HIGH-SPEED VIDEO OBSERVATION ON MECHANISM OF RE-ENTRANT MOTION AND CLOUD SHEDDING IN CLOUD CAVITATION

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ABSTRACT

It is known that attached or partial cavitation has a periodic character under a certain flow condition and is related to high cavitation impact with a shedding and collapse of cavitation cloud. The detailed mechanism of the periodic behavior remains to be solved though it appears to be caused by a re-entrant motion from the cavity trailing edge to the leading edge. In this study, we present our previous data as well as new results about a shedding process of cavitation cloud and a mechanism of re-entrant behavior. First, the partial cavitation phenomena are divided into two types. In addition, for these two types of cavity, the re-entrant motions in the cavity are discussed with high-speed-video-camera observations and a digital image processing technique. As the result, a re-entrant motion which plays an important role in unsteady or periodic characteristics of cloud cavitation is formed by the chain-reaction-like collapses of bubbles which are strongly related to the pressure impulse followed by the collapse of cavitation cloud.

Keywords: Cavitation, Partial cavitation, Periodic behavior, Re-entrant motion, Bubble collapse

1. INTRODUCTION

Under a certain condition an attached-type or partial cavitation shows an unsteady periodic character with a shedding and collapse of cavitation clouds which causes severe cavitation impacts. Many previous works clearly indicated that the periodic characteristics can be caused from the feed-back mechanism due to a re-entrant motion within a cavity (e.g., Knapp [1], Furness [2], Franc and Michel [3], Yakushiji et al. [4]).

Several important points, however, remain to be solved about the periodic cavity behavior. For an example, the starting mechanism and the driving force of the re-entrant motion have not been solved perfectly though it is a flow-related motion from the trailing edge of attached cavity to the body leading edge. In addition, a big question exists about the re-entrant motion itself whether it is a flow/jet which has been considered in the previous many investigators or a wave moving upstream along the bottom surface of cavity.

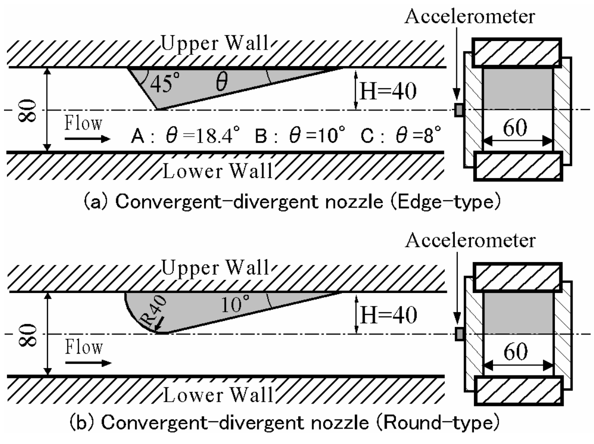
In this paper the authors present a summary of our works including new results and show some unsolved problems through our previous results [5-8] about a shedding process of clouds and re-entrant motion for unsteady cloud cavitation.

2. EXPERIMENTAL PROCEDURE

2-1 Cavitation Test Facility

Cavitation experiments were conducted using a small re-circulation type cavitation tunnel [5] with a rectangular test section. The test section is a convergent-divergent channel using a triangular plate as shown in Fig. 1(a). The plate was inserted into the channel to be a full span nozzle which was called an edge-type nozzle. An another nozzle called round-type was also made to examine the effect of flow separation as shown in Fig. 1(b) which was shaped to be round near the throat part. The experiments were done in these two nozzles.

The observations of cavitation bubbles were mainly made using a high speed video camera (Kodak, EXTAPRO Model-4540, maximum frame speed 40500 fps), where fps denotes frame per second. A super-high speed video camera with the frame speed of 1Mfps [9] was also used for a part of the experiments.



