# Self-Exciting Behavior of Cloud-like Cavitation and Micro-Vortex Cavities on the Shear Layer

Keiichi SATO*, Yasuhiro SAITO* and Hirokazu NAKAMURA*

In the present study the self-exiting motion of cloud-like cavitation is experimentally investigated in a convergent-divergent nozzle installed in a rectangular channel. It is made clear by the observation using a high-speed video camera that the transverse-type of shear-layer cavitation on the separated shear layer develops to the cloud cavitation of shedding type through the pairing and coalescing of micro-vortex cavities, and in the case of higher cavitation number it does not develop to a large-scale shedding motion though it shows a weak periodic motion. In addition the details of the large-scale shedding process are photographically shown for the cloud cavitation.

***Key Words*** : Cavitation, Cloud cavitation, Vortex motion, Shedding motion, Cavitation impact

## 1. Introduction

Cavitation is one of the most important problems in the fluids engineering of high-speed liquid flows. The typical recent topic is on the cloud cavitation [e.g. (1), (2)] because it has been pointed out [(3)] that it can cause high cavitation impacts when it behaves unsteadily in a self-exciting manner. Recently it is also found [(4)-(7)] that the unsteady behavior has at least two characteristic modes, the modes can be divided for the range of cavitation number, and they are also dependent on an incident angle of hydrofoil.

In the case of internal flows, on the other hand, it has been known that various kinds of contracted flow fields such as valves, Venturi tubes and long orifices produce unsteady cloud-like cavitation [(8)-(10)]. Most of them may be related to separated shear flow with reattached and relatively thick separation. The authors [(10), (11)] investigated about the mechanism of self-exciting behaviors of unsteady cavitation in a long orifice with inlet separation and as a result found the existence of pairing and coalescence in the cavity shedding process, and the important role of the re-entrant motion. In addition, they [(12)] also examined about a cloud-like cavitation in a convergent-divergent channel to make clear the mechanism of high impact cavitation.

* Kanazawa Institute of Technology
Ogigaoka 7-1, Nonoichi, Ishikawa 921-8501
ksato@neptune.kanazawa-it.ac.jp

In the present work, the cloud cavitation in a convergent-divergent (rectangular) channel is experimentally examined using a high-speed video camera, especially from a viewpoint of the unsteady motion of vortex cavities on the separated shear layer.

## 2. Experimental Apparatus and Method

The experiment was made using a closed and recirculating type of cavitation tunnel with a resorber [(10)]. The test channel with rectangular cross section of 60x80 mm had a convergent-divergent nozzle as shown in Fig.1. The nozzle throat was 40 mm high and 60 mm wide. The different nozzle with the throat of 30 mm high and 80 mm wide was also used for the spanwise observation. The two channels had equal tunnel-blockage ratio each other.

The observation of cavitation appearance was mainly made with a high-speed video camera (Kodak Extapro Model 4540, Maximum frame rate 40500 fps; frames per second) [(13), (14)]. In the present work the frame rate was 9000 or 18000 fps. The

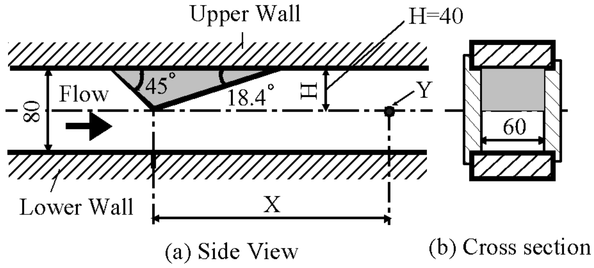


**Fig.1 Convergent-divergent channel**

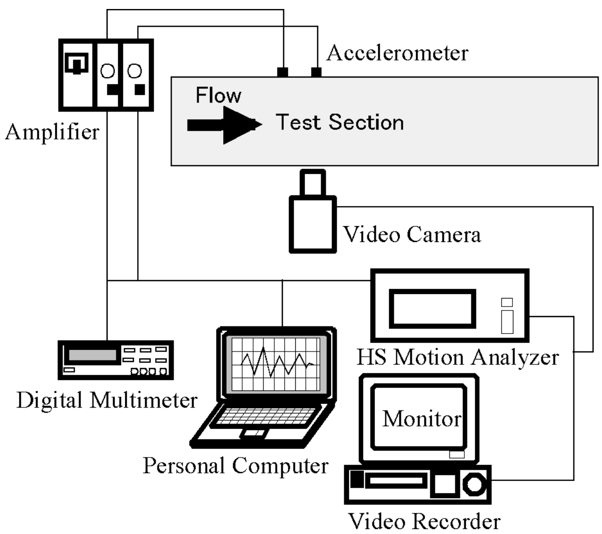


**Fig.2 Measurement and observation system**

impulse measurement accompanied with cavitation collapse was made using an accelerometer (TEAC, 0.3-50KHz ± 3dB) positioned at the point Y of X/H=10 downstream of the nozzle throat.

