photograph

1. Introduction

Recently, Fujikawa and Akamatsu reviewed the research on the motion of a cavitation bubble and impulsive pressure generation in the Transaction of JSME⁽¹⁾, so a survey is omitted here. Generally speaking, however, the cause of impulsive pressure generation at the collapse-reexpansion stage of a cavitation bubble has not been completely clarified, yet.

It is known that a shock wave is delivered at the collapse-reexpansion stage of a cavitation bubble which is near or even on a solid boundary⁽²⁾⁽³⁾. For a microjet, on the other hand, a lot of uncertain points, i.e. the order of its impulsive pressure and the time of its generation, etc., still remain.

Using a spark-induced cavitation bubble, Kimoto and others revealed in a previous report⁽⁴⁾ that impul-

sive pressure generation at the collapse-reexpansion stage was often due to both actions of the microjet and the shock wave. It was also shown that a microjet was not generated for a hemispherical cavitation bubble, which was produced on a solid wall by emitting a pulsed laser beam of relatively low intensity⁽⁵⁾.

For a spark-induced cavitation bubble near or on a solid boundary, Shima, et al. used an image-converter camera and a piezo-electric pressure transducer to clarify the experimental condition under which both impulsive pressures of the microjet and the shock wave act at nearly the same time on a solid boundary⁽²⁾⁽⁶⁾. However, in their experiments, microjet formation was not necessarily clarified. As they used only one pressure transducer in their experiment, the action of the microjet could not be perfectly separated from that of the shock wave. Therefore, Fujikawa and Akamatsu did not accept the idea that both the microjet and the shock wave act on the solid boundary almost simultaneously⁽¹⁾.

In the present experiment, four local pressure sensor elements with very small sensitive areas were installed flush with a solid wall and a local pressure sensor was manufactured. The sensor was used to

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Fig. 3 High-speed photographs of a cavitation bubble for $Ln=1.11$

surface of the transducer was about 5.5 mm.

In the calibration, the sensitive surfaces of the local pressure sensor elements and the pressure transducer were set face-to-face in a water bath. A spark-induced cavitation bubble was generated between them and the impulsive pressure of the shock wave was detected by the local pressure sensor elements and the pressure transducer, simultaneously. Their peak values were compared with each other and calibration charts were made.

3. Experimental results and discussion

In this report, the non-dimensional normalized wall distance (Ln) defined in the previous report⁽⁴⁾ is used to express the distance between the cavitation bubble and the solid wall. In the following, experimental results are shown for three typical normalized wall distances. The time origin of the photographs was defined as the instant of electric discharge, which was clear in the photograph showing the brightest discharge of light in water.

3.1 Cavitation bubble collapsing upon contact with a solid wall

In the present experiment, in the range of the normalized wall distance of about 1.0~1.1, a cavitation bubble collapsed upon contact with the solid wall. Typical high-speed photographs of a cavitation bubble taken under this experimental condition are shown in Fig. 3. Under each photograph in Fig. 3, lapsed time from the above-defined time origin is indicated.

The four-channel digital memory equipment was triggered by the shock wave emitted in water at the electric discharge, and the output waveforms of the local pressure sensor elements were recorded at a writing rate of 1 μ s/word.

The recorded waveforms of the impulsive pressure were expanded in a lapsed time range between 800 and 1 020 μ s. They are shown in Fig. 4. In the figure, four

Fig. 4 Output waveforms of the local pressure sensor elements ($Ln=1.11$)

waveforms of each pressure sensor element (No.1-No. 4) are shown on the same time-coordinate as CH1-CH4. The pressure rise of only the CH2 waveform is obvious at a lapsed time of about 910 μ s and the pressure reaches about 1.0 MPa at about 950 μ s. At a lapsed time of around 960 μ s, the impulsive pressure is recognized in each waveform, and the pressure reaches about 2.7 MPa in the CH2 waveform.

In the high-speed photographs shown in Fig. 3, it is seen that a microjet is generated at the upper bubble wall, penetrates the interior of the bubble and then collides against the solid wall. In order to make it easier to see the movement of the microjet, some enlarged photographs taken from the high-speed negative film are shown in Fig. 5. The microjet and bubble in the photographs are reversed in their bright and dark portion, because they were printed on a roll of positive film.

Under the photographs in Fig. 5 the relative positions of the local pressure sensor elements with

Fig. 5 Microjet formation in a collapsing bubble ($Ln=1.11$)

respect to the cavitation bubble are shown. The numerals (1,2,3,4) correspond to the CH numbers in Fig. 4. The lapsed time from electric discharge is also shown under each photograph. At the bottom of Fig. 4, the lapsed time corresponding to photographs (A) ~ (J) in Fig. 5 is indicated by the capital letters A-J. In Fig. 5 it is clearer than in Fig. 3 that a microjet is generated, penetrates the interior of the bubble and collides against the solid wall. The distances between the upper and lower bubble walls and the solid wall or the microjet tip and the solid wall were measured in the photographs of Fig. 5 and their time-changes are plotted in Fig. 6.