(a) Convergent-divergent nozzle (Edge-type)

(b) Convergent-divergent nozzle (Round-type)

Fig.1 Test section

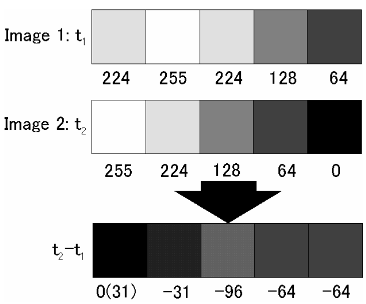


Fig.2 Image processing method

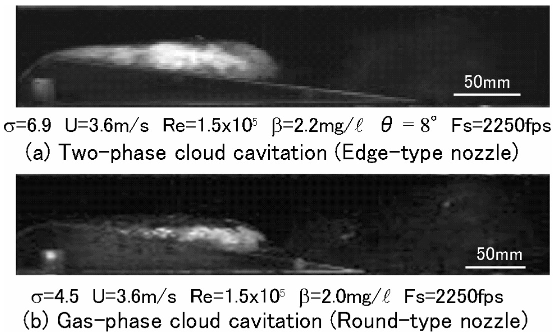


Fig.3 Two types of cloud cavitation

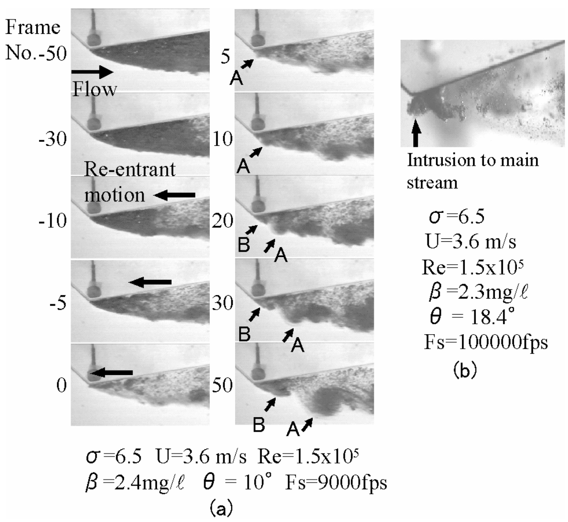


Fig.4 Re-entrant motion and its final stage on edge-type nozzle

2-2 Method of Image Processing

At the collapse of cavitation cloud, the shade change in the image of cavitating flow area occurs from black to white due to a chain-like disappearance of micro-bubble clusters. In the present study, the qualitative estimation of cavitation cloud behaviors was made using an image procedure technique.

A gray-scaled image of 256 gradations was used to examine the cloud behavior. As schematically shown in Fig.2, the difference of the gray levels on each video flame was estimated to obtain the shade change of the cavitating region at different pick-up times t_1 and t_2 (t_1 : Image-1, t_2: Image-2), where the direction from white to black was finally chosen to be positive by turning the sign of the difference in Fig.2 and the negative value was neglected to be 0 for simplicity.

This image processing technique was applied to some high-speed video pictures every measurement time so that the time-series change of the shade was investigated as shown in Fig. 6, where the bubbling region was expressed as white color in the case of the present image analysis. In this result the change from white to black was mainly analyzed to capture the bubble collapsing motion.

3. PERIODIC BEHAVIOR OF CLOUD CAVITATION

3.1 Classification of attached-type or partial cavitation

Cloud cavitation is defined as the one which presents high impulsive power with periodic shedding of vortex-like bubbling clouds. Typical examples of this cavitation type are as follows; for an external flow the partial cavity on hydrofoil and for an internal flow an attached-type cavitation on the throat in a convergent-divergent nozzle. Either cavitation state corresponds to that of relatively partial development.

According to the present observation the study of cloud cavitation requires the treatment based on classification into two large groups, though Michel& Franc [3] showed the maps on the occurrence region of cloud cavitation and the cavity type. These two groups are called in this paper as Type-A: (gas-liquid) two-phase cavity and Type-B: (quasi-) single-phase cavity.

