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CONTROL OF CAVITATION WITH SEPARATION BUBBLE BASED ON FREE STREAM TURBULENCE

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ABSTRUCT Cavitation is one of the serious problems on fluid machinery. This study is the fundamental research to control the cavitation breakdown and other cavitation behavior on the step with the separation bubble. The control method is to induce the disturbance by the circular cylinder placed at the upstream of the step. The experiment and the observation were carried out with two-dimensional LDV and sequence photographs. As the results, the cavitation behavior changes with the disturbance level in the shedding vortex cavitation region. At the low disturbance level, the two-dimensional vortex cavitation develops in the separation bubble and sheds out to the downstream maintaining its own shape. At the high disturbance level, the complex three-dimensional intertwined string vortex cavitations are contributed to shed the cavitation cluster to the downstream. And also, the disturbance level can control the cavity length as well as the separation-bubble length. But in the fully developed cavitation, any disturbance level is not able to control the cavity length.

Key Words: Cavitation, Cavitation breakdown, Separation Bubble, Free-Stream Turbulence, Control

1. INTRODUCTION

Cavitation brings about many serious problems on fluid machinery. In particular, the cavitation breakdown generates the violent vibration and noise in the machinery. The cavitation breakdown is mostly generated by interaction between cavitation and separation bubble formed along the separated shear layer. Although a large number of studies have been made on the cavitation breakdown [1], little is known about the control of this phenomenon.

In the non-cavitation flow, Kiya et al. [2] suggested that the characteristic of the separation bubble changed with the free stream turbulence level. And many other studies investigated that the separation-bubble length was exactly controlled using the periodic disturbance [3],[4].

By applying these results about the separation bubble control, this experimental study attempts to control the cavitation generated on the step using the forced upstream disturbance and investigates the disturbance effect on the interaction between the cavitation and the separation bubble. The disturbance is induced with a circular cylinder setting up at the upstream position of the step and the disturbance level is executed to change the diameter of the circular cylinder. The step is constructed from the long bluff plate having the sufficient length not to be affected from the wake disturbances. The experiment and the observation are carried out with two-dimensional LDV and sequence photographs under three cavitation flow regions; the non-cavitation; the shedding vortex cavitation and the fully developed cavitation.

2. EXPERIMENTAL APPARATUS AND PROCEDURES

Figure 1 illustrates the arrangement of the step and the circular cylinder. This step is composed from the long bluff plate having the right angle corners and the sufficient length not to be influenced from the wake disturbances. The plate made of polyvinyl chloride has the fluid dynamically smooth surface and is $2h$=0.06m height, W=0.08m width and L=0.75m length. This plate was installed in the center

