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A Qualitative Study on the Relationship Between Cavitation Structure and Erosion Region around a 3D Twisted Hydrofoil by Painting Method *

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ABSTRACT

Cavitation erosion usually can be seen on shaft brackets and rudders of ships, which is generally considered to be related to cloud cavitation that contains high erosive potential. However, little has been known about the relationship between the cavitaton structure and erosion region. In this paper, a 3D twisted hydrofoil was selected to investigate the relationship between cloud cavitation resulting from the shedding of sheet cavitation and its reduced erosion region qualitatively by painting method in a cavitation tunnel. The erosion region was evaluated with the extent of paint loss, and the structure of cloud cavitation was recorded by high speed cameras. The results showed that the unsteady part of cavitation sheet might be the most erosive structure in the process of cloud cavitation evolution, and U-shaped vortex structure could also be erosive but causes much less damage. In the end, three role of U-shaped vortex in erosion were proposed.

Keywords

cavitation structure; erosion

1 INTRODUCTION

For fast running ships, cavitation is generally unavoidable on propellers, shaft brackets and rudders, which can cause severe damage on relative components besides the vibration and noise. Cavitaiton erosion is a complicated problem related to hydrodynamic loads and material properties. So far various hypotheses have been proposed to illustrate the source of hydrodynamic loads, inclouding micro jet mechanism, shock wave mechanism, and bubble interaction mechanism. These hypotheses are the basis of most theoretical analysis on hydrodynamic loads in the process of cavitation erosion.

In addition， cloud cavitation containing high erosive potential was considered to be the most erosive type of cavitation. Recent investigations (Cao et al 2015, Peng et al 2016) have shown that there exist distinct U-shaped vortex structures in large scale cavitating flows under various flow configurations. However, few investigations have been made on the relationship between these structure and cavitation erosion. Petkovsek, M. & Dular, M., (2013) have conducted simultaneous observation of cavitation structures and cavitation erosion to illuminate individual cavitation events with specific damage. But the overall contribution of different cavitaton structures existed in the development of cloud cavitation is still confusing. Consequently, it is of great interest to make clear what the role of cavitaton structures play in the process of caivtation erosion. It may shed some light on the understanding of different parts of cavitation structures' contribution to cavitation erosion, so as to propose available suggestions on the prediction and suppression of cavitation erosion.

In this paper, we choose a 3D twisted hydrofoil that can produce periodic shedded cloud cavitation resulting from sheet cavitation to estimate the relationship between the cavitaton structures and erosion regions. Cavitaton structures were synchronously recorded by two high speed cameras and the status of erosion regions were qualitatively evaluated by paint loss.

2 TEST FACILITY AND EXPERIMENTAL SETUP

Cavitation tests were conducted in a high speed cavitation tunnel (as shown in Figure 1) located in China Ship Scientific Research Center (CSSRC). The test section is composed of 8 perspex window which permits to observe cavitation structures from different sides. The length of test section is 1600mm and the size of the square cross section is 225mm×225mm. The maximum flow velocity can reach 25m/s and the background pressure can be adjusted from 5kPa to 500kPa, which allows the cavitation number defined as formula 1 to be easily changed. Above all, this tunnel has a fast degassing system allowing to degass the water in limited time.

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

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The test model used in this test is a NACA0009 three dimensional twisted hydrofoil (as shown in Figure 2) with a cord length of 112.5mm and a spanwise length of 225mm. It is a symmetric hydrofoil with spanwise varied attack angle and the maximum angle of 11 degree in the middle. Before test the foil surface was coated with paint made of oil and some powder. Then it was left in the air to dry naturally. The purpose of painting is to use the peeled coatings to show the high erosion risk region.

The cavitation structures were observed synchronously by two high speed cameras from the bottom and side of test section, which consequently can get both the top view and side view of cavitation structures around the hydrofoil. Two LED lights provide light for high speed cameras. The images were recorded at a frame rate of 2000 fps during the experiment.