Two-Phase Cavity: This type can be found in the separated flow with relatively large thickness such as a flow separated from a sharp-edged corner. Cavitation occurs and develops as a cluster of vortex cavitation bubbles on separated shear layer at a distance from body surface. After the development with decreasing cavitation number the condition has a transition to an attached type and a state of cloud cavitation. There remains to be a gas-liquid two-phase condition inside the cavity within a limit of development though the limit depends on the thickness of separated flow region. A typical example is shown in Fig. 3(a).

(Gas or Vapor) Single-Phase Cavity: This type is a quasi-single phase cavity. It can be found in the flow zone closely related to the separation bubble with relatively thin thickness such as a flow separated from a rounded body surface (i.e. a hydrofoil of low attack angle).

When an attached-type cavitation develops on the basis of something like a small separation bubble on the body surface, the cavity becomes a state of cloud cavitation with almost clear vapor or gas phase in the front-half part which may correspond to a quasi-single gas cavity. An example is shown in Fig. 3(b). In the present paper the cavity will be simply called a single-phase cavity.

3.2 Closure of re-entrant motion and formation/ development/shedding of cavitation clouds

Formation of a vortex cavitation bubble starts as a seed of cavitation cloud when the re-entrant motion reaches the leading part of cavity.

As far as two-phase cavity in an edge-type nozzle throat channel is concerned, the formation process can be pointed out as shown in Fig. 4 [5, 8]. Here, After the arrival of the re-entrant motion at the leading edge of cavity, a vortex cavity appears on the separated shear layer, moves downstream with coalescence and development, and finally sheds away as a large-scale vortex cavity, namely a cavitation cloud. The point is as shown in Fig. 4(b) that the penetrating of re-bounded cluster consisting of fine bubbles towards the main stream can be observed at the leading part after the collapse of bubble near the leading part. After this peculiar behavior a new vortex cavity is formed and then a new attached cavity is also formed.

Figures 5(a) and 5(b) show the results about the round-type nozzle. For this test body the leading shape of cavity shows a finger-type as shown in Fig. 5(b), which is common to that of round bodies with separated flow such as a hydrofoil. When a re-entrant motion reaches this leading part, small attached cavities break into a cluster of fine bubbles and finally disappear. In downstream region a cavity part rolls up as a large group of bubbles to form a cavitation cloud. After that a new attached cavity forms and grows to a large scale.

From these observations some results are obtained as follows. At the arrival of re-entrant motion the cavity collapses into fine bubbles, where this fact means a local pressure rise in the surrounding flow. There are some string-like vortex cavitation bubbles with an axis perpendicular to the body surface. A re-entrant motion cannot be observed in the special manner of a surface-penetrating type at the leading part of cavity.