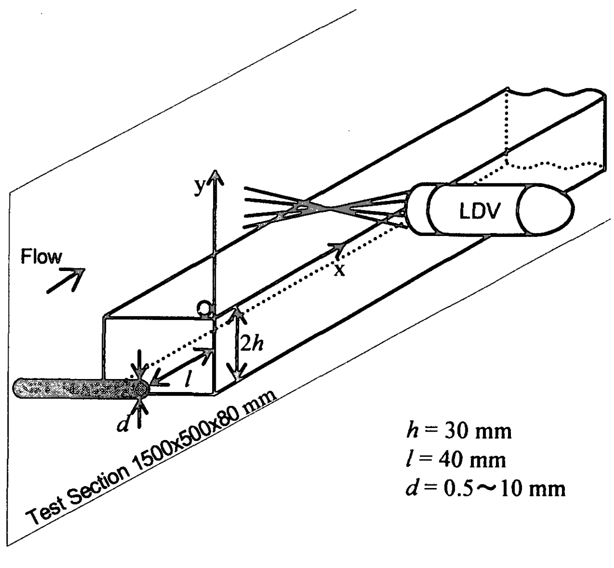

Fig.1 Arrangement of the Step and Circular Cylinder

of the two-dimensional test section (0.5 m height, 0.08 m width and 1.5 m length) of a closed water tunnel [5]. The disturbance level of the flow in the two-dimensional test section was suppressed to under 0.5%. The circular cylinder inducing the disturbance to control the cavitation was set up at the upstream position of the step centerline (*l*=40mm). Some different diameters of the circular cylinder were used in the experiment on the non-cavitation region and three diameters of the circular cylinder (*d* =0mm; not installed, 5mm, 10mm, *W*=80mm) were used in the experiment on the cavitation regions as mentioned above. Each circular cylinder was made from steel rod and was installed normal to the free stream. Any cavitation has never generated in the wake behind the circular cylinder in any experimental condition. The origin point of the coordinate axes was defined as the upstream corner of the step and the axes *x* and *y* were defined respectively as parallel and normal to the free stream. The measurement using two-dimensional Laser Doppler Velocimetry (LDV) was carried out to observe the velocity field. Cavitation flow patterns were observed with the synchronous photographs and the sequence photographs. Cavitation Number was defined as $\sigma=2(P_\infty-P_v)/\rho U^2$ (upstream static pressure: P_∞, saturation vapor pressure of water sample: P_v). This experiment was carried out on three cavitation regions, σ =4.0 (non-cavitation region), σ=1.2 (the shedding vortex cavitation region) and σ=0.9 (the fully developed cavitation region).

In this study, first, the characteristics of the separation bubble under some disturbance levels were investigated at Reynolds number $Re=U\cdot 2h/\nu=3.5\times10^5$ ($2h$ =60mm, the free stream velocity: U=6.5～7.2m/s) and $Re=8.0\times10^4$ in the non-cavitation region (σ=4.0). Next, the characteristics of the cavitation under three disturbance levels were investigated at $Re=3.5\times10^5$ in the shedding vortex cavitation region and the fully developed cavitation region.

3. RESULTS AND DISCUSSION

3-1 Non-Cavitation Region(σ=4.0)

Table 1 shows the diameter of the circular cylinders and their disturbance levels at $Re=8.0\times10^4$ and $Re=3.5\times10^5$. These disturbance levels are defined as root mean square values $v_{rms}=\sqrt{\overline{v^2}}/U$ of the normal fluctuating velocity measured with LDV at nearby the upstream corner of the step. Naturally, the maximum diameter cylinder (*d*=10mm) has the maximum disturbance level and the minimum diameter cylinder (*d* =0mm; not installed) has the minimum one. This means that the disturbance level increases as the diameter of the circular cylinder increases.

Figure 2 shows the time mean stream wise velocity $\bar{u}/U$ near the surface of the step at the same disturbance levels in Table 1. In general, the characteristic of the separation bubble can be distinguished with the length from the separation position to the reattachment position. But there are some definitions of the reattachment point, because this point has the temporally fluctuation and the three-dimensional perturbation to the span wise direction.

Table1 Diameter of Circular Cylinder and Its Disturbance Level

$Re=8.0\times10^4$	3.5×10^5	*d* [mm]	v_{rms}
○	◉	10.0	0.063
□	▣	5.0	0.027
◇	-	3.0	0.024
+	-	1.5	0.012
X	-	1.0	0.013
*	-	0.5	0.012
△	△	0	0.001

