Observation of Cavitation Bubble Collapse by High-speed Video

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Abstract

Collapse of cavitation bubble clusters was observed on a two-dimensional foil, with a digital high-speed video camera that was triggered by the signal of impulsive force sensors imbedded on the foil surface. The high-speed video was taken at a speed of 40,500 fps. Duration of collapse was the order of 10 to 100 microseconds, which was by far slower than that of an impulsive force that was around 5 microseconds. According to theoretical calculations the impulsive pressure is generated when the cloud cavity collapses completely. But in our experiment, the peaks of impulsive force did not meet the instant of final collapsing, but were often some 10 to some 100 microseconds earlier than the final collapsing. These results suggest that an impulsive force may not be caused by the global behavior of a bubble cluster but by the behavior of a part of cloud cavity.

Keyword: cavitation, bubble collapse, high-speed video camera, impulsive force.

1. Introduction

Cavitation sometimes gives detrimental effects on fluid machinery such as pumps[1], water turbines and marine propellers[2]. These effects are erosion, severe vibration and noise, and are mainly caused by cavity bubbles collapsing very violently at the final stage of cavity life. The maximum pressure generated by this collapse is estimated more than a few hundred MPa in very short time of less than a millisecond. Because of such a high pressure in very short time, it is difficult to examine especially in an actual flow field.

So far, theoretical and numerical schemes were chiefly used to simulate collapse or vibration of bubble clusters[3-7]. However, results of these simulations were seldom verified by experimental facts. For example, researchers believe that the bubble cluster produces the high pressure at the time when it collapses completely. But nobody verified this assumption. Development of experimental technique to investigate the collapsing stage of the bubble cluster is of vital requirement to understand and prevent the harmful effects of cavitation.

The present paper reports observation results of collapsing cavity bubbles on a foil section by high-speed video camera, together with impulsive force measurement. As far as the authors know, such observation had only been made by Sato and Ogawa[8] for the vortex cavitation in the wake of a circular cylinder.

2. Experimental Procedure

2.1 Impulsive force sensors

Impulsive force was measured by sensors designed and manufactured by the authors, with PVDF (polyvinylidene fluoride) piezoelectric polymer film. These sensors were based on the sensor described in [9,10] and were modified to be easy to manufacture and to imbed on a foil section. The sensors could only measure impulsive force, not pressure, because the area of impulsive pressure acting on the sensor was not known. Figure 1 shows the structure of the sensors. A PVDF film of 110μm in thickness was pasted on a cubic block of brass each side of which was 10mm, and covered by thin polyimide tape for water insulation. Sensitive area size was 3mm×3mm. This impulsive force sensor had a high resonance frequency (about 10MHz) with relatively high output, so that it was suitable for the present purpose.

A transient converter (TCFL-8000SR by Riken Denshi Co. Ltd.) was used to record the output voltage of the sensor. This converter holds the transient amplitude when it exceeds the predefined threshold voltage, and at that time produces trigger output. In the present experiment this output was connected to a high-speed video controller to hold images. The detail is given below.

2.2 High-speed video camera

Observation was made by a high-speed video camera (FASTCAM-ultima® by PHOTRON Limited) mostly at a speed of 40,500 frames per second, which is the maximum of all high-speed video cameras existing at this time. Size of imaging area depends on the recording speed and 64×64 pixels at 40,500fps. Images are stored as a sequence of digital monochrome pictures in which depth of gray-scale is 8bit (256 levels), and these can be recorded to a normal video recorder or into memory of computer. The video controller has a trigger input to hold the current sequences of images recorded, and by triggering it when an impulsive force had been measured by an appropriate sensor, we took sequential pictures of cavity bubbles before and after the collapse of them, which corresponded to the impulsive force.

2.3 Test body, experimental facilities and conditions

Four sensors were embedded on a 2D NACA 0015 section (Chord: 150mm, Span: 150mm) as shown in Fig.2. Before this experiment we made a paint test with the same foil, and decided the position of sensors where many erosion pits (or more precisely, pits where the paint came off) had been observed. We chiefly observed the phenomena above Sensor 3 or 4 because these were near the window so we could avoid other bubbles' obstructing a view. Figure 2 also shows facilities for the present experiments.

Experiments were conducted in the Marine Propeller Cavitation Tunnel of the University of Tokyo fitted with a 150mm×600mm rectangular test section. The angle of incidence could be accurately varied using a digital micro-protractor. Free-stream velocity was measured with a laser-Doppler velocimeter and the tunnel static pressure was obtained from a pressure transducer.

Experimental conditions were the following: angle of attack was 8 degree, main flow velocity 8m/sec. and cavitation number 1.5.