The diameters of the microjet tip and the microjet trunk, seen in the bubble of Fig. 5(E)~(G) are about 0.5 mm and 1 mm, respectively. The velocity of the microjet tip measured in Fig. 6 is about 100 m/s. The velocity is larger than 10~35 m/s, which was obtained by Benjamin and Ellis⁽⁷⁾ under a decompressed condition, and is almost equal to the value which was measured in a hemispherical spark-induced cavitation bubble by Naudé and Ellis⁽⁸⁾

Figure 5 (H) indicates that the microjet collides against the solid wall (i.e. on the sensitive surface of sensor element No.2), and only the CH2 pressure detected by the No.2 sensor element begins to increase at this time. Therefore, it is certain that the detected pressure rise was due to the microjet impact. At around the time when the bubble size shows its minimum in Fig. 3, on the other hand, an impulsive pressure is observed in all pressure waveforms in Fig. 4. Therefore, it is also certain that these pressure peaks are due to the shock wave generated at the collapse-reexpansion stage of the cavitation bubble.

Fig. 6 Time-change of the upper and the lower bubble wall and the microjet tip ($Ln=1.11$)

From these results, it is certain that the impact pressure of the microjet could be separately measured from the impulsive pressure of the generated shock wave at the collapse-reexpansion stage of the cavitation bubble.

In order to observe the behaviour of the bubble top surface at the collapsing stage, a cavitation bubble was generated on the local pressure sensor under a similar experimental condition as stated above, and the motion of the bubble was photographed stereographically by a high-speed camera. A typical result is shown in Fig. 7.

The dark square under the bubble in each photograph is the surface of the local pressure sensor shown in Fig. 2. The sensor elements were installed as No.1 to No.4 from the left, and in this case the bubble is above the No.2 sensor element.

At a lapsed time of around 880 μ s, the top of the bubble begins to be depressed, and at 916 μ s it is observed through the bubble wall that the microjet

Fig. 7 Stereographic high-speed photographs of a cavitation bubble above the local pressure sensor

collides against the solid wall (No.2 sensor element). In Fig. 8, which shows the pressure waveforms of the sensor elements, only the pressure of CH2 rises at a lapsed time of about 920 μ s. At around 980 μ s, noisy waveforms are observed in each output of the sensor elements and shock wave generation is expected at this moment. However, the bubble still holds a ring-shape. It should be noted here that the noise level of the No.4 sensor element, which is farthest from the bubble in this case, is very low.

3.2 Cavitation bubble collapsing near the solid wall

Under the experimental condition of a normalized wall distance of about 1.3, a cavitation bubble contracts with deformation. At the reexpansion stage of the bubble, it rapidly approaches the solid wall and then collides against it. The motion of the bubble was photographed by a high-speed camera. A typical result is shown in Fig. 9. In the figure, a microjet begins to form at 810 μ s and it collides against the lower bubble wall at around 834 μ s. Then it penetrates the water layer under the bubble and collides against the solid wall at a lapsed time of about 870 μ s. Fig. 10 shows the waveforms of the pressure sensor elements which correspond to the photographs of Fig. 9.

Photographs of a bubble taken at the last stage of contraction are shown in Fig. 11. The three dark shadows of a half-circle seen under each photograph in Fig. 11 correspond to the points where the lead wire is soldered to each sensor element, as shown in Fig. 2. They indicate the position of each sensor element. They are faintly recognized under the bubble in Fig. 9, too.

Fig. 8 Output waveforms of the local pressure sensor elements corresponding to Fig. 7

The microjet seen in photograph (B) of Fig. 11 collides against the lower bubble wall and enters into the water again in photograph (F). The ring-shaped bubble, which remains after microjet penetration through the contracting bubble, collapses in photograph (J). Then, the microjet is pushed and accelerated by the reexpanding ring-shaped bubble and collides against the solid wall (in this case the solid wall is the No.2 sensor element) in photograph (L). Therefore, in this experiment, the impulsive pressure of the shock wave (probably generated at photograph (J)) must be detected earlier than that of the microjet impact. In Fig. 10 the impulsive pressure of the shock wave is seen at around 860 μ s.

Fig. 9 High-speed photographs of a cavitation bubble for $Ln=1.29$

Fig. 10 Output waveforms of the local pressure sensor elements ($Ln=1.29$)

Fig. 11 Microjet formation in a collapsing bubble ($Ln=1.29$)

It should be noted here that the pressure on the No.2 sensor element begins to increase at the time of microjet collision against the lower bubble wall. This phenomenon corresponds to the pressure waveform detected on the solid surface in our previous experiment with a model microjet⁽⁹⁾ while the model microjet was travelling through a thin water layer.

In these photographs, the distances between the upper or lower bubble wall and the solid surface and the distance between the microjet tip and the solid surface were measured, and their time-changes are shown in Fig. 12. In this case, the diameter of the microjet tip is about 0.5 mm in Fig. 11 and this value is almost the same as the one measured in Fig. 6. The velocity of the microjet tip is about 110 m/s while penetrating the interior of the bubble and is about 30 m/s in water after penetration. The latter value is about half the velocity which was measured in a thin water layer by a model microjet about 1 mm in diameter⁽⁹⁾⁽¹⁰⁾.