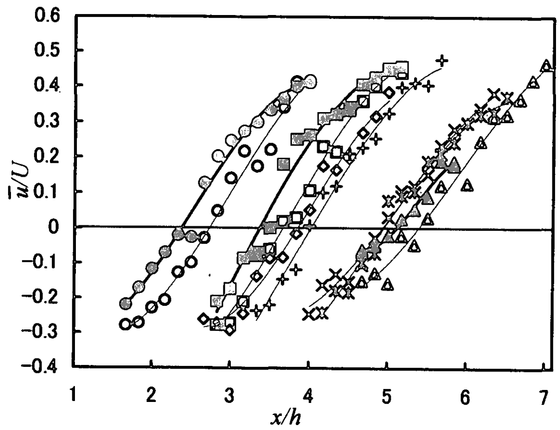

Fig. 2 Time Mean Streamwise Velocity near the Step Surface

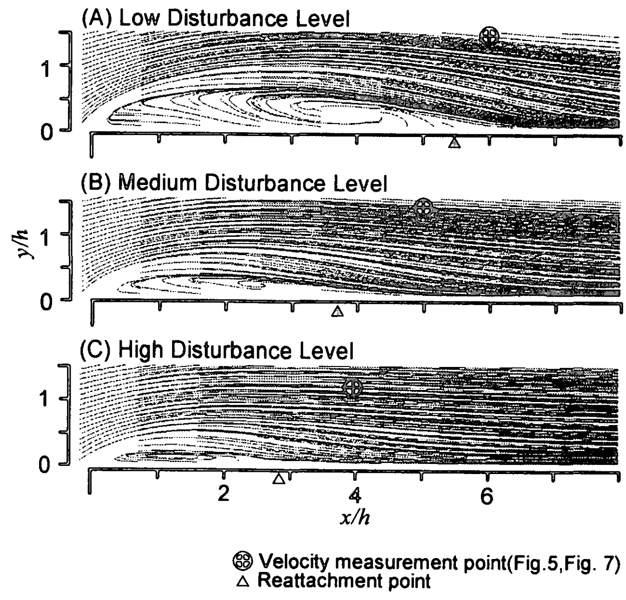

Fig. 3 Streak Lines around the Separation Bubble on the Step

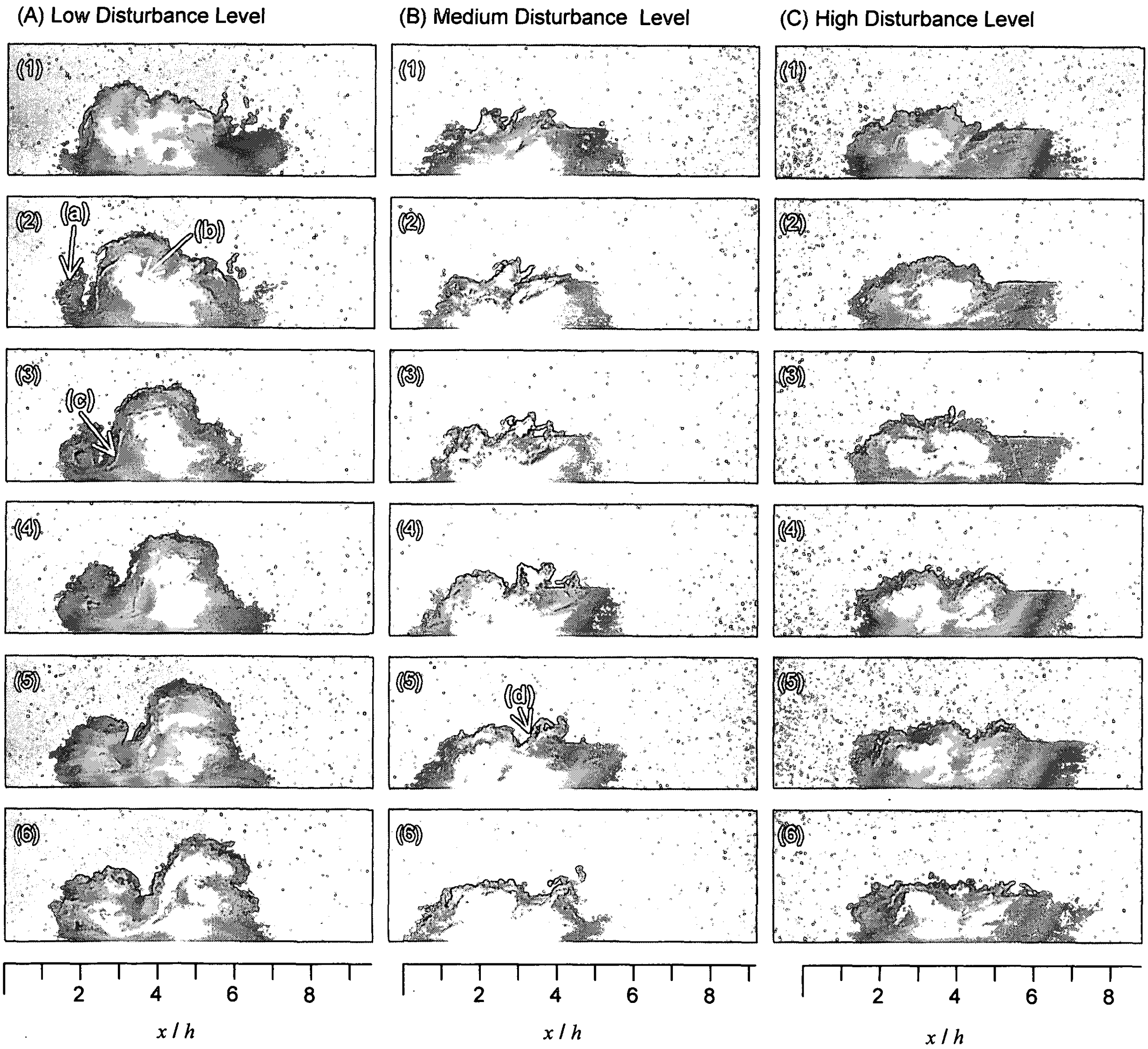

Fig. 4 Flow Pattern of the Shedding Vortex Cavitation (σ=1.2)

