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An experimental observation on the interaction of a hydrofoil surface on the free stream vortex cavitation*

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ABSTRACT

The interaction between vortex cavitation and a lifting surface is commonly seen on a ship's propeller and rudder. Such interaction would affect the stability of the vortex cavitation and thus induce various undesirable effects. However, there is few research focused on this phenomenon due to the complexity of the flow configuration. In this paper, the interaction between an upstream vortex cavity produced by an elliptical hydrofoil and a symmetric NACA profile hydrofoil in the downstream was observed using a high-speed camera in a cavitation tunnel. The results indicate that the radius of the vortex cavity grows gradually and the affected part shows remarkably discrepancy along streamwise with the decrease of cavitation number. Under certain cavitation number, the influenced part became unstable and thus produces the inner flow at the rear of the enlarged cavity. In addition, sheet cavitation would present on the hydrofoil surface influenced by the vortex cavity on which cavitation should not occur if there is no interaction when the cavitation number was decreased further. The unsteady shedding sheet cavity induced periodically shedding of the vortex cavity and inversely affected the instability of the upstream part of the vortex cavity.

Keywords
Experimental observation; vortex cavity; interaction with foil surface

1 INTRODUCTION

Vortex cavitation is commonly found on the tip and hub of ship propellers, and it usually could spread for a relatively long distance, making it possible to interact with the rudders located downstream of the propellers. Such interaction would affect the stability of the vortex cavitation and thus induce various undesirable effects including vibration and noise enhancement, serious impacts and even material removal.

Much work has been conducted on this kind of flow configuration (Felli et al. 2009, Prothin et al. 2014, Chen et al. 2018, Felli 2021). However, these contributions are mainly focused on the wet flow field features without cavitation. The understanding on basic rule for interactions between vortex cavitation and a lifting surface is still limited for the moment.

Taking into account the complexity of the interaction mechanism of the propeller–rudder combination, the present research focuses on the presence of a single isolated vortex cavity. An elliptical hydrofoil in the upstream was used to produce the vortex cavitation and a symmetric NACA profile hydrofoil in the downstream was used to act as the rudder interaction. Then the vortex cavitation behavior was observed using a high-speed camera in the high-speed cavitation tunnel in China Ship Scientific Research Center (CSSRC).

2 TEST FACILITY AND EXPERIMENTAL SETUP

The test was conducted in the high-speed cavitation tunnel in CSSRC, as is shown in Figure 1. The size of the test section is 1600mm×225mm×225mm, the turbulence intensity is less than 0.5%, the maximum velocity is 25.0m/s, and the pressure range of the test section is 5kPa~500kPa. The dissolved gas content and nuclei can be controlled.

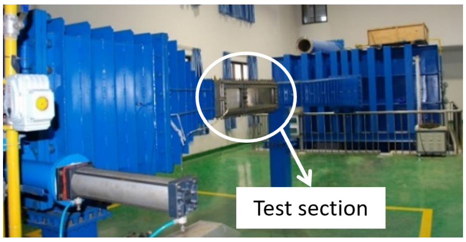

Figure 1 High-speed cavitation tunnel in CSSRC

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The test conditions are controlled by adjusting the cavitation number σ, which is defined as:

$$\sigma = \frac{p_\infty - p_v}{0.5\rho U^2} \tag{1}$$

U is the incoming flow velocity, p_∞ is the pressure of the test section, p_v is the saturated vapor pressure, and ρ is the water density.

The test equipment includes a high-speed camera to observe the cavitation behavior and a hydrophone to monitor the pressure pulsation. The test arrangement is shown in Figure 2. Tip vortex cavitation is generated by the NACA66-2-415 elliptical hydrofoil in the upstream, and a NACA0012 hydrofoil is located downstream of the vortex cavity to investigate the interaction. The distance between the center of the foils is d. The installation of the test model is shown in Figure 3.

