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REENTRANT MOTION IN CLOUD CAVITATION DUE TO CLOUD COLLAPSE AND PRESSURE WAVE PROPAGATION

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ABSTRACT

It is well known that reentrant jet motion in periodic cloud cavitation means upward flow from the cavity closure area of cloud cavitation. However the mechanism of reentrant motion seems to remain unsolved clearly.

In the present study some experiments were conducted about the mechanism of reentrant motion in a fixed type cavity for a convergent-divergent nozzle. High speed video observation and image analysis based on the frame difference method were made about unsteady cloud cavitation with a periodic structure of cavitation cloud shedding.

As a result, the main points are experimentally found as follows; 1) a typical pattern of reentrant motions can be caused by the pressure wave propagation from the collapse of cavitation cloud shed downstream and 2) the frame difference method is very useful in an image analysis for high speed video observation of cavitating flow because the trajectory of pressure waves can be clearly visualized by the method.

INTRODUCTION

Behavior of bubbly clouds as well as behavior of a single bubble has been paid an attention from a viewpoint of energy concentration effect [1]. Cloud cavitation which consists of many micro-scale bubbles is a typical example of such phenomena [2, 3]. Cloud-like cavitation bubbles which are denoted as cavitation cloud in the present paper occur and develop in the flow field such as separated shear layer which is made from micro-scale vortices.

Many studies for cloud cavitation with an unsteady periodic character have been conducted so far about the mechanism of the periodicity (see, for example, [4-7]). A typical example is in the case of hydrofoil or convergent-divergent nozzle. It is well known in the study of cloud cavitation that a reentrant motion makes an important role on the periodic motion of shedding cloud. According to most previous investigations it is pointed out that cavitation cloud is shed downstream by the break-off of cavity interface through the penetration of the reentrant jet caused from the rear part of cavity. However there are several unsolved points about the mechanism of the periodic cloud cavitation including the reentrant jet. For example, it is a question whether the reentrant jet is simply a flow or not. In addition, there remains to be solved about the mechanism to induce the reentrant motion.

In the present paper the cloud cavitation is experimentally examined in the flow past a convergent-divergent nozzle. Through a high-speed video observation and an image analysis it is pointed out that the pressure wave due to the collapse of cloud shed downstream can induce the reentrant motion. A periodic structure of cloud cavitation is summarized using the present result together with previous results due to the authors

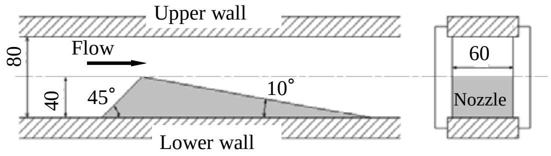


Figure 1. Convergent-divergent nozzle

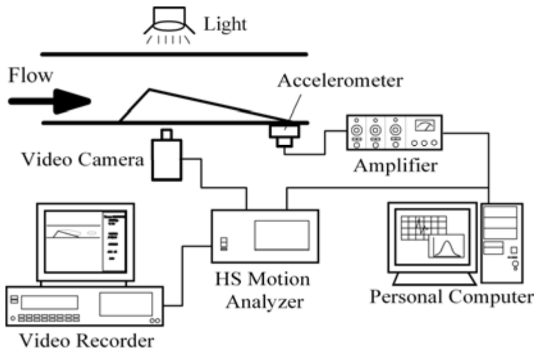


Figure 2. Measurement system of cavitation cloud

[8-12]. As a result the whole process of cloud cavitation is explained in which cavitation clouds are shed periodically.

EXPERIMENTS

Experimental Method

A closed-type recirculating cavitation tunnel was used in the present experiment. The tunnel has a test section with a convergent-divergent nozzle installed in full spanwise location [8]. The nozzle has convergent angle of 45-degree and divergent angel of 10-degree as shown in Fig.1. In this experiment the cavitation state was made by decreasing the tunnel pressure under constant upstream velocity of U=3.7m/s.

The cavitation appearance was observed using a high speed video camera (Photron FASTCAM SA5). Figure 2 shows a schematic view of the measurement system. The high speed video camera is synchronized with an accelerometer (TEAC 703FB) installed on the outer surface of the test section. Thus the impulsive acceleration due to the collapse of cavitation cloud can be used as a trigger signal to start the high speed video camera. The frame rate of video camera was mainly 40000 fps. The back lighting was used to illuminate the observation area. Therefore the cavitating (cloud) part was pictured as black and the water flow part as white.