And so, in this study, the reattachment position is defined as the point where the time mean stream wise velocity changes from negative sign to positive sign in Fig.2. In the case of the minimum disturbance level which the circular cylinder is not installed, the reattachment point is located at x/h=5.4 and the length of the separation bubble is longest compared with those in other disturbance levels. Namely, in the case of the low disturbance level in the range from d= 0.5mm to 1.0mm, the reattachment point is located near x/h=4.9. In the case of the medium disturbance level in the range from d= 1.5mm to 5mm, the reattachment point is located about x/h=4.0. In the case of maximum disturbance level at d= 10mm, the reattachment point is located about x/h=2.7. These results mean that the reattachment point moves to the upstream as the disturbance level increases, and so the length of the separation bubble becomes shorter. Finally, the reattachment points can be mostly classified into three regions corresponded to the disturbance levels. For the reasons mentioned above, we adopt three classified disturbance levels when we discuss later about the velocity field measurement and the observation of the cavitation flow patterns due to the interaction between the separation bubble and the cavitation. The first case is the low disturbance level that the circular cylinder is not installed (A). The second case is the medium disturbance level induced by the circular cylinder of d=5mm (B). The third case is the high disturbance level induced by the circular cylinder of d=10mm (C).

Figure 3 shows the streak lines calculated from the time mean velocity measurements (50x32 points, cell size 5x2 mm) in the non-cavitation region. The solid triangle on the scale designates the reattachment point and the cross mark designates the velocity measuring point of LDV in Fig.5 and Fig. 7. The separation bubble exists on the step from the upstream corner to the reattachment point. The reverse flow and the rotating flow are formed inside of the separation bubble in all disturbance levels. And also, this separation bubble turns into smaller one as the increase in the disturbance level.

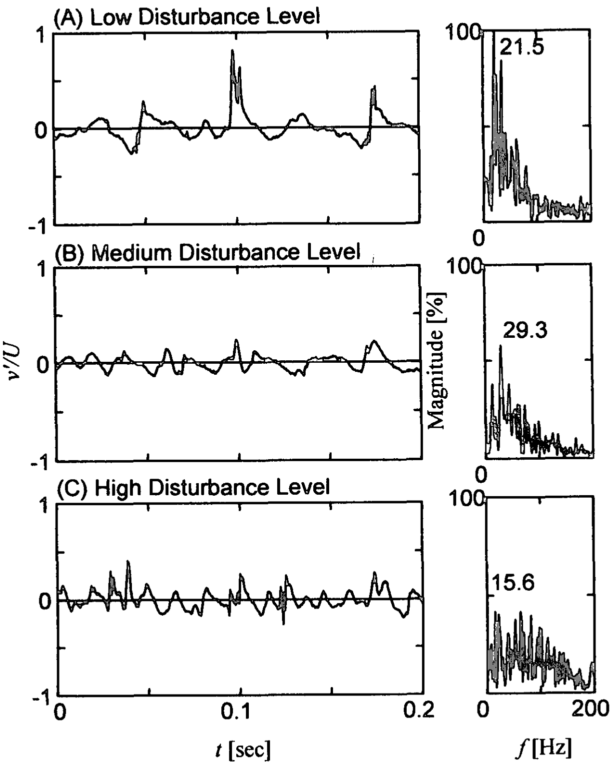

Fig. 5 Normal Velocity Fluctuation and Spectrum (σ=1.2)

3-2 Shedding Vortex Cavitation Region(σ=1.2)