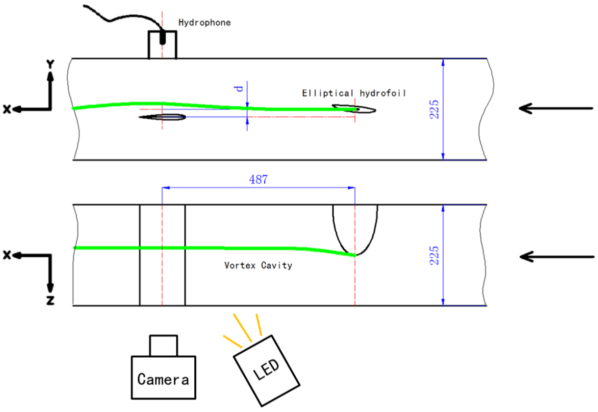

Figure 2 Sketch of the test arrangement

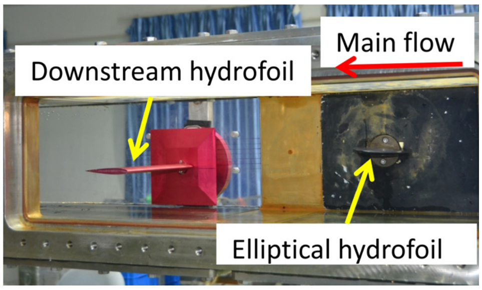

Figure 3 Test model installation

3 RESULTS AND DISCUSSION

This section conducts experimental observations on the behavior of vortex cavity under different cavitation numbers at different interaction distances and different downstream hydrofoil attack angle under the condition that upstream elliptical hydrofoil is fixed at an attack angle of 7 degree.

3.1 The results with d=14.5mm

(1) U=7m/s, d=14.5mm

Figure 4 shows the typical behavior of vortex cavity under different cavitation numbers with an incoming flow velocity of 7m/s and center distance of 14.5mm between the front and rear hydrofoils. The results show that as the cavitation number decreases, the diameter of the vortex cavity increases gradually. At a relatively high cavitation number, the hydrofoil has little impact on the vortex cavity. As the cavitation number decreases, the influence from the lifting surface on the vortex cavity becomes more and more significant, mainly reflected in the significant growth in the diameter of the affected part. And when the diameter increases to a certain value, inner flow inside the vortex cavity occurs in the rear part of the sections with enlarged cavity diameter (σ=0.75). On the other hand, the cavity appears to be a quasi-steady stationary wave and the wave number along the flow direction of the vortex cavity changes significantly in the affected part. As is shown in Figure 5, the wave length for the affected part grows much larger than other parts ($\lambda_1 > \lambda_2 > \lambda_3$). And the magnitude of the growth diminishes gradually as the impact decreases.

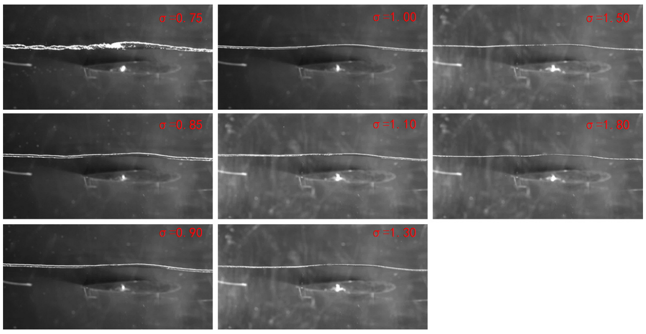

Figure 4 U=7m/s, d=14.5mm

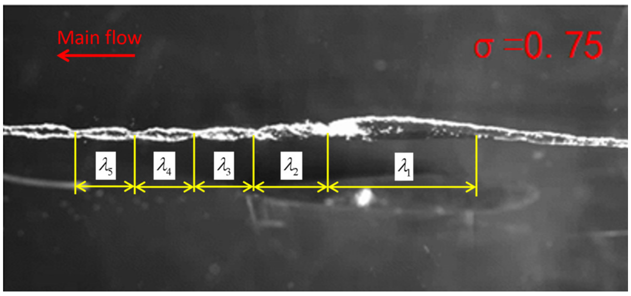

Figure 5 The wave length along the flow direction

(2) U=10m/s, d=14.5mm

Figure 6 shows the typical behavior of vortex cavity under different cavitation numbers with an incoming flow velocity of 10m/s and center distance of 14.5mm between the front and rear hydrofoils. The results show that as the cavitation number decreases, the diameter of the vortex cavity increases; at a relatively high cavitation number, the hydrofoil has little impact on the vortex cavity; as the cavitation number decreases, the impact on vortex cavity becomes more and more significant, mainly reflected in the significant increase in the diameter of the part affected by the hydrofoil. However, compared with the results of 7m/s under the same cavitation number (σ=0.75), the growth of the cavity diameter at the influenced part is much smaller. In addition, no inner flow within the cavity is observed in this condition. On the other hand, in the part affected by the hydrofoil, the wave number along the flow direction of the vortex cavity changes significantly. The wave length for the affected part grows much larger than other parts.