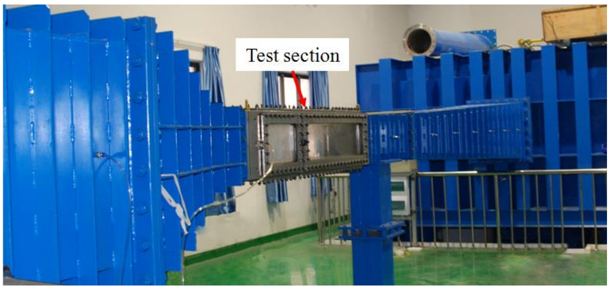

Figure 1 The high speed cavitation tunnel in CSSRC.

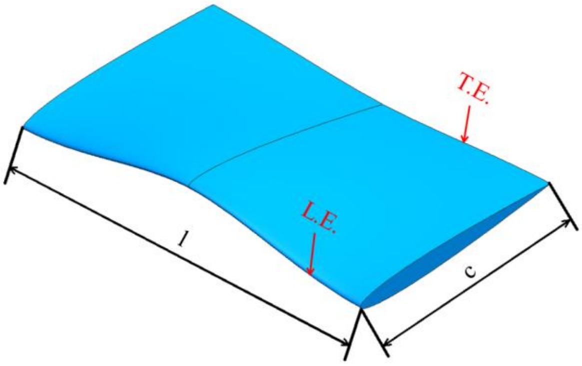

Figure 2 A sketch of NACA0009 3D twisted hydrofoil.

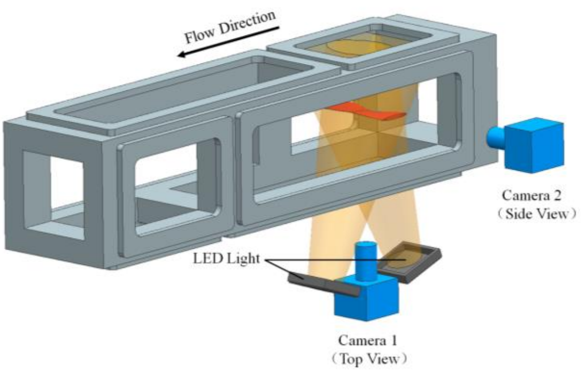

Figure 3 A sketch of the setup of high speed cameras.

The surface condition of hydrofoil before and after the erosion test was recorded with a high resolution camera so as to obtain more detailed information.

Additionally, every time before test, the water is degassed for 3 hour using nuclei seeding degassing system to reduce the effect of gas content on erosion.

3 RESULTS AND DISCUSSION

To acquire the relation between the cavitation structures and its corresponding erosive capability, cavatation tests were performed. The evolution of cavitation structure were captured simultaneously by two high speed cameras and the status of surface coating was recorded with a high resolution camera.

3.1 The Evolution of Cavitation Structure

From the high speed observation, it can be found that the shedding process of large scale cloud cavitation around 3D twisted hydrofoil is qusi-periodic. As is shown in figure 4 (Top view) and figure 5 (Side view), the cavitation sheet attaches on the surface of hydrofoil to the leading edge (①). Re-entrant flows (marked with arrows) beneath the sheet form in both side of the rear area of this sheet, then they move forward to the center of hydrofoil and gather together in the spanwise symmetric plane (②). Subsequently, the converged re-entrant flow cuts off the cavitation sheet (③), which seems to be the generation mechanism of large scale cavitation. And then the detached part of the sheet moves downstream with the incoming flow and evolves into a U-shaped vortex structure (④). The U-shaped vortex structure continues to be convected downstream and damps in the downstream (⑤,⑥).