Figure 4 shows the sequence photographs of the cavitation flow pattern due to the change of the disturbance level in the shedding vortex cavitation region(σ=1.2). The time interval is three milliseconds and the number in each photograph indicates the time history order of the forming and shedding process of the vortex cavitation. In the case of the low disturbance level (A), the cloud cavitation (a) as if it is the fixed cavitation grows from the front corner of the step and its rear end extends to the vertical direction apart from the step surface. The cloud cavitation is about to tend into the two-dimensional vortex cavitation (b) having an axis of the span wise direction (1). The vortex cavitation continues the growth and the movement toward the downstream and then new cloud cavitation starts to generate on the step (2). The cloud cavitation grown along the step surface pushes the vortex cavitation away to the downstream direction (2)~(4). The three-dimensional intertwined string vortex cavitations (c) are rolling around the two-dimensional vortex cavitation and connecting with the cloud cavitation. This complex intertwined string vortex cavitations contribute to shed out the two-dimensional vortex cavitation toward the downstream direction (5), (6).
The two-dimensional vortex cavitation sheds out to the downstream and finally disintegrates. On the other hand, the cloud cavitation occupies the time mean separation bubble region as shown in Figure 3. This vortex cavitation shedding process corresponds with the cavitation breakdown generated the violent vibration and noise. In the case of the medium disturbance level (B), the thickness of the cloud cavitation grown from the front corner of the step is more thinner than that in the case of (A) and the rear end of the cloud cavitation is more complex and more irregular (2)~(4). The cloud cavitation is about to tend the smaller vortex cavitation compared with (A) (5), (6). The tale of this vortex cavitation has the stream wise string vortex cavitations (d). In the case of the high disturbance level (C), the cloud cavitation similar to the case of (B) generates near the front corner of the step (1), (2). But this cloud cavitation is not so clear and immediately changes into the cavitation cluster (e) consisting of the weak vortex cavitation and the small string cavitations (3), (4). Finally, the cavitation cluster becomes into the small and wavy string cavitations only (5), (6). As the above results, in the low disturbance level, the two-dimensional vortex cavitation develops in the separation bubble. This cavitation breaks down with the violent noise and sheds out to the downstream maintaining its own shape. In the high disturbance level, the In this way, the scale of the cloud cavitation generated in nearby the separation bubble is smaller as the disturbance level is higher. And the vortex cavitation tends from the strong two-dimensional one to the weak three-dimensional one. These results mean that the control of the separation bubble using the disturbance level can directly apply to the control of the cavitation.

Figure 5 shows the normal velocity fluctuation and frequency spectrum measured at the similar characteristic points of the separation bubble level as shown in Fig.3. In the spectrum chart, the number described inside represents the maximum peak frequency and the vertical axis indicates the magnitude divided by the maximum intensity value of the peak frequency in Fig.5 (A). In the case of the low disturbance level (A), the velocity fluctuation is periodic and its peak frequency has 21.5Hz. This magnitude of the peak frequency is the highest in all spectrum charts. This periodical velocity fluctuation is most likely caused by the two-dimensional vortex cavitation breakdown observed in Fig. 4. In the case of the medium disturbance level (B), the period of the fluctuating velocity with large amplitude becomes irregular. The peak frequency is 29.3 Hz, but the frequency distribution becomes broad. These results coincide with that the cavitation flow patterns in Fig. 4 change from the large and strong vortex cavitation shedding process to the small and weak cavitation shedding process. In the case of the high disturbance level (C), the period of the velocity fluctuation is the shortest one in all cases and the spectrum does not have the clear peak frequency. This velocity fluctuation is generally regarded as the small string cavitations shedding process. From these facts, we can conclude that the cavitation shedding process depends on the characteristics of the separation bubble in this cavitation region (σ=1.2).

3-3 Fully Developed Cavitation Region (σ=0.9)

Figure 6 shows the sequence photographs of the cavitation flow patterns due to the change of the disturbance level in the fully developed cavitation region (σ=0.9). In the case of the low disturbance level (A), the cloud cavitation (a) grows from the front corner of the step and the length of the cavitation in this range is longer than that in the shedding vortex cavitation range (σ=1.2). The cloud cavitation rolls up and forms the two-dimensional vortex cavitation (b) near about the reattachment point (1). The cloud cavitation grows up along the step surface and