Image Analysis: Frame Difference Method

Using a high speed video camera it is possible in general to catch very high speed phenomena such as a collapsing motion of cavitation cloud. On the other hand, the characteristics in the phenomenon depending on time change rate are dropped off when the video movies are converted to a range of still pictures. Therefore, within the limit of still pictures, it is difficult in general to investigate time-dependent phenomena with large

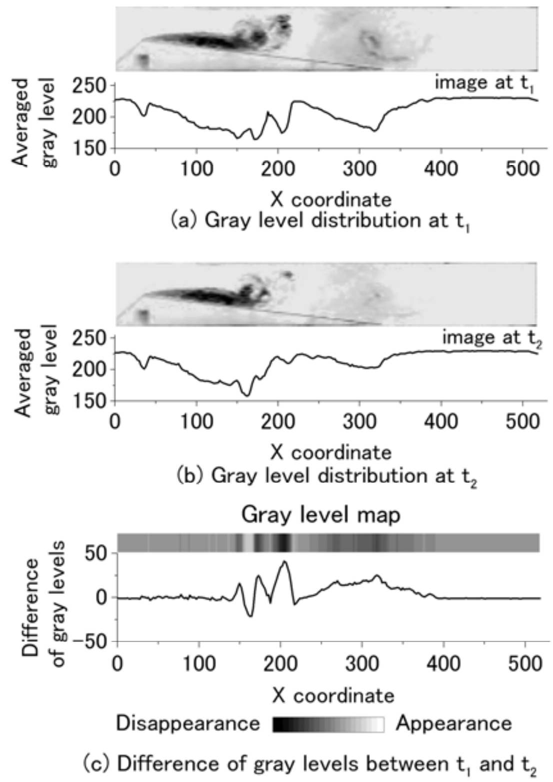
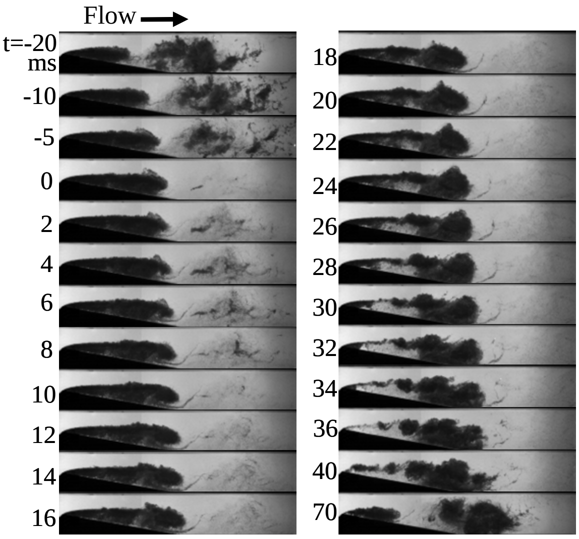


Figure 3. Frame difference method for cavitating flow

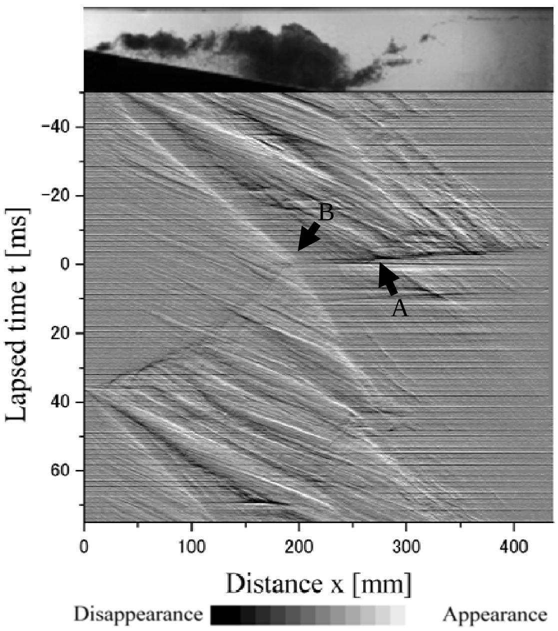
change rate such as occurrence or collapse of cavitation clouds. In the present study the frame difference method [11, 12] is used to estimate quantitatively the unsteady cavitating flow field. This image analysis method can catch very rapid unsteady motion such as cavitation clouds and cavitating flow field.