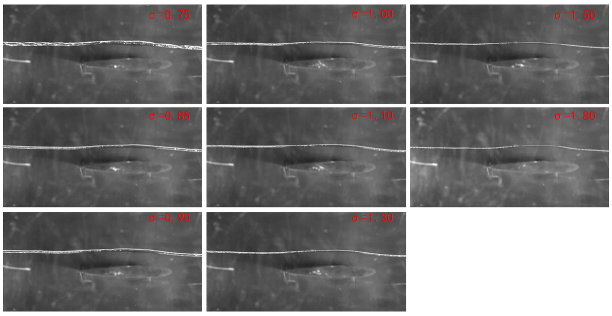

Figure 6 U=10m/s, d=14.5mm

(3) U=12m/s, d=14.5mm

Figure 7 shows the typical behavior of vortex cavity under different cavitation numbers with an incoming flow velocity of 12m/s, a distance of 14.5mm between the front and rear hydrofoils. The results are similar to those under the condition of 10m/s. The main difference in this case is that sheet cavitation appears on the hydrofoil surface under relatively low cavitation number (σ=0.75, 0.85), though the installation angle of attack (AOA) of the hydrofoil is 0, and there is no cavitation on the other side, indicating that the sheet cavitation here is caused by the influence of the vortex structure. However, for these cases, sheet cavitation is quasi-steady and its area is too limited to disturb the behavior of vortex cavity.

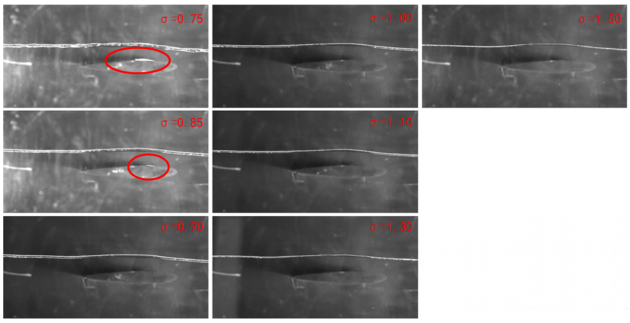

Figure 7 U=12m/s, d=14.5mm

(4) U=14m/s, d=14.5mm

Figure 8 shows the typical behavior of vortex cavity under different cavitation numbers with an incoming flow velocity of 14m/s, a distance of 14.5mm between the front and rear hydrofoil center. The basic rule is same with that of 12m/s. The unique for this velocity is that it allows the equipment to reach a relatively much lower cavitation number (σ=0.45) with higher velocity as described in formula (1). Further reducing the cavitation number to 0.45, sheet cavitation appears on the hydrofoil itself, as shown in Figure 9. The time interval in the picture is 187.5μs, and the time sorting rule for images is from top to bottom, and then from left to right. The first picture is located in the top left corner, and the last picture is located in the bottom right corner. All images arranged in chronological order obey this rule in this paper. Under this condition, the cavity diameter of the affected part increases significantly due to the lifting surface and its stability is affected by the unsteady sheet cavitation on the surface of downstream hydrofoil, showing strong unsteady and unstable characteristics. The inner flow occurs at the rear part of the diameter enlarged vortex cavity and its front moves forward and backward in the flow direction with the periodic shedding behavior of sheet cavitation on the hydrofoil surface.

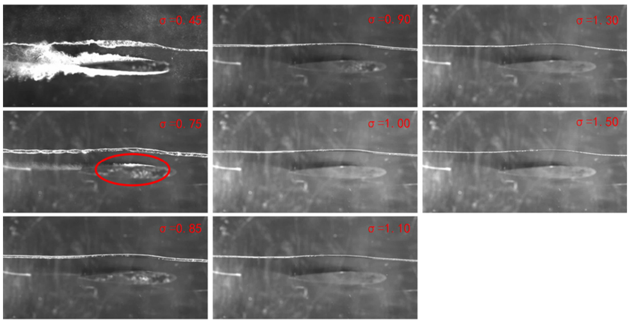

Figure 8 U=14m/s, d=14.5mm

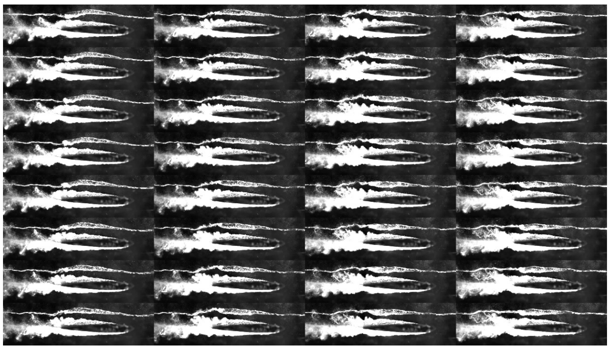

Figure 9 Dynamic behavior of cavitation under σ =0.45 (time interval 187.5μs)

3.2 Influence of hydrofoil center spacing

To observe the distance effect of interaction between the vortex cavity and the downstream hydrofoil, the distance between the upper and lower hydrofoil center was further reduced.