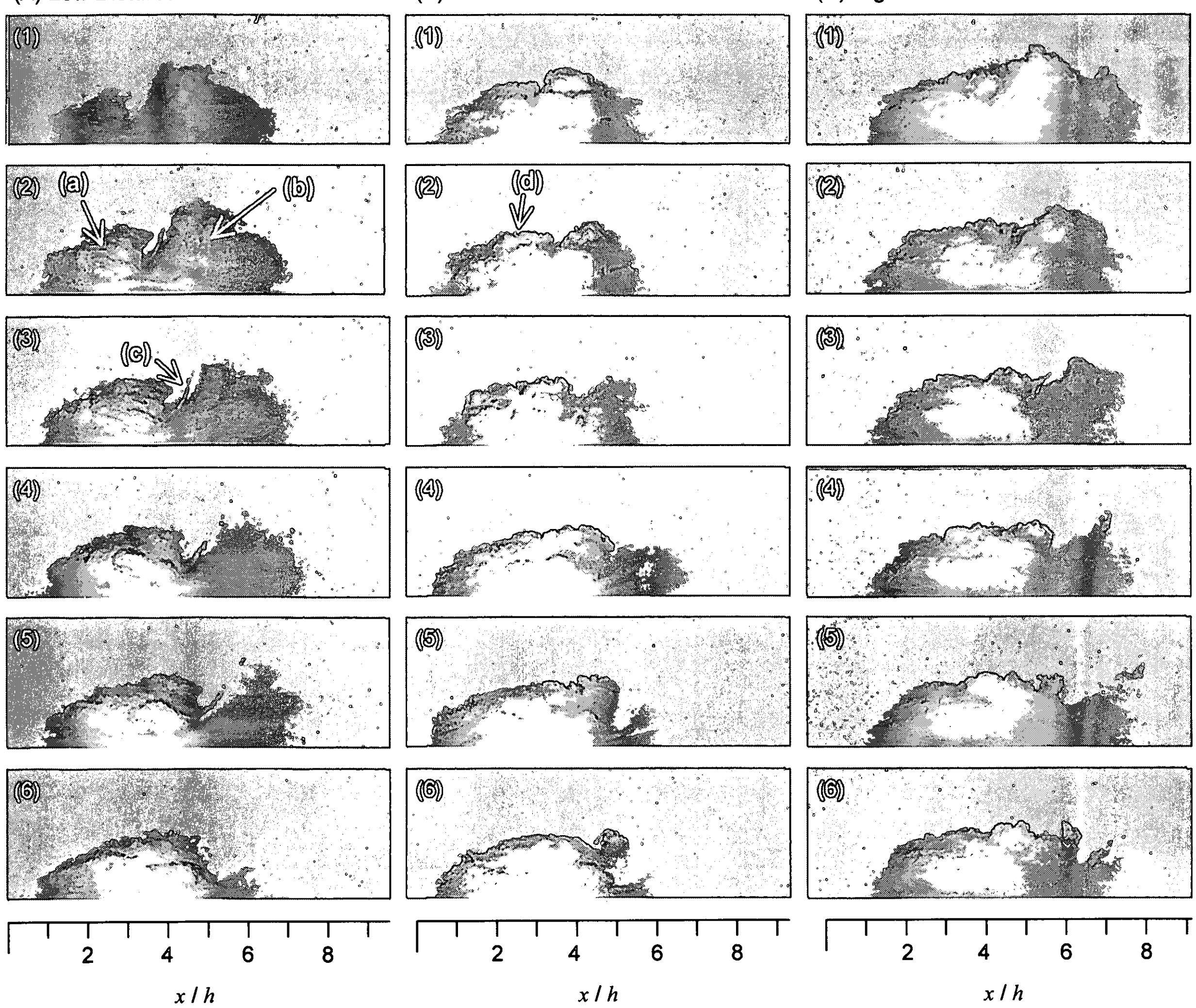

Fig. 6 Flow Pattern of the Fully Developed Cavitation (σ=0.9)

the vortex cavitation moves toward the downstream. The intertwined string cavitation (c) is connecting between the cloud cavitation and the vortex cavitation (2)~(4). Finally, the cloud cavitation covers on the separation bubble area and the vortex cavitation breaks down toward the downstream (5), (6). In the case of the medium disturbance level (B), the cloud cavitation occupies the extensive area on the step surface and the scale of the vortex cavitation is smaller than that in (A). And small cavitation clusters (d) appear on the cloud cavitation and shed out at the downstream. In the case of the high disturbance level (C), the cloud cavitation pattern is similar to that in the case of (B). On the other hand, the cavitation shedding process turns from two-dimensional mechanism to strong three-dimensional one at the downstream. From these cavitation flow patterns, the cavitation shedding process changes due to the disturbance level and the three-dimensional effect is increasing in the case of the medium and the high disturbance level, although the disturbance level does not efficiently contribute to the control of the cavitation scale.