The outline of the frame difference method is shown in Fig. 3. For example two images with short time interval $\Delta t = t_2 - t_1$ are chosen as shown in Figs. 3(a) and (b). Figure 3(a) shows a gray level averaged in the vertical direction of the image at time t_1 and also Fig. 3(b) at time t_2. In the image the black colored portion corresponds to a cloud of cavitation bubbles. And Fig. 3(c) shows the difference between the former image and the latter one at the time interval Δt, where it should be noticed that in the case of the difference gray level the high positive value (namely, cloud collapse) is chosen to be black colored side. Thus we can find the line or zone where the gray level changes rapidly which means cavitation cloud rapidly disappears or appears. Next the gray difference is colored gray, depending on the value of the difference level map at time t_1 as shown in Fig.3(c). The final result of image analysis can be obtained by the above-mentioned procedure over the whole time range of observation as shown later.

The main points of this image analysis method based on the frame difference method are as follows.



(a)



(b)

σ=6.9, Re=1.67×10^5, U=3.7m/s,
β=1.4mg/ℓ, Fs=40000fps

Figure 4. The trajectory of bubble collapses due to pressure waves (result of image analysis based on frame difference method)

1. A rapid time change, namely unsteady cavitation cloud area, can be caught quantitatively through the observation using a high speed video camera.
2. Some unnecessary information independent of time change can be neglected; for example some structures such as a convergent-divergent nozzle.

The usefulness of the method was experimentally verified [11, 12] for the behavior analysis of high speed liquid flow accompanied with growth and collapse of bubbly cloud as shown in the present study. For example, see the results about a cavitating flow around a convergent-divergent nozzle as well as the result about a cavitating water jet. The former study [11] explained the details of the frame difference method and the existence of black band-like zone extending upstream together with the collapse of cavitation cloud shed downstream. In addition, the latter study [12] made clear that the black band-like zone obtained from the frame difference method can correspond to the trajectory of pressure wave propagation using the measurement of acoustic pressure.

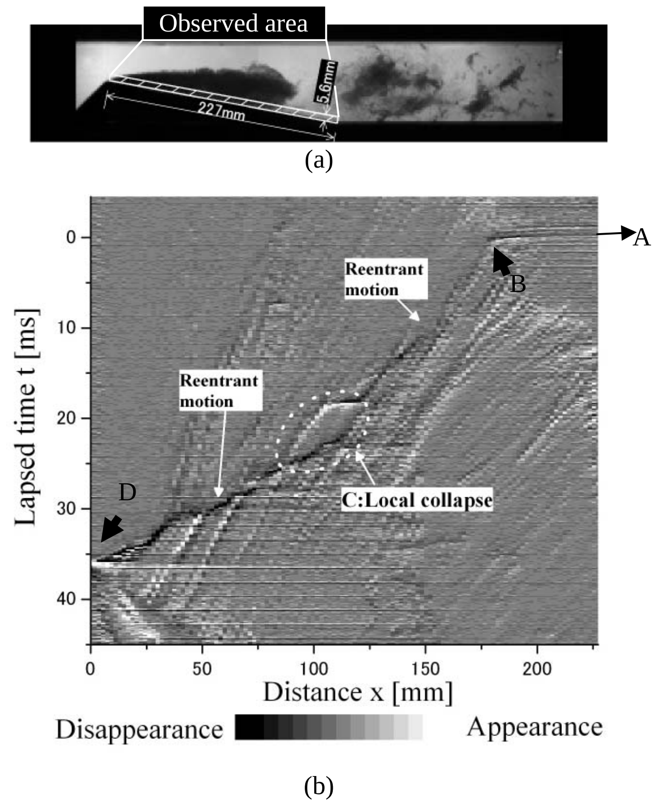
RESULTS AND DISCUSSIONS

Trigger Mechanism of Reentrant Motion in Cloud Cavitation

As a typical example of high speed video observation, Fig. 4(a) shows a series of still pictures expressing a reentrant motion caused in the process of the shedding downstream and the collapse of cloud for the cloud cavitation. Here, σ denotes cavitation number, Re Reynolds number, and β air content of water, based on the upstream pressure and velocity, height of nozzle throat and kinetic viscosity, respectively. The black colored portion in the picture corresponds to cavitation cloud for back lighting. The flow direction is from left to right. It is found that an attached cavity forms from the throat of the convergent-divergent nozzle, and grows or shrinks with a reentrant motion. The numerals at the side of pictures mean a lapsed time "ms" in the case of the origin t=0 at the trigger due to the accelerometer.