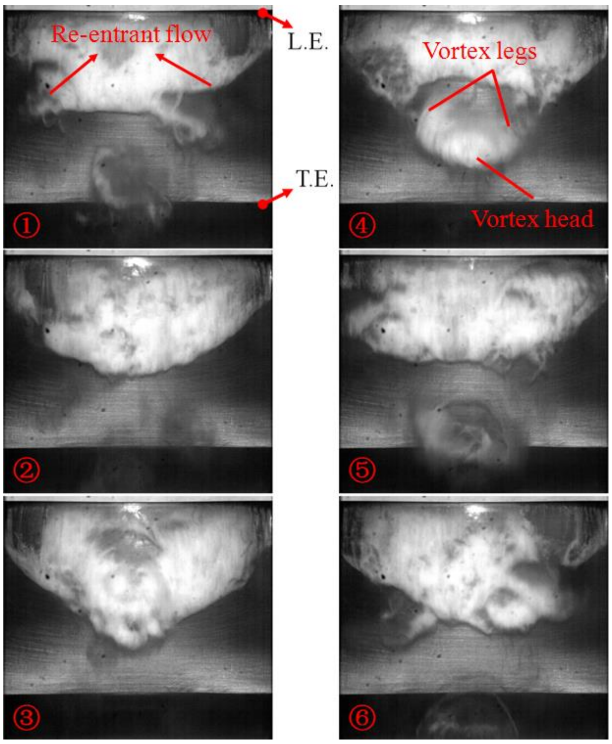

Figure 4 Behavior of cloud cavitaion

(Top view, $U = 14m/s$, $\sigma = 1.2$)

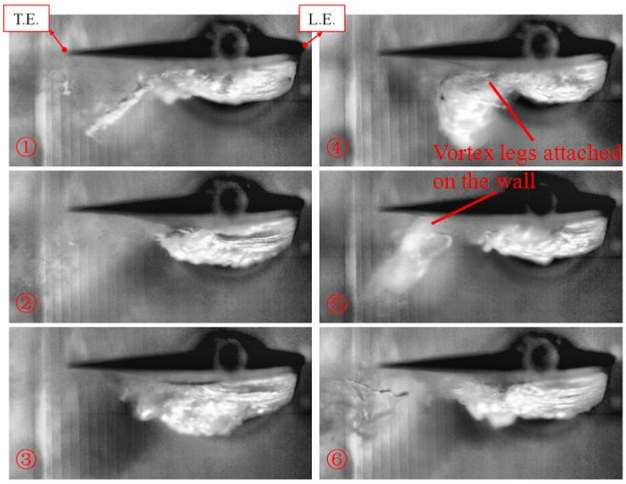

Figure 5 Behavior of cloud cavitaion

(Side view, $U = 14m/s$, $\sigma = 1.2$)

It can’t be denied that the cavitation structure doesn’t evolves exactly the same in different cycles, but in most cases it develops in this way or tend to be in this way.

3.2 The Surface Coating Status of Hydrofoil Before and After Test

Painting method is used to evaluate the relationship between cloud cavitation resulting from the shedding of sheet cavitation and its reduced erosion region.

As is shown in figure 6, before test the hydrofoil surface is uniformly coated with paint and left in the air dry naturally. Thus a good polished surface can be obtain to compare with that of after test so as to find out the regions in high erosion risk.

Figure 6 The surface coating status before test.

($U = 14m/s$, $\sigma = 1.2$)

Figure 7 shows the surface coating status after 3 hour’s test at $U = 14m/s$, $\sigma = 1.2$. As is displayed that there are mainly 3 region peeled by cavitation structures. Region 1 is the most severe part and the peeled area appears in conterminous, which means that this region is in high erosion risk. In this paper, it is assumed that cavitation erosion was caused by the collapse of micro bubbles, regardless of whether the impulse pressure was generated by micro jet or shock wave. From the cavitation appearance depicted in figure 4 and figure 5, we can see that this region is corresponding to the unsteady part of sheet cavitation where the cloud cavitation comes into being. Comparing cavitation structure directly with paint loss area (Seen in figure 8), we can see that the rear part of sheet cavitation coincides well with the region where paint loss is the most severe. It can be imaged that in this region the cavitation cloud has just been generated from the break of cavitation sheet, so that large numbers of micro bubbles abound here. The adequate bubbles could provide abundant collapse, which subsequently supplies enough impingement to peel the coating on the wall.

Besides the rear part of sheet cavitation, another two coating peeled regions (Region 2 and Region3) can be found on the surface of hydrofoil. These two region corresponds to the area where the two legs of U-shaped vortex pass (Shown in figure 9). This area is much smaller than Region1 and the peeled parts occur as isolated spots which can be seen more clearly in the partial enlarged view in figure 10. It means that region 2 and region 3 are also erosion risk area but the risk is much smaller than region 1.