(1) U=7m/s, d=8mm

Figure 10 shows the typical behavior of vortex cavity under different cavitation numbers with an incoming flow velocity of 7m/s, a distance of 8mm between the front and rear hydrofoils. Compared with the incoming flow velocity of 7m/s and the distance between the front and rear hydrofoils of 14.5mm, due to the reduction of the center distance between the hydrofoils, the influence of the lifting surface on the vortex cavity has a tendency to increase. The diameter of the influenced part of the vortex cavity grows more obviously than situations with larger spacing, such as the case under σ=0.9. However, the basic rule for the interaction is consistent with that under relatively larger space. That is, as the cavitation number decreases, the vortex cavity diameter shows an increasing trend; at a relatively high cavitation number, the hydrofoil has little influence on the vortex cavity. As the cavitation number decreases, the influence of the hydrofoil on vortex cavity becomes more and more significant, which is mainly reflected in the significant increase in the diameter of the part affected by the hydrofoil. When the cavitation number decreases to a certain level (σ=0.7), inner flow occurs inside the vortex cavity. In addition, as the cavitation number continues to be reduced, sheet cavitation appears on the hydrofoil surface on the side where the vortex cavity is located (σ=0.5) though the installation angle of attack of the hydrofoil is 0, and there is no cavitation on the other side, indicating that the cavitation here is caused by the influence of the vortex structure.

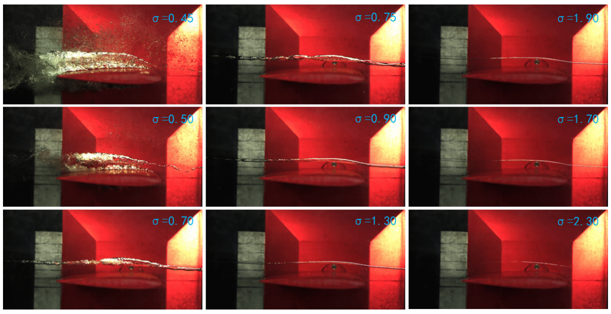

Figure 10 U=7m/s，d=8mm

(2) U=7m/s，d=-2mm

On the basis of the above, continue to reduce the distance between hydrofoil center. Figure 11 shows the typical behavior of vortex cavity under different cavitation numbers with an incoming flow velocity of 7m/s, a center distance between the front and rear hydrofoils of -2mm. At this distance, the vertical position of the vortex cavity is almost flush with the position of the hydrofoil leading edge. Compared with the case where the spacing between hydrofoil centers is larger, the influence of the hydrofoil on vortex cavity is further enhanced. Significant changes in streamwise wave number begin to appear at relatively higher cavitation number (σ=1.33), and apparent deformation begins to occur at relatively higher cavitation number (σ=1.9). The basic rule for the interaction is consistent with that under relatively larger space.

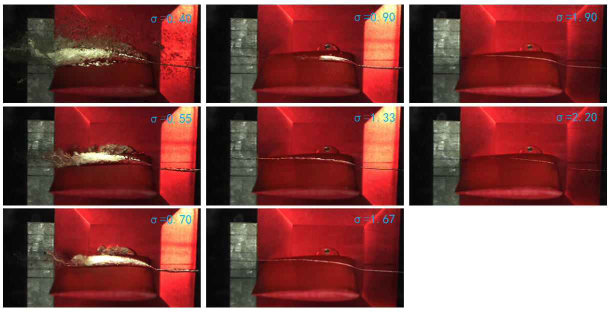

Figure 11 U=7m/s, d=-2mm

Specially, as the cavitation number continues to be reduced, the rear part of vortex cavity sheds from the main part. Due to the limited distance between the vortex cavity and the surface of hydrofoil, the dynamic behavior of the cavity is similar with sheet cavitation (as is shown in Figure 12). The upstream part of the vortex cavity in this case is also affected by the dynamic behavior from downstream, with diameter expands and contracts periodically and cavity center swings up and down (as is shown in Figure 13).