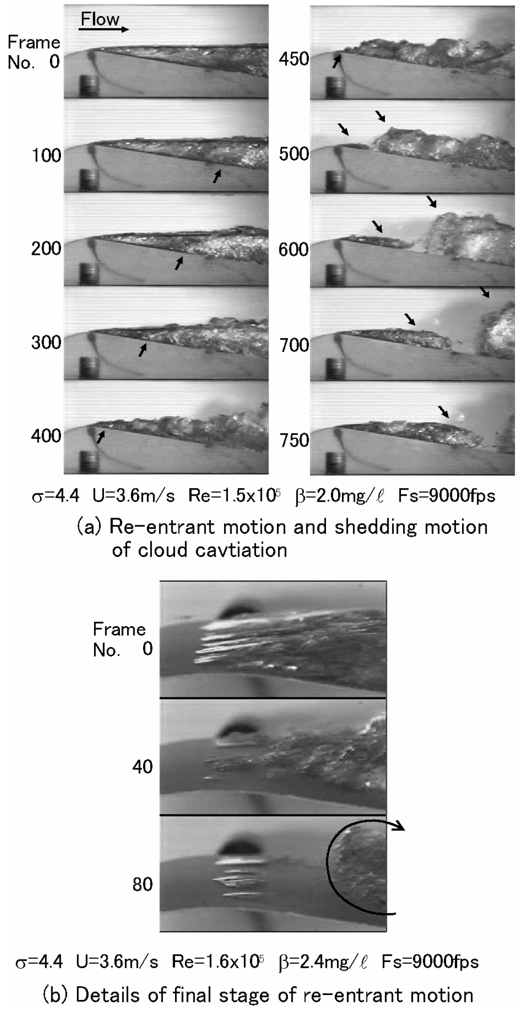
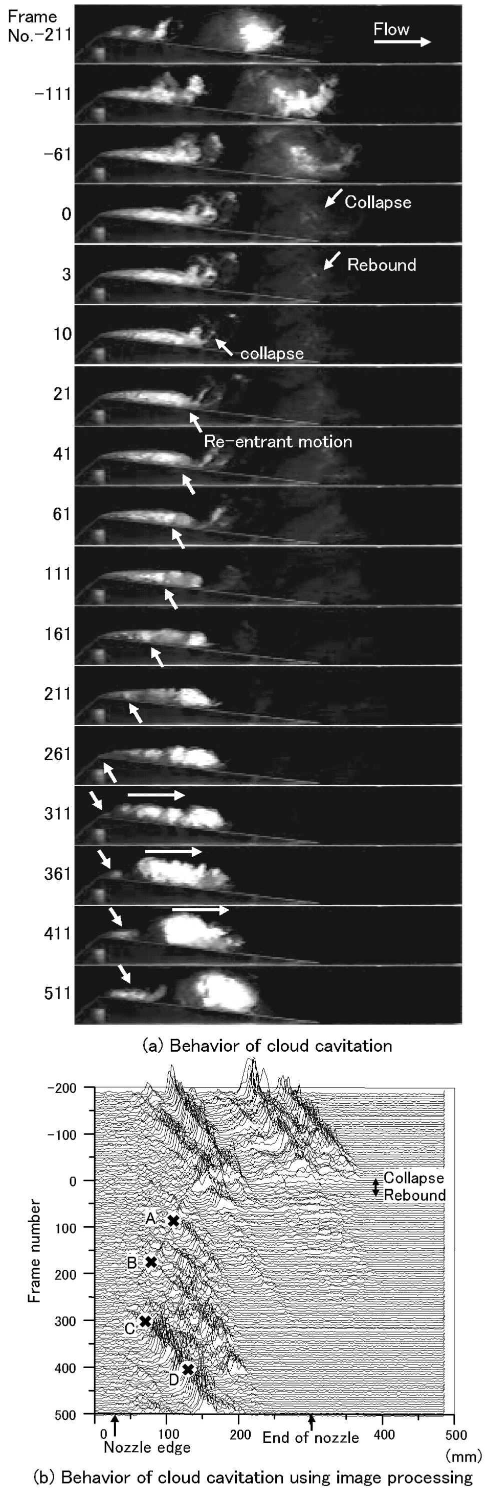


Fig.5 Re-entrant motion on round-type nozzle

3.3 Collapse of shedding cloud and re-entrant motion

What is a trigger of re-entrant motion inside an attached cavity? According to the present study the occurrence of pressure waves can be counted in as one of important mechanisms, though some possibilities have been pointed out [3, 4, 10]. The strong pressure wave can be caused by the collapse of cavitation cloud. There are at least two places of the occurrence. The first one is related to the collapse of cavitation cloud shed downstream and the second one is an intermediate place of the re-entrant motion on the way to the leading part from the trailing edge of cavity. The collapse and occurrence of high pressure at the second place can make a negative effect on the regular periodicity of cavitation cloud shedding.