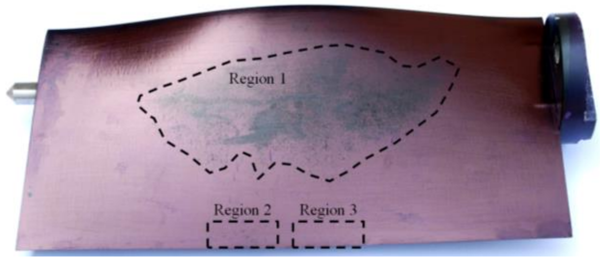

Figure 7 The surface coating status after 3 hour’s test.

($U = 14m/s$, $\sigma = 1.2$)

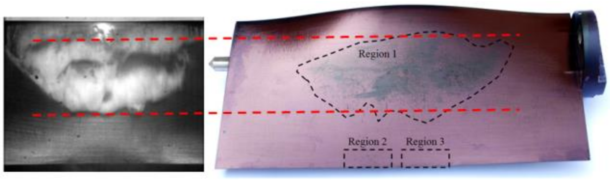

Figure 8 Comparison of cavitation structure and erosion region shown by paint loss. ($U = 14m/s$, $\sigma = 1.2$)

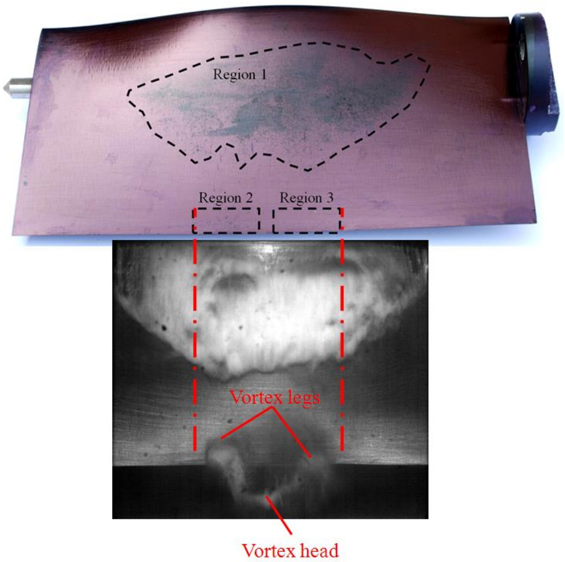

Figure 9 Comparison of cavitation structure and erosion region shown by paint loss. ($U = 14m/s$, $\sigma = 1.2$)

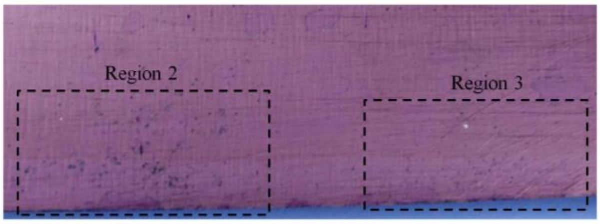

Figure 10 Partial enlarged view of surface condition after 3 hour's test. ($U=14m/s$, $\sigma=1.2$)

In summary, the relationship between cavitation structure and erosion region can be interpreted as follows: For large scale shedding cavitation around a 3D hydrofoil, the unsteady rear part of sheet cavitation is the most erosive structure, and the corresponding region is the high erosion risk region. The route where the U-shaped vortex structure evolved from cavitation cloud passes can also be erosion risk region, but the erosion strength is much weaker than that of unsteady sheet region. With these recognizations, it may be possible to predict the erosion regions and damage extent qualitatively just by the cavitation behavior.

These analysis was confirmed by another test condition $U=14m/s$, $\sigma=1.3$, at which the cavitation evolution process was very similar to last case described above. Figure 11 and figure 12 show the surface coating status before and after test respectively. The paint loss area could also be divided into 3 region, which agrees well with that of last case. This confirms that such kind of cavitating flows may share the same erosion mechanism.