The experiments were conducted at given cavitation number under constant flow velocity. The cavitation number $\sigma$ and Reynolds number $Re_t$ are defined as follows.

$$\sigma = (P_\infty - P_V)/\rho U^2 \quad (1)$$

$$Re_t = U_t H/\nu \quad (2)$$

Here, $P_\infty$ is upstream static pressure, $P_V$, $\nu$ and $\rho$ are vapor pressure, kinetic viscosity and density of tested water, H is throat height of nozzle, and U, $U_t$ are flow velocities at the upstream point and at the nozzle throat, respectively. In addition, $T_w$, $\beta$ and $F_s$ are water temperature, dissolved oxygen content of tested water and video frame rate, respectively.

## 3. Results and Discussion

### 3.1 Shedding behavior of separated vortex cavitation in convergent-divergent nozzle: sidewise view

**3.1.1 Overall aspect** With decreasing cavitation number the cavitation state becomes inception at about $\sigma$=13, when the impact due to bubble collapse can be first measured. The cavitation impact rapidly increases in the transition cavitation stage with further decrease in cavitation number [12]. This impact-peak cavitation number is around $\sigma$=6.5 in the present case. Figure 3 shows the cavity appearance at this cavitation number, which is taken by a high-speed video camera of 9000 fps. The white portion in the picture corresponds to the cavitating area.

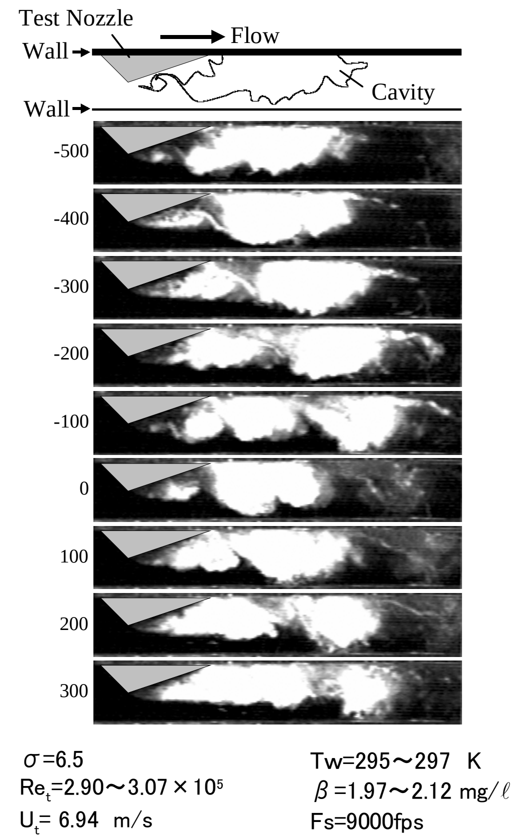


**Fig.3 Shedding behavior of cavitation cloud : side-view observation**

A large cluster of bubbles appearing in Frame No.-500 to No.-200 is clearly shed downstream around No.-100 to No.0. A new cluster begins to develop near the nozzle throat. The cavitation cloud shed downstream shows collapsing behavior and then almost disappears around Frame No.0. The new cluster of bubbles grows to a large scale and after the lapse of time becomes a new shedding cloud toward the downstream direction. The shedding motion is periodically repeated in this way. Here, the frame of No.0 corresponds to that detecting the trigger signal from cavitation impact which is produced at the collapse of shedding cloud.

**3.1.2 Aspect just behind separation (coalescence and growth of micro-vortex cavities)**

Figure 4 shows the details of vortex cavity motion on the separated shear layer just behind the nozzle throat because the aspect of them seems to be insufficient in Fig.3. The experimental conditions are almost same as those of Fig.3.