Figure 7 shows the normal velocity fluctuation and frequency spectrum measured at the same points as shown in Fig.5. In the case of the low disturbance level (A), the velocity fluctuation has periodical pulse and this period is longer than that in the σ=1.2 range. These periodical pulses are corresponded with the vortex cavitation shedding process observed in Fig. 5(A). And the cloud cavitation is growing during the long interval between these pulses. In the case of the medium disturbance level (B), the velocity fluctuation has the irregular spike pulse. The spectrum distribution becomes broad and does not have the peak frequency. In the case of the high disturbance level (C), the velocity fluctuation and spectrum are similar to those in the case of (B) and this similarity corresponds with the sequence photographs in Fig.6. In the fully developed cavitation region (σ =0.9), the disturbance level can control the vortex cavitation shedding process, although it does not

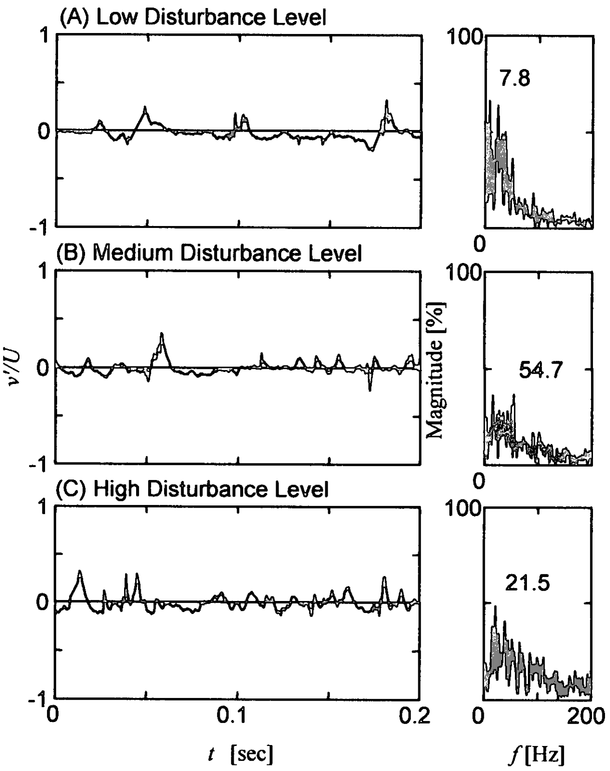

Fig. 7 Normal Velocity Fluctuation and Spectrum (σ=0.9)

contribute to control the cavitation scale. The reason is considered for that either the strong fluctuation generated by the cavitation dominates the flow field instead of the disturbance level induced at the upstream or the fluctuation collapses the separation bubble and changes the vortex from two-dimensional structure to three-dimensional one. It needs further precise discussion.

All these results lead to the conclusion that the cavitation on the step with the separation bubble can be controlled with free stream turbulence. Namely, the turbulence intensity can control the cavity length as well as the separation bubble length in the shedding vortex cavitation region, but the disturbance level does not efficiently contribute to control the cavitation scale in the fully developed cavitation region.

4. CONCLUSIONS

This experimental study attempts to control the cavitation and the cavitation breakdown generated on the step using the free stream turbulence. The experiment and the observation were carried out with two-dimensional LDV and sequence photographs under some cavitation regions. The free stream turbulence can control the cavity length as well as the separation bubble length in the shedding vortex cavitation region, but the turbulence does efficiently not contribute to control the scale of the cavitation. The main results can be summarized as follows.

(1) The reattachment point moves toward the upstream as the disturbance level induced by the circular cylinder is higher, and so the length of the separation bubble becomes shorter. The reattachment points are classified into three regions corresponded with the disturbance levels.

(2) In the shedding vortex cavitation region (σ=1.2), the scale of the cloud cavitation generated in nearby the separation bubble is smaller as the disturbance level is higher. And the cavitation flow pattern tends from strong two-dimensional vortex cavitation to weak three-dimensional one. These results mean that the control of the separation bubble using the disturbance level can directly apply to the control of the cavitation.

(3) In the fully developed cavitation region (σ=0.9), the cavitation shedding process changes corresponding to the disturbance level and the three-dimensional effect is increasing in the case of the medium and the high disturbance level, although the disturbance level does not efficiently contribute to the control of the cavitation scale. The reason is considered for that either the strong fluctuation generated by the cavitation dominates the flow field instead of the disturbance level induced at the upstream or the fluctuation collapses the separation bubble and changes the vortex from two-dimensional structure to three-dimensional one.

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