First, an attached cavity and a large shedding cloud are discerned in the image of time t=-20ms. The shedding cloud collapses rapidly around time t=0, then shows a rebounding motion and disappears again with a lapse of time. Here, after the trigger time of t=0, the existence of reentrant motion can be confirmed because the disappearance zone is translating to the upstream direction along the bottom area of the attached cavity. The reentrant motion reaches the leading part of the cavity around the time of t=36ms, and changes to the formation and growth of new attached cavity.

Figure 4(b) shows the result of image analysis due to the frame difference method. In the images it should be noticed that thin streaks over the whole horizontal axis or the whole observed area correspond to the blinking of light to illuminate and are independent of the cavitation phenomena. From the results it is found that there is a black band-like zone near the time of t=0, especially around the point A. This means the collapsing region of shedding cloud [11, 12]. The black line continues around the point A to the point B with a slight slope to the left direction. The point B corresponds to the trailing edge of the attached cavity. The black line from A to B corresponds to the history of trajectory in which minute bubbles disappear or collapse due to the pressure waves [12, 13] formed by the severe collapse of shedding cavitation cloud. The inclination of the black line



σ=6.9, Re=1.67×10^5, U=3.7m/s,
β=1.4mg/ℓ, Fs=40000fps

Figure 5. The details of reentrant motion within attached cavity analyzed by frame difference method

means the propagation speed so that in this case it can be estimated to be about 130m/s which may be considered to be valid as the propagation speed on the inside of bubbly flow with many minute bubbles.

From the point B the reentrant motion starts on the inside region of the attached cavity with relatively small value of translational speed (3.1m/s) because of the slope of the black line in Fig. 4(b). In the case of this observation, the inclination of the reentrant curve decreases around the area C and then reaches the leading point D of the cavity. The translational speed can be estimated to be about 8.5m/s around this stage from C to D. The area C corresponds to the picture near the time of t=22ms shown in Fig. 4(a) where there appears to be relatively large collapse (disappearance) on the inside of the attached cavity.

In order to further examine the reentrant motion shown in Fig. 4(b), the details of the reentrant motion on the inside of the cavity is shown in Fig. 5(b) where the rectangular area enclosed by the white lines shown in Fig. 5(a) is chosen as the image analysis zone to examine the behavior of them near the nozzle surface. As before mentioned it is clearly found that there are near-horizontal (that is, very high speed) thin black line to the point B (from A), oblique black line from B to C, complex behavior around the zone C and relatively high speed (clear) black line from C to D.

Periodic Process in Cloud Cavitation

Through the existing results (see, the previous papers [8-12]) in addition to the present result shown in the preceding chapter, a periodic shedding and reentrant mechanism of cloud cavitation can be proposed as schematically shown in Fig. 6. First, the important point found in the preceding chapters is the role of the pressure wave propagated from the collapse of shedding cloud on the cause of the reentrant motion. Further from the whole viewpoint the periodic characteristics of cloud cavitation can be explained as the following process.

① The pressure wave is formed due to the collapse of shedding cloud and propagates upstream. [10-13]
② The pressure wave reaches the trailing edge of attached cavity and induces the reentrant motion on the inside of the cavity.
③ At the trailing edge of the cavity the pressure wave propagates upstream on the inside of the cavity together with rolling-up flow.
④-⑤ On the inside of the cavity a collapse of small-sized cavity or bubble occurs on the way of reentrant motion. After that, the reentrant motion proceeds upstream with the propagation of bubble collapses. This process④-⑤ can be found at least within the present scope. [9]
⑥ Near the leading part of the attached cavity a collapse of bubble or small cavity is caused to cut off the supply of vorticity from the upstream boundary layer. [9, 10]
⑦-⑧ A large-scaled cloud is formed through the process of translation, coalescence and growth of minute vortex cavities on the interface area of attached cavity. After that a new attached cavity is formed. [8, 9]
⑨ After the formation of large cavitation cloud, the cloud is shed downstream as cavitation cloud. [8, 9]

Thus the reentrant motion and the formation of shedding cloud have periodicity, depending on the formation and coalescence of vortex cavities on separated shear layer.