First of all, it should be noted that there is a break in the attached cavity around Frame No.-100 (see, the black arrow in the picture). This gap of cavity expands toward the nozzle throat with the lapse of time and indicates a re-entrant motion. This re-entrant motion can be estimated to be at the

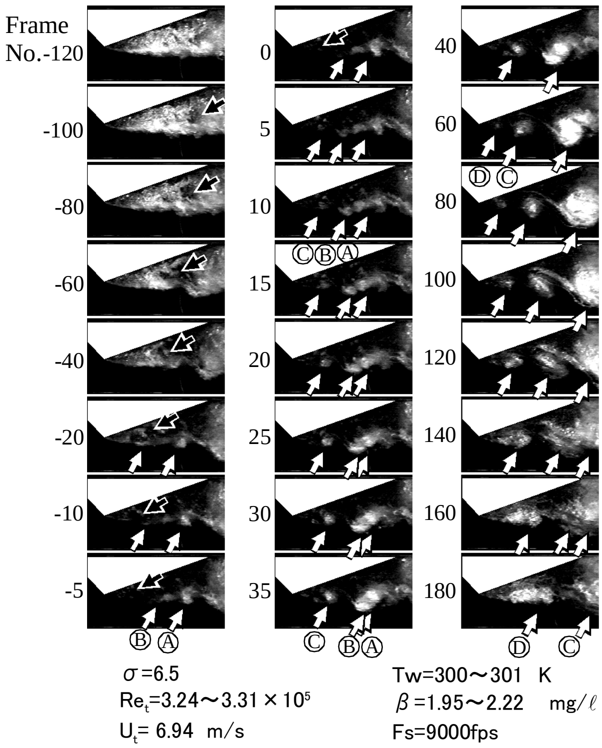


**Fig.4 Details of vortex-cavity motion just behind nozzle throat: side-view observation**

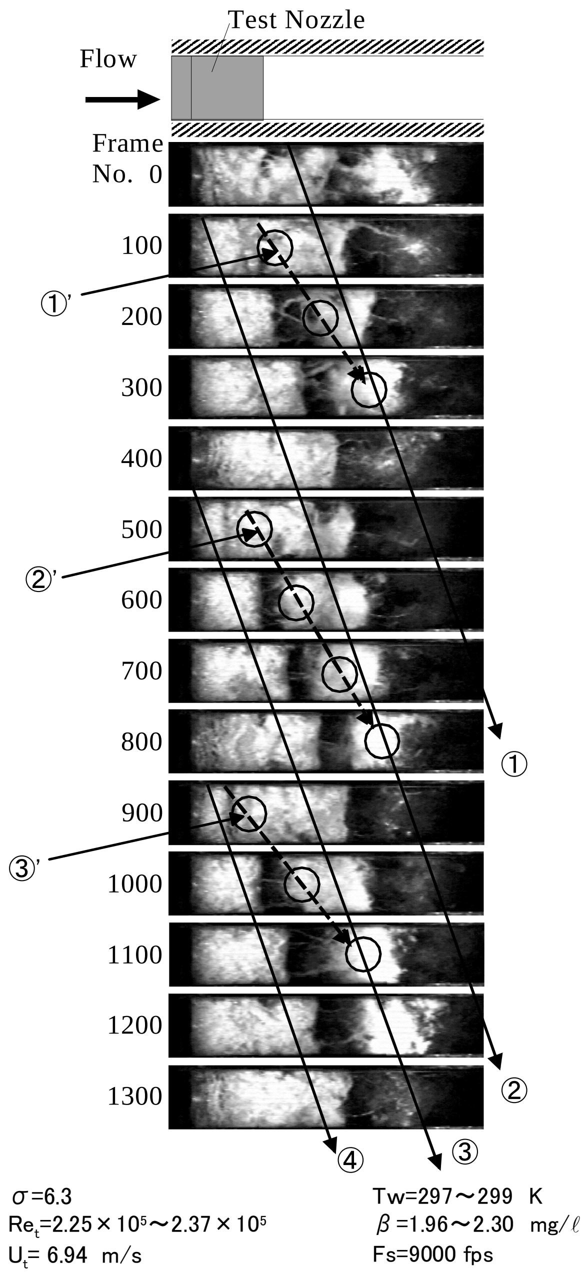


**Fig.5 Shedding behavior of cavitation cloud : span-view observation**

separation point of the nozzle throat around No.0. In this situation, micro-vortex cavities are recognized to be on the separated shear layer. The cavities will be denoted as cavities A, B and C in this paper.