3. Results and Discussions

Figure 3 shows appearance of cavitating foil in the condition described above. This picture was taken from the suction side by the high-speed video camera at a speed of 4,500 fps. Sheet type cavitation was generated on the foil from the leading edge, and when it grew larger, it shed a large-scale cluster of cavity bubbles. This cluster is called cloud cavity. The cloud cavity collapsed on one of the sensors at the final stage of its life.

Figure 4 shows a series of pictures at cavity collapsing stage with impulsive force signal on sensor 3. Frame (0) corresponds to the time of trigger signal. It should be noted that both the frames of negative numbers (before the trigger) and positive numbers (after the trigger) could be observed through the memory of the video system. Corresponding impulsive force signal is shown in Fig.5.

From these observations with impulsive force measurements, the following was obtained.

1. The impulsive force always occurred with the collapse of cloud cavity and was never observed without cloud cavity collapse.
2. A second peak of impulsive force was observed in some cases, which corresponded to the second collapse of cavity after its rebound. The same phenomena are reported in [8].
3. The frame interval of the video was about 24.7μsec. Whereas the breadth of impulsive force was only about 5μsec. So although the frame rate is very high, it seems still insufficient for the observation of collapsing stage. Frame size (64×64 pixels) is also insufficient for the precise observation. It is required of such experiments to improve both frame rate and size of high-speed imaging systems.
4. Duration of the collapse was the order of 10 to 100μsec., which is by far slower than that of the impulsive force that was around 5μsec. as mentioned above.
5. In most cases the impulsive force peak was observed several frames (25μsec. to some 100μsec.) before the

cloud cavity became a minimum in its volume. Not observed was the case that the impulsive force was after the collapse. The same phenomenon seems to be seen (but is not mentioned) in Fig.13(a) of [8].

The last item is important to know the mechanism of impulsive pressure generation. According to the theoretical calculation of cloud cavity collapse[3-7], the impulsive pressure is generated when the cloud cavity collapses completely. One possible explanation is partial collapse of cloud cavity. For instance, collapse of a large single bubble in the cavity and generation of micro-jet[11] may cause such phenomenon. When a relatively large cavity bubble (a few millimeters) collapses near a solid surface, the cavity does not collapse spherically, but generates micro-jet. When the micro-jet hits the bubble surface, impulsive pressure might be generated. However we could not observe such a large cavity bubble at the present experiment. This new finding should be verified more experimentally as well as theoretically, because the complete understanding of the mechanism of such high pressure is inevitable for preventing erosion, vibration and noise caused by cavitation.

4. Conclusion

The appearance of cavitation bubbles near the bubble collapsing stage was investigated on the foil section with a high-speed video camera that was triggered by the signal of impulsive force sensor. The minimum frame interval of the high-speed video camera was about 24.7μsec., whereas the breadth of impulsive force was only about 5μsec. So it seems still insufficient for the observation of collapsing stage. The impulsive force always occurred with the collapse of cloud cavity and was never observed without cloud cavity collapse, and in most cases the impulsive force peak was observed several frames (25μsec. to some 100μsec.) before the cloud cavity became minimum in its volume. These results suggest that an impulsive force may not be caused by the global behavior of a bubble cluster but by the behavior of a part of cloud cavity. For instance, collapse of a large single bubble in the cloud cavity and generation of micro-jet may cause such phenomenon. This new finding should be verified more experimentally as well as theoretically.

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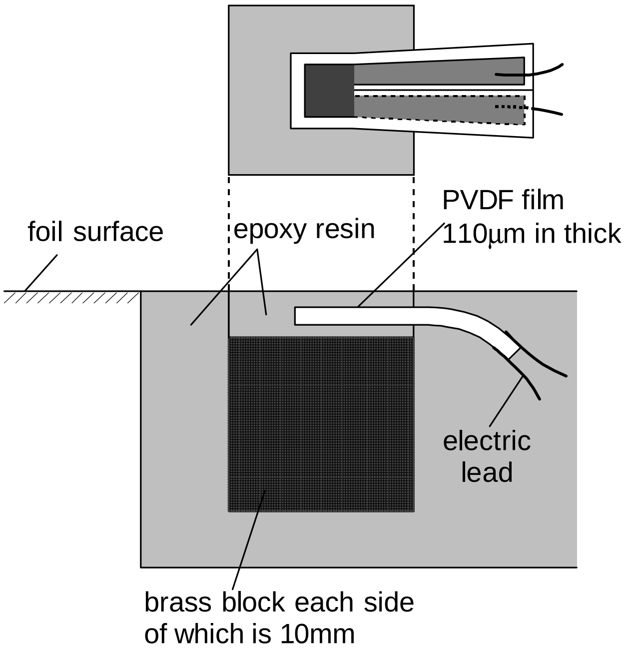