A typical example of the first case is shown about a triangular throat channel in Fig. 6(a), where the collapsing point of shedding cavitation cloud approximately corresponds to the area shown in Frame



(a) Behavior of cloud cavitation

(b) Behavior of cloud cavitation using image processing

σ=6.9 U=3.6m/s Re=1.5x10^5 β=3.1mg/ℓ θ = 8° Fs=9000fps

Fig.6 Collapse of shedding cloud and re-entrant motion

where the appearance is shown by the gradation change from white to gray. The gradation change occurs over the whole part in the direction of cavity thickness, including the rolled-up region with the re-entrant motion. The collapse of bubbly clouds propagates one after the other toward the upstream direction, where refer to the authors' results [7, 8] and recent results of Matsudaira et al. for a cavitation flow around a circular cylinder [11]. Around Frame No.261 the collapsing motion reaches the leading part of cavity and then the transition to a new periodic motion in the similar manner to that in Fig.4. The appearance of the bubble collapse propagation can be also checked in Fig.4 where the bubbly region appears to be black because of the use of back lighting. Figure 6(b) shows a result from the pictures of Fig.4 using the image processing technique, where the gradation change is expressed as a kind of movement line or band. It can be estimated from the slopes of these lines AB and CD that the travel velocity of the re-entrant motion is about 3.3 m/s and the traveling velocity of the vortex cavity on the shear layer is about 5.3 m/s in these cases.

A typical example for the second case is shown in Fig. 7. The collapse in this case is not dependent on the cavity shedding. The collapse occurs near the roll-up of the trailing part of attached cavity as shown in the symbol of arrow which corresponds to the local black-colored area of Frame No.0. The collapsing point is propagating to the upstream direction. After that it reaches the leading part of cavity and makes a transitional behavior to form a new cavitation cloud.

3.4 Re-entrant motion

As before-mentioned, it is necessary to divide the re-entrant motion itself into two large groups. One is a type of bubble collapse propagation to the upstream direction in the form of pressure wave. The other one is the second type of bubble collapse propagation, namely a type of re-entrant flow or jet which is accompanying with the movement of a single liquid phase or gas-liquid two-phase fluid. Though the existence of two-kinds of re-entrant motion has been proved experimentally, there may be a combined type of the re-entrant flow and the bubble collapse propagation due to pressure waves. In addition the latter pressure-wave type can be followed by liquid flow. Since the propagation speed of pressure wave can be on the same order as that of the liquid flow under normal liquid-flow condition in the case of high void ratio, the distinction is very difficult between two types of re-entrant motions from the video observation. The point is that the re-entrant motion is not a simple re-entrant flow or jet which flows toward an upstream direction on the body surface and does not show a penetrating flow on the cavity surface of the leading part in the similar manner to that previously pointed out by many researches [1-4].

4. CONCLUDING REMARKS

A periodic behavior of cloud cavitation is summarized and discussed together with some unsolved problems. The periodic motion means a cycle from the formation/growth of cavitation cloud to the shedding/collapse of the cloud, the initiation/travel/closure of re-entrant motion and the formation of new cloud. The following main points are experimentally obtained through the detailed observation using a high-speed video-camera.

(1) The collapse of cavitation cloud and the pressure wave are indicated as a trigger for re-entrant motion. The trigger mechanism occurs at the point after the shedding of cavitation cloud as well as in the intermediate process inside an attached cavity.

(2) The collapse propagation of pressure wave motion in the bubbly cluster can be given as one of the most important forms for the re-entrant motion.

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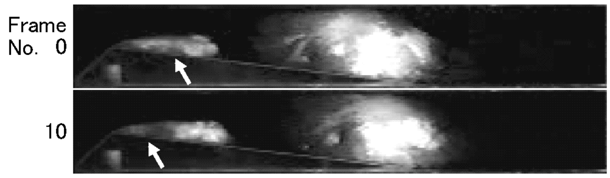

σ=6.8 U=3.6m/s Re=1.5x10^5 β=2.2mg/ℓ θ = 8° Fs=2250fps

Fig.7 Re-entrant motion without collapse of shedding cloud

NOMENCLATURE

σ: Cavitation number, $2(P-Pv)/\rho U^2$
U: Flow velocity, m/s
P: Upstream pressure of nozzle, Pa
Pv: Vapor pressure of water, Pa
Re: Reynolds number, UH/ν
ν: Kinetic viscosity, m^2/s
H: Height of nozzle, m
θ: Diffuser angle, degree
β: Air content, mg/ℓ
Fs: Frame rate of high speed video camera, fps