The vortex cavities A and B move downstream with the progress of time and at the same time present a pairing motion as shown in Frame No.15 to 60. In the pictures after Frame No.60 they show the further developing motion. Next, as shown in the pictures of No.80 to 180 the vortex cavity C also makes a pairing motion to coalesce with the previous cavity A/B. On the other hand, it should be noticed that the other new cavity D shown in No.60 presents no pairing motion with the previous cavity A/B/C and develops to a new attached cavity.

### 3.2 Shedding behavior of separated vortex cavitation in convergent-divergent nozzle: spanwise view

#### 3.2.1 Overall aspect and cavity coalescence

Next, the spanwise view of cloud cavitation is discussed in a convergent-divergent nozzle. The aspect of transverse vortex cavities just after the separation appears to be very two-dimensional as shown later though the channel width of 80mm may be narrow. First, the overall appearance of cavity shedding is shown in Fig.5. In the case of the channel for the spanwise-view observation, the impact-peak cavitation number is estimated to be $\sigma$=6.3 [12]. The pictures in Fig.5 are arranged in time sequence in the same manner as Figs. 3 and 4.

From the results of Fig.5, it can be found that the cavitation cloud is periodically shed downstream. In order to analyze the result, the lines of No.1 to 4 were drawn on Fig.5 between the points of the approximate center in the bubble clusters. For instance, the cloud of Line No.3 is focused on. In the case of Frame No.400, the leading-edge part near the nozzle throat is almost clear and indicates little signs of cavitating spots. This means the arrival of the re-entrant motion in the leading area. A new

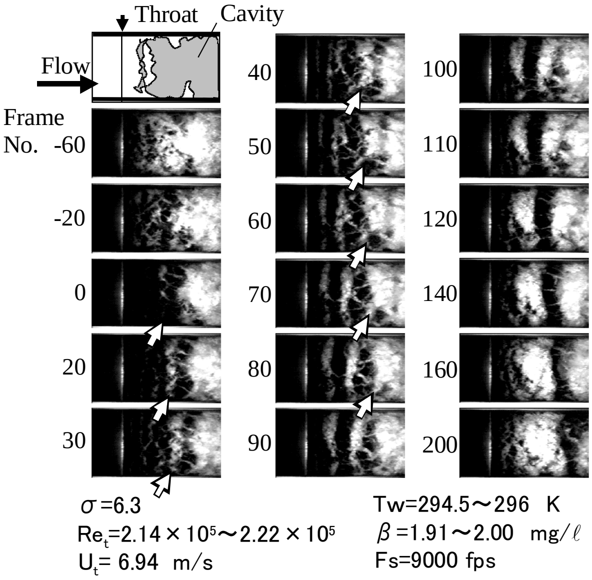


**Fig.6 Details of vortex-cavity motion just behind nozzle throat: span-view observation**

cavity occurs around Frame No.400 to No.500 because there appears to be a white cluster in the leading area of the nozzle throat. In addition, it can be found in No.500 that there is a gap between the new bubble cluster and the existing one. The downstream part of the gap is shed at almost constant speed as a cavitation cloud following the locus of Line No.2 as shown in Frame No.500 to No.800. On the other hand the upstream part of the gap is also shed at almost constant speed after the locus of Line No.3 as shown in Frame No.500 to No.1200. It should be noted that the vortex cavity grows and moves downstream through the coalescing motion with several sub-cavities as shown in No.1' as well as No.2' and No.3'.

**3.2.2 Coalescing motion of vortex cavities just behind separation area** The behavior of vortex cavities on the separated shear layer is examined from a spanwise viewpoint in the same way as that in the section 3.1.2. One of typical results are shown in Fig.6. In every picture, the white transverse line at the left edge shows the nozzle throat.

First, in Frame No.-60 the cavity appears to be a large cluster of bubbles. Then around No.0 to 30, a line cluster of shear layer cavitation can be observed to be parallel to the throat line of the nozzle (see, the arrow in the picture). This transverse type of cavitating cluster moves downstream and coalesces together with the rear transverse cavities through the streamwise vortex as shown in Frame No. 20 to 80. At that time a new transverse vortex cavity has already appeared around Frame No.20 to 30. This vortex cavity also coalesces with the rear cavity