Fig.1 Impulsive force sensor

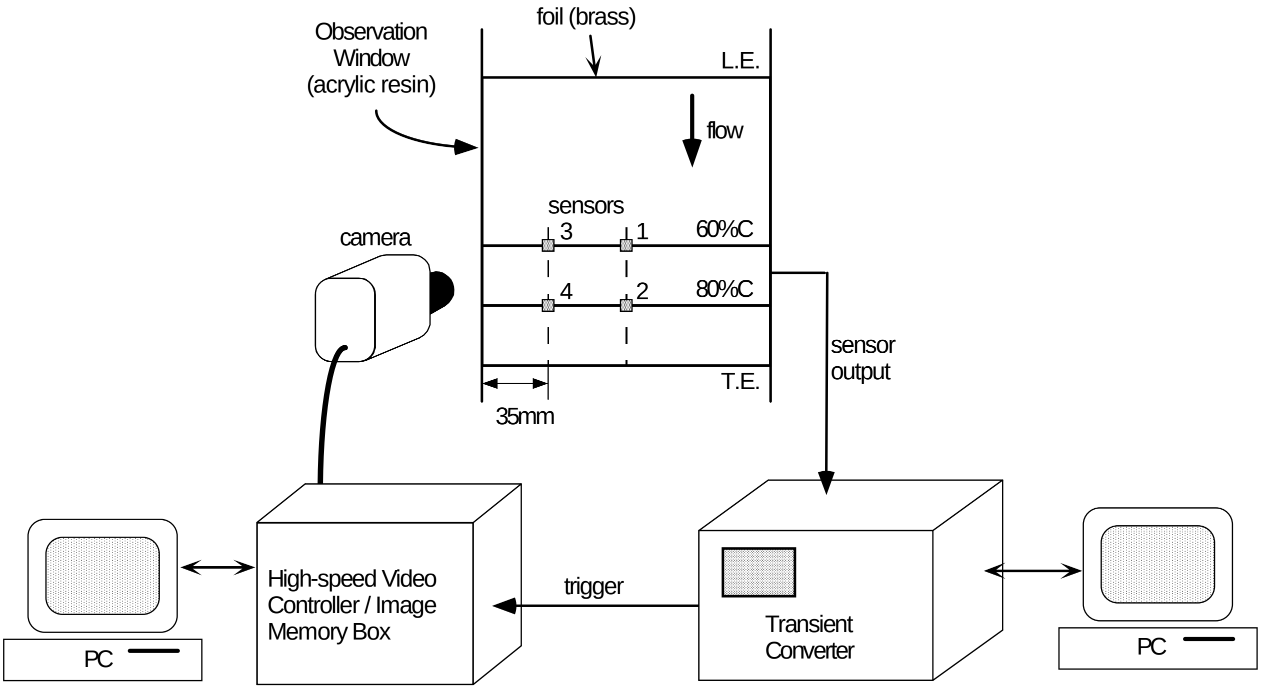

Fig.2 Sensor embedded positions and experimental facilities

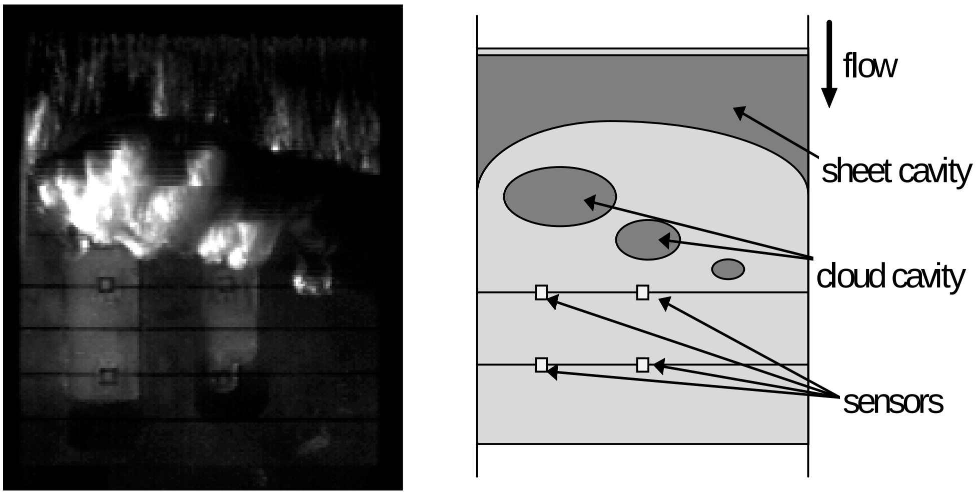