3.3 Cavitation bubble collapsing farther from the solid wall

Generally speaking, a cavitation bubble far from a solid boundary contracts and reexpands while holding a spherical shape, and a microjet is not generated. However, in its reexpansion stage, a strong shock wave is generated.

High-speed photographs of a cavitation bubble, generated farther from a solid boundary ($Ln=2.90$),

and the output waveforms of the local pressure sensor elements are shown in Figs. 13 and 14, respectively. The cavitation bubble in this experimental condition seems to contract to its minimum while holding a spherical shape, but a microjet is observed in the bubble right after its reexpansion.

In Fig. 13 the high-speed photograph was taken with a time duration between the frames of about 12 μ s, in order to adequately observe the bubble motion. The cavitation bubble in the figure reaches its first minimum at around 789 μ s and reexpands, and it becomes minimal again at around 1270 μ s and reexpands. At these times the impulsive pressure is seen in the output waveforms of the local sensor elements

Fig. 12 Time-change of the upper and the lower bubble wall and the microjet tip ($Ln=1.29$)

Fig. 13 High-speed photographs of a cavitation bubble for $Ln=2.90$

Fig. 14 Output waveforms of the local pressure sensor elements ($L_n=2.90$)

shown in Fig. 14.

It should be noted here that a microjet penetrating the interior of the bubble is observed in the photograph at a lapsed time of $801\mu\text{s}$, which was taken right after the first reexpansion of the cavitation bubble. The microjet remains in the bubble till the second reexpansion of the bubble in Fig. 13. This result is similar to the one which Lauterborn, et al.⁽¹¹⁾ obtained for a laser-induced cavitation bubble near a solid boundary. The pressure of the microjet impact can not be characterized on the waveforms in Fig. 14.

From the fact that a microjet is observed in the bubble right after reexpansion, it is natural to think that the microjet is generated before the bubble becomes smallest. Therefore, in this case a microjet penetrates the interior of the cavitation bubble at the last stage of bubble contraction, and then the tiny ring-shaped bubble reexpands. With reexpansion, the velocity of the microjet decreases, and the microjet impact against the solid wall becomes very weak or it does not occur.

3.4 Effect of a microjet

The impulsive pressures of the microjet and shock wave measured in the present series of experiments are plotted in Fig. 15. They are shown for the normalized wall distance of the cavitation bubble. The measured pressure of the microjet was in the range of about $0.5\sim 2.5\text{ MPa}$. The diameter of the microjet tip was about 0.5 mm and its velocity was in the range of $100\sim 110\text{ m/s}$.

It should be noted that the pressure of the microjet impact could be several times the originally measured value indicated in Fig. 15, because first, the length of the pressure sensor element is about 4 mm

Fig. 15 Relations between measured original impulsive pressure of the microjet and shock wave and normalized wall distance

excluding the point of its electrode, although the microjet diameter is not that large. As stated in section 2, 3, the pressure sensor element was calibrated with an impulsive pressure which acts on the entire sensitive surface of the sensor element. Secondly, the width of the sensor element is 0.45 mm and it might be possible that the microjet center did not necessarily impact the center of the sensitive surface of the sensor element.

Even if these possibilities are true and the pressure of the microjet is several times the originally measured value, it is still one order smaller than the calculated value (about 150 MPa) assuming a water-hammer phenomenon of the microjet.

The acting duration of the impulsive force of a microjet in the present experiment shows a great deal of scatter under the present experimental conditions, but it is much longer than the values previously estimated by other authors. In the present experiment, it ranges between 20 and $60\mu\text{s}$ as shown in Figs. 4 and 8. Such a result is very similar to the value obtained in the experiment of a model microjet which was collided against a solid wall covered with a thin water layer⁽⁹⁾.

From the present experimental results it is certain that the impulsive pressure of a microjet is caused by stagnation pressure⁽¹²⁾ rather than by water-hammer pressure. This conclusion agrees well with the one which we reached in the experiment on model microjet impact⁽¹³⁾.

4. Conclusions

The main results obtained in the present research are summarized in the following ;

(1) The velocity of a microjet of a spark-induced cavitation bubble is in the range of $100\sim 110\text{ m/s}$. The diameters of the microjet tip and the microjet trunk are about 0.5 mm and 1 mm , respectively.

(2) The detected impulsive pressure of the micro-

jet is close to the stagnation pressure of the microjet rather than to its water-hammer pressure.

(3) In general, microjet impact on a solid wall occurs before the generation of a shock wave, but it sometimes comes immediately after the shock wave generation, depending on the state of bubble contraction.

(4) When a cavitation bubble collapses near a solid wall, the stagnation pressure of the microjet travelling in water acts on the solid wall.

(5) When a microjet is generated at the first collapse-reexpansion stage of a cavitation bubble which collapses relatively far from the solid wall, the impulsive pressure of the microjet might not act on the wall.

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