Figure 12 U=7m/s, d=-2mm, σ=0.55

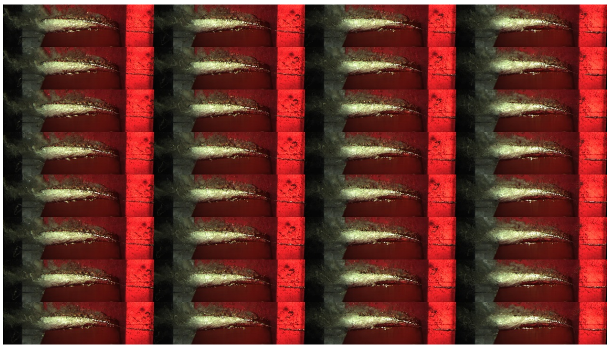

Figure 13 U=7m/s, d=-2mm, σ=0.40

3.3 Influence of pressure gradient

In this part, by changing the angle of attack of the downstream hydrofoil to 10°, the influence of changes in the pressure gradient produced by downstream structure is observed.

Figure 14 shows the typical behavior of vortex cavity under different cavitation numbers with an incoming flow velocity of 7m/s, a center distance between the front and rear hydrofoils of -2mm. Under this series of operating conditions, due to the increase in the attack angle of the downstream hydrofoil, the interaction between the vortex cavity and the hydrofoil increases significantly. The vortex cavity and the hydrofoil cavitation are coupled to form a local complex cavitation cloud. The vortex structure itself was completely destroyed, and the stable vortex structure downstream disappeared.

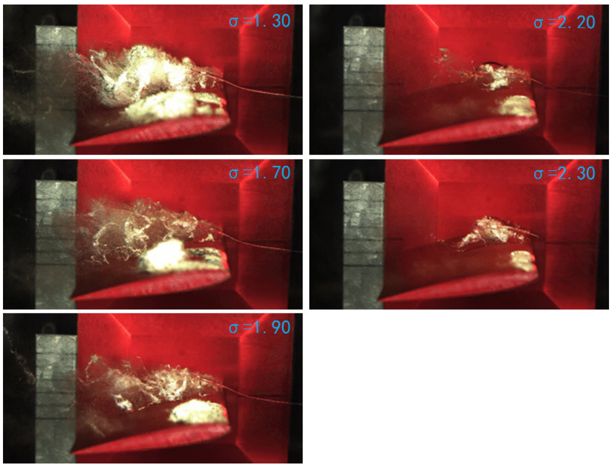

Figure 14 U=7m/s, d=-2mm, AOA=10°

4 CONCLUSIONS

This paper mainly introduces an experimental observation on interaction between an upstream vortex cavity and a downstream hydrofoil in the highspeed cavitation tunnel in CSSRC. Some conclusions can be obtained as follows:

(1) The cavity radius grew gradually with the decrease of cavitation number in general.

(2) Under relatively high cavitation number the difference in radius between the influenced part and the upstream uninfluenced part was small, but when the cavitation number was decreased to a certain value, the discrepancy in vortex radius along different streamwise locations presented with the affected part enlarged remarkably. The streamwise wave number along the vortex cavity was changed.

(3) Farther decreasing of the cavitation number, the interface of influenced part of vortex cavity became unstable and thus produced the inner flow at the rear of the enlarged cavity.

(4) Sheet cavitation was present on the hydrofoil surface at the side with vortex cavity though the attack angle of the hydrofoil was 0 when we continued to lower the cavitation number. The unsteady shedding sheet cavity induced periodical shedding of the vortex cavity and inversely affected the stability of the upstream part.

(5) Smaller interaction distance and greater pressure gradient would enhance the interaction between the vortex cavity and the foil.

REFERENCES

Chen, C., Wang, Z., & Gursul, I. (2018). Experiments on tip vortices interacting with downstream wings. Experiments in Fluids, 59, 1-24.

Felli, M., Roberto, C., & Guj, G. (2009). Experimental analysis of the flow field around a propeller–rudder configuration. Experiments in Fluids, 46, 147-164.

Felli, M. (2021). Underlying mechanisms of propeller wake interaction with a wing. Journal of Fluid Mechanics, 908, A10.

Prothin, S., Djeridi, H., & Billard, J. Y. (2014). Coherent and turbulent process analysis of the effects of a longitudinal vortex on boundary layer detachment on a NACA0015 foil. Journal of Fluids and Structures, 47, 2-20.