Fig.3 Cavity appearance

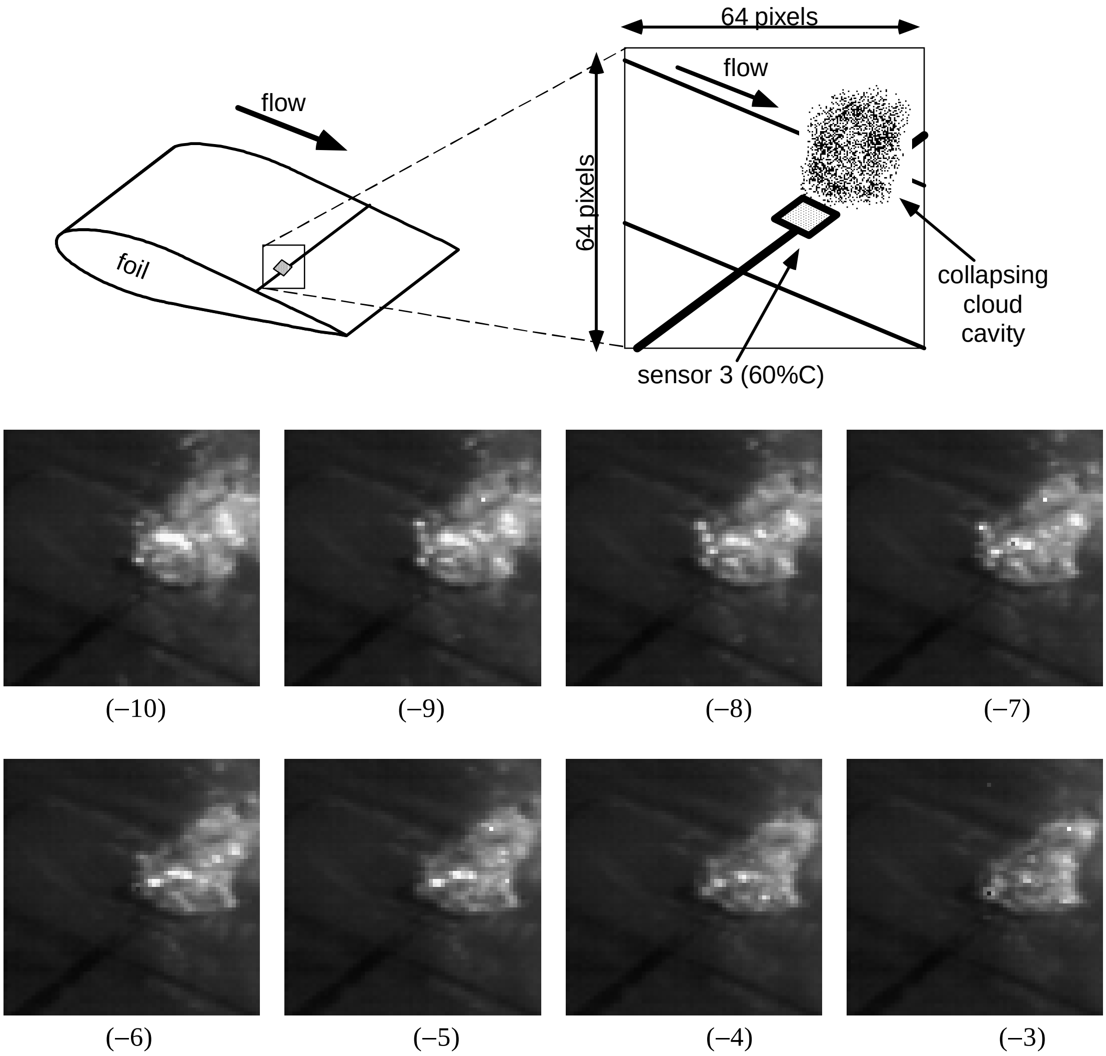

Fig. 4 An example of sequence of bird's-eye pictures by high-speed video camera at the time when impulsive force was measured