Figure 11 The surface coating status before test. ($U=14m/s$, $\sigma=1.3$)

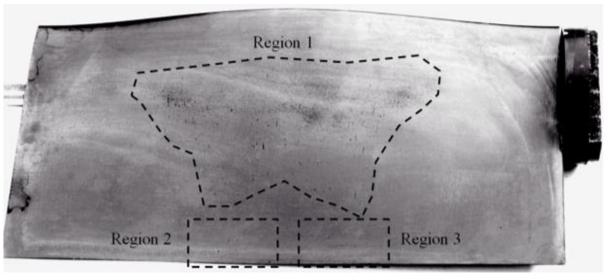

Figure 12 The surface coating status after 3 hour's test. ($U=14m/s$, $\sigma=1.3$)

3.3 The Role of U-shaped Vortex in Erosion

The evolution of U-shaped vortex was a reflection of inherent vortex properties. Under the domination of vortex kinematic and dynamic property, the cavitation cloud shedding from cavitation sheet attached on the surface of hydrofoil developed into a U-shaped vortex. The head of this vortex tended to depart from the hydrofoil surface while the two legs of this vortex were both absorbed on the wall. With the assumption that cavitation erosion was due to the collapse of micro bubbles, three role of U-shaped vortex could be interpreted from its particular spacial structure according to the experimental results describe above.

(1) Broaden the range of erosion risk region. Imaging that the cavitation cloud shedding from cavitation sheet is composed of masses of micro bubbles, the rotating effect of vortex can concentrate bubbles to the center of vortex core. It can be guessed that this concentration effect could gather the damage power of scattered collapse, which could maintain the erosion strength of this cloudy structure in a longer distance. As the micro bubbles collapse continuously while traveling and concentrating, all of the passing regions of U-shaped vortex might encounter erosion risk. Of course, this risk becomes weaker and weaker since the number of bubbles contained in the vortex drops continually while travelling downstream due to the collapse(As is shown in figure 4 and figure 5 ④-⑥). Therefore, the existence of U-shaped vortex could broaden the range of erosion risk region, but the risk lowers while the cloud travelling downstream along with incoming flow.

(2) Intensify the local aggressiveness of cloud cavitation. As is described above, U-shaped vortex can concentrate bubbles to the center of vortex core, thus enhances the local collapse density at the hydrofoil surface where the two vortex legs attach. Therefore, the local aggressiveness of cloud cavitation is intensified because of the two legs of U-shaped vortex are both absorbed on the wall (Shown in figure 4 and figure 5 ④-⑥).

(3) Weaken the whole aggressiveness of cloud cavitation. The cloud cavitation's damage capibility to the wall is related to the local collapse intensity and the collapse distance from the wall. As the head of U-shaped vortex tends to depart from the hydrofoil surface, the distance from the collapse spot to the wall of this part is enlarged. Hence the aggressiveness of the vortex head part is weakened.

As is illustrated above, it seems that the U-shaped vortex just act as the muscle to cloud cavitation governing the motion of micro bubble clusters. The erosion was probably caused by the collapse of micro bubbles and the occurrence of U-shaped vortex just changes the whole distribution of micro bubbles.

4 CONCLUSIONS

This paper mainly introduces the recent experimental study of cloud cavitation erosion in CSSRC. Combining high speed video and painting method, the relationship between cavitation structure and cavitation erosion was evaluated. It is revealed that the most erosive cavitation structure in cloud cavitation evolution is the unsteady rear part of sheet cavitation. The U-shaped vortex structure can also be erosive but contains much less damage power. In addition, the U-shaped vortex could be supposed to be the muscle of cavitation cloud, governing the motion of micro bubble clusters. Three function of U-shaped vortex in cavitation erosion was surmised from its particular spacial structure.

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DISCUSSION

Questions from Rickard Bensow

Wavelet is a very powerful technique for the analysis of such problems. Is the use of wavelets in your plans for future works?

1. Is the foil scale similar to the Twist11 foil that was tested at Delft?

2. Did you apply any leading edge roughness?

3. Did you do any simultaneous pressure pulse or noise measurements that could be correlated to collapse events?

Author's closure

1. Yes, the foil scale is similar to the Twist11 foil that was tested at Delft. The geometry is the same and the only difference is the chord length to match with the test section of our cavitation tunnel.

2. No, we didn't.

3. No, we didn't. But this is a good way on the analysis of collapse events, which we had intended to do but not done yet.