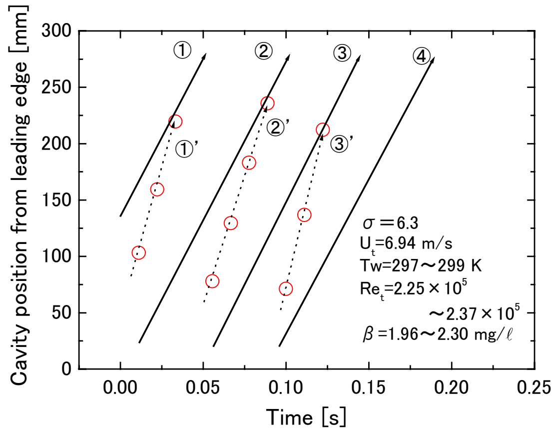


**Fig.7 Loci of shedding cavities and sub-cavities based on Fig.5**

around No.140. It is further found that a new transverse-vortex cavity appears again around Frame No.40 to 60 (probably it starts around Frame No.0 from the throat area). The new cavity begins to form a new attached cavity without the coalescence of the rear cavities, different from the case of the two cavities stated before. These facts are in quite agreement with the results due to the side-view observation as mentioned in the section 3.1.

**3.2.3 Loci of shedding vortex cavities** As mentioned above, the cloud cavitation is largely developed through the pairing and coalescing of micro-vortex cavities generated on the separated shear layer, and then periodically shed downstream to collapse as cavitation cloud. Figure 7 shows the loci of cavity movements from the result of Fig.5 to make clear such cavity behaviors.

As shown in Figs. 5 and 7, it is found that the shedding of vortex cavity shows constant periodicity and speed. The following approximate estimation can be made from Fig.7 though the exact value may be obtained from the detailed estimation of every vortex cavities. The shedding periodicity is about 23Hz and the speed of the main cavity denoted by the solid lines is almost constant of 2.8 m/s. The whole velocity of coalescing sub-cavities on the separated shear layer is estimated to be about 5.9 m/s on an average as shown by the dotted line in Fig.7. The value is approximately twice the velocity of the main shedding cavity and is close to the averaged velocity of the nozzle throat $U_t$=6.94m/s. It should be further discussed if the cloud shedding is dominated by the remaining main-cavity or the coalescing sub-cavity [11]. Here, in this paper, it should be noted that main cavity denotes the remaining cavity after the shedding, for convenience.

**3.3 Shedding process at relatively large cavitation number: spanwise view**

It was shown in the previous section that the

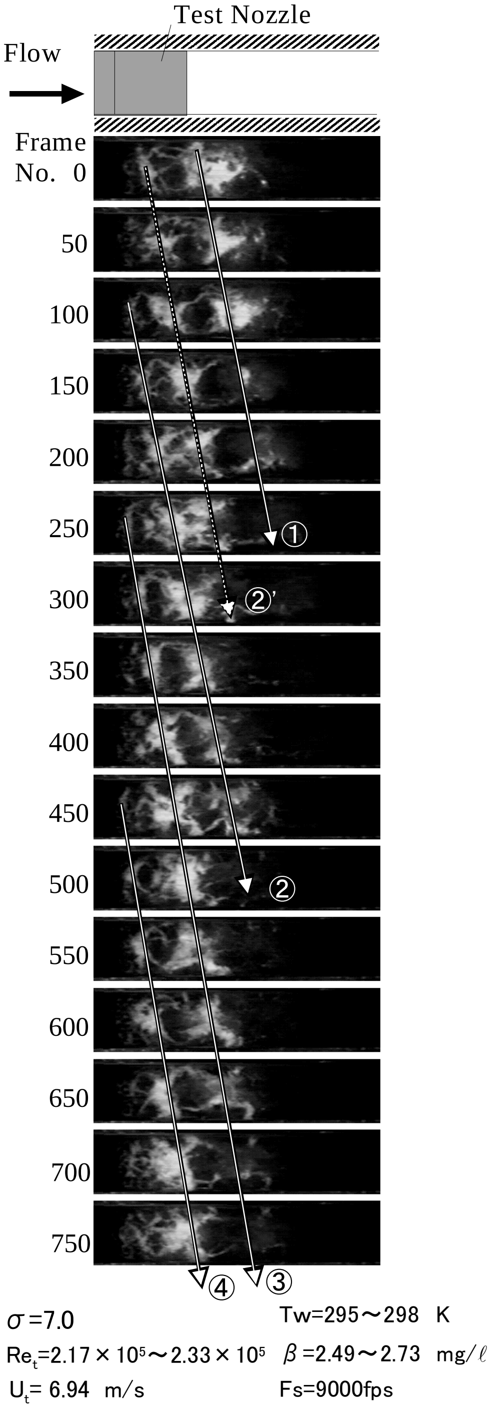


**Fig.8 Behavior of vortex cavities at higher cavitation number: span-view observation**

periodic cavitation cloud occurs near impact-peak cavitation number and is shed downstream through the pairing and coalescence of micro-vortex cavities on separated shear layer. This periodic behavior should be also focused the attention on from a viewpoint of high impulsive cavitation.