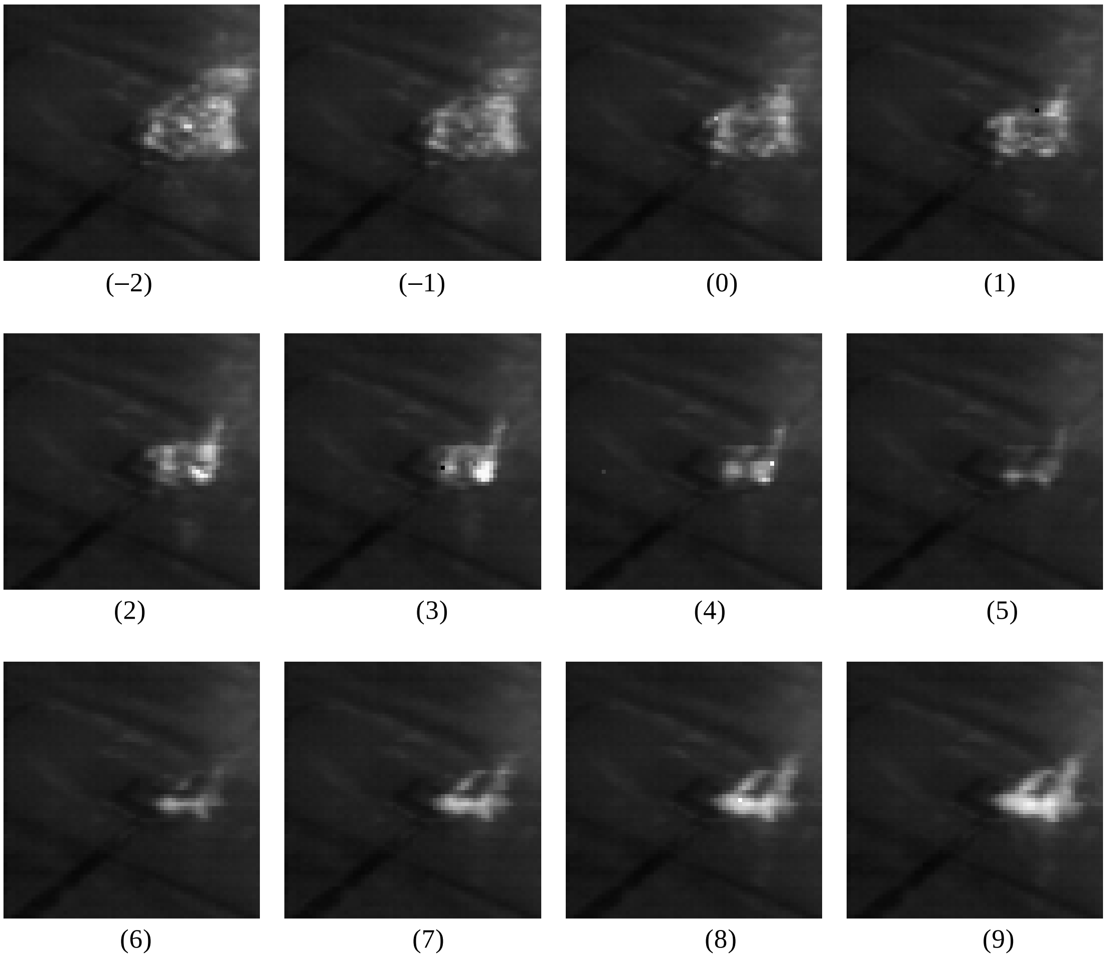

Fig. 4 (continued)

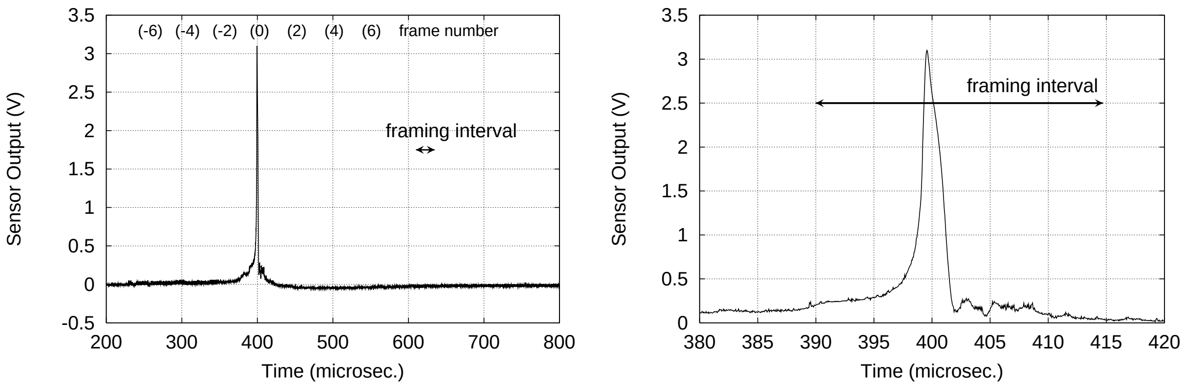

Fig. 5 Output voltage of impulsive force sensors corresponding to Fig. 4