CONCLUSIONS

Periodic cloud cavitation was experimentally investigated in the case of a convergent-divergent nozzle. The mechanism of cloud cavitation was made clear through the image analysis based on the high speed video observation and the frame difference method. The main points are summarized as follows.

The formation of pressure wave due to the collapse of shedding cloud is pointed out as one of the mechanisms to induce the reentrant motion of cloud cavitation.

Summing up the present result in addition to the previous one, the pressure-wave-propagation type mechanism is proposed about the periodic motion of cloud cavitation.

The frame difference method is shown as a powerful visualization method for cavitating flow. It is possible to quantitatively analyze the highly time-dependent bubbly flow phenomena including pressure waves such as a cavitation cloud.

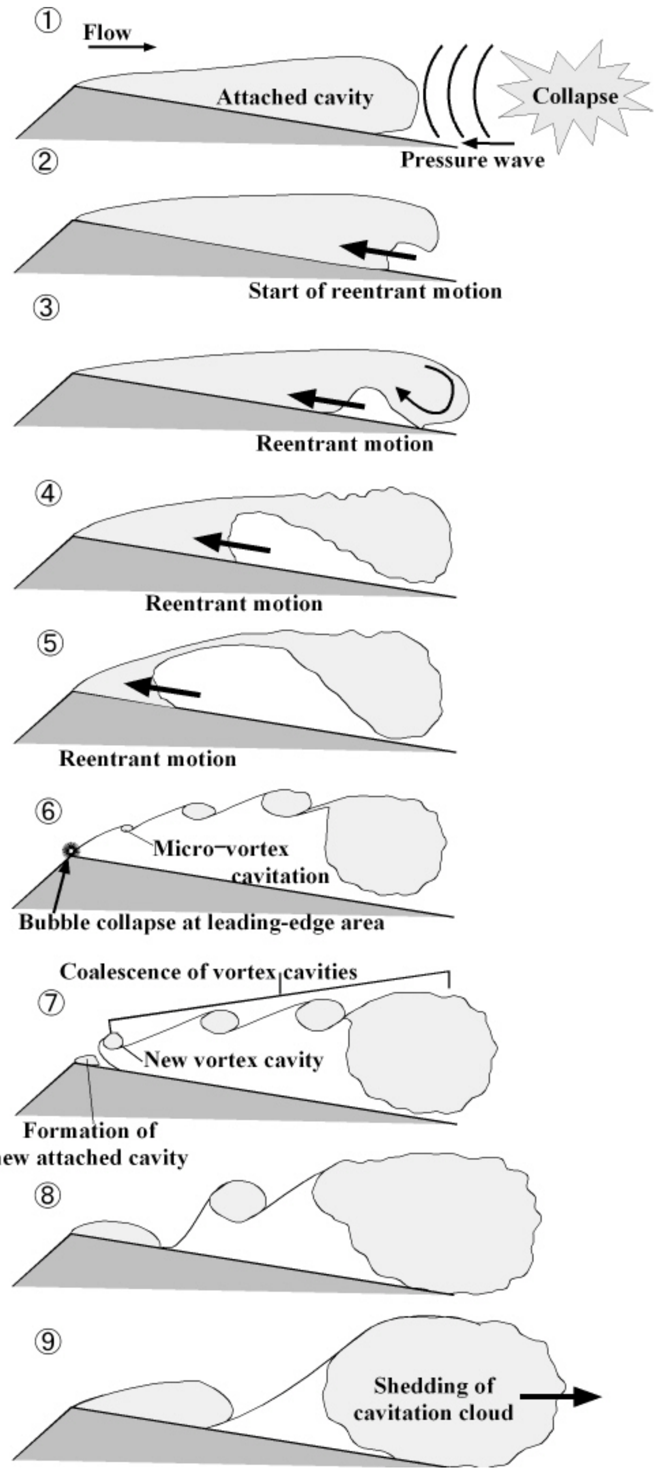


Figure 6. A periodic cycle of pressure-wave-propagation type for cloud cavitation

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