The cavitation stage at higher cavitation number was also investigated because it corresponds to the state of smaller cavitation impact compared with that of the impact-peak cavitation number. The

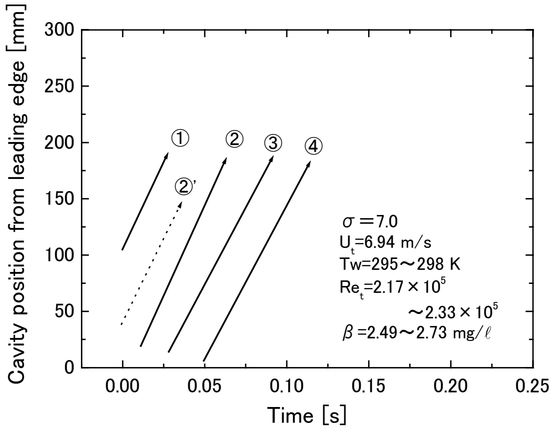


**Fig.9 Loci of shedding cavities and sub-cavities based on Fig.8**

results at higher cavitation number of $\sigma$=7.0 are shown in Fig.8. It can be found that the cavitation appearance is much different from that at $\sigma$=6.3 shown in Fig.5. These pictures at two cavitation numbers are shown in the same scale in space but different interval of video-frames (time interval).

From the results in Fig.8, some points are found in the comparison with Fig.5 as follows; the cavity shedding is weak and not very clear in periodicity, the transverse type of vortex cavities just after the nozzle throat has weak two-dimensionality and some three-dimensionality in the existence of the X-shaped cavity. In addition it should be noticed that the cavity shedding has almost half the periodicity of that at the impact-peak cavitation number.

The cavitating-zone length in Fig.8 is approximately equal to the final coalescing point with the sub-cavity as shown in Fig.5. The large-scale shedding of cavitation cloud in Fig.5 is produced and strengthened by the coalescence of vortex cavities on the separated shear layer, where the coalescence may be repeated at several steps. It is expected that the periodically-shedding vortex cavitation produces the self-exciting cloud cavitation through the coalescence of vortex cavities on the separated shear layer and the interference with the transitional cavitation state as well as the re-entrant motion, where the re-entrant motion and the relation with the cavitating length have been studied in the other paper [11].

Figure 9 shows the loci of vortex-cavitation movement made using the result in Fig.8. It can be also found clearly from the comparison with those in Fig.7 that the time period has half the value, the translational speed has almost same value, and the cavitating zone length is in rough agreement with the final coalescence point of vortex cavities in Fig.7. The values estimated from Fig.9 are that the shedding frequency is about 45 Hz, twice the value of Fig.7 and the translational velocity of the main vortex is about 2.9 m/s, approximately equal to that of Fig.7. The results indicate that the phenomena (cavitation cloud) in Fig. 5 and 7 are closely related to those in Fig. 8 and 9 (insufficiently developing cavity).

## 4. Concluding Remarks

The behavior of separated-type cavitation was studied in detail in a convergent-divergent channel with reattached separation flow peculiar to an internal flow field.

As a result, it was observed in the present flow that a relatively large-scale of cavitation cloud was periodically shed downstream around the impact-peak cavitation number. The cavitation cloud developed through the pairing and coalescing of micro-vortex cavities was shed downstream to collapse.

The appearance of separated-type cavitation was also examined in the stage of cavitation number higher than the impact-peak cavitation number. In this case the periodic shedding could be also observed, but both the scale of shedding and the two-dimensionality of transverse cavity were weak. The translational and shedding behavior of vortex cavity showed the same value in speed and half the value in time period compared with those at the impact-peak cavitation number.

These facts suggest that the occurrence of periodic cavitation cloud can be closely related to the coalescing motion, the shedding frequency and the cavitating-zone length due to micro-vortex cavities on the separated shear layer.

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