U-shaped Vortex Structures in Large Scale Cloud Cavitation

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Abstract. The control of cloud cavitation, especially large scale cloud cavitation (LSCC), is always a hot issue in the field of cavitation research. However, there has been little knowledge on the evolution of cloud cavitation since it is associated with turbulence and vortex flow. In this article, the structure of cloud cavitation shed by sheet cavitation around different hydrofoils and a wedge were observed in detail with high speed camera (HSC). It was found that the U-shaped vortex structures always existed in the development process of LSCC. The results indicated that LSCC evolution was related to this kind of vortex structures, and it may be a universal character for LSCC. Then vortex strength of U-shaped vortex structures in a cycle was analyzed with numerical results.

1. Introduction
Cloud cavitation, named from its appearance that looks like a cloud, can be seen in many cavitating flows. Usually there are two main type of cloud cavitation, one generates from sheet cavitation shedding and exits downstream of sheet cavity, another results from vortex cavitation and occur downstream of vortex cavity. Here we refer cloud cavitation to the former one. Conventionally, cloud cavitation is not appreciated in hydraulic machines, propellers and water conservancy facilities for the undesirable effect coming with it, such as vibration, noise and even cavitation erosion. Consequently, much attention has been paid on it, as seen in the former researches. Among them, a U-shaped structure in the development of cloud cavitation has been reported by different researchers[1-3]. However, few analysis have been focused on whether it is a unique or a universal phenomenon. More detailed study may do a great help in the understanding of cloud cavitation and offering available suggestions on evaluation of cavitation erosion or its control.

In this article, cloud cavitation on different hydrofoils and a wedge were visualized by HSC. To make the special structure more clearly to see, the lens of HSC was put in back side (for the hydrofoils) or front side (for the wedge) of the tested models. Then numerical simulation on one of the hydrofoils was done to help to analyse this phenomenon.

2. Experimental results
The experiment was conducted in cavitation mechanism tunnel located in China Ship Scientific Research Center (CSSRC). Firstly NACA16012 3D twisted hydrofoil (attack angle varies spanwise but has constant chord length) was tested in different install angles and different incoming velocities, as well as different cavitation numbers. With steady and homogeneous incoming flow, LSCC shows

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periodic characteristics: Sheet cavitation forms on the leading edge of foil, then begin to grow until reach its maximum length; simultaneously re-entrant and side-entrant flow at the bottom of sheet cavitation move forward to the leading edge direction. When the reverse flow impinges on the surface of vapour sheet, the rear part of sheet structure starts to shed from the main structure and convect downstream. In this stage, the shedding sheet evolves into a cloud and become a distinct U-shaped structure eventually. Figure 1 is one example of the results, which clearly indicate that the cloud cavitation shed from the sheet cavitation is not simply a water and vapour mixed cloud, it is actually an distinct and inerratic U-shaped vortex structure ( red arrowhead denotes flow direction).

To understand U-shaped vortex structure is an occasional case on a special hydrofoil or a general phenomenon applicable to other cases, other test models are also observed. Figure 2 shows LSCC structures on a 3D NACA0012 straight hydrofoil (constant attack angle and constant chord length in spanwise). Figure 3 shows LSCC in a nonvertical (not vertical to the leading edge) incoming flow around a hydrofoil with chord length varied but attack angle fixed in spanwise, which is similar to the flow condition of a propeller. It seems that cavitation induced by this model has no difference with that on straight hydrofoil. Figure 4 is the appearance of LSCC on a wedge which may occur in many water conservancy facilities. U-shaped structures can also be seen in this flow condition, moreover, multi-U-shaped structures interact with each other and develop into complicated vortex groups or clusters.

Figure 1. U-shaped vortex structure around twisted hydrofoils. \( \alpha = 0^\circ, V = 14 \text{ m/s}, \sigma = 1.0 \)

Figure 2. U-shaped vortex structure on straight hydrofoils. \( \alpha = 8^\circ, V = 7 \text{ m/s}, \sigma = 1.8 \)

Figure 3. U-shaped vortex structure around a hydrofoil in nonvertical incoming flow. \( \alpha = 6^\circ, V = 7 \text{ m/s}, \sigma = 0.85 \)

Figure 4. Cloud cavitation around a wedge. \( \alpha = 0^\circ, V = 7 \text{ m/s}, \sigma = 2.0 \)

According to the results above, it can be convinced that U-shaped vortex structure is prevalent in large scale cloud cavitating flows which may exhibit a little difference on different models and in different conditions. Thereby it might be possible to assess the cavitation erosion intensity by the vortex strength of U-shaped structures with some other parameters, such as shedding frequency, nuclei density and its distribution, in the future work. Then investigation of vortex strength in the
The development of cloud cavitation is of great significance for the moment. Hence numerical simulation of cloud cavitation around NACA16012 3D twisted hydrofoil was done to illustrate the vortex strength during the evolution process.

3. Numerical results and discussions

Among the tested models, a 3D twisted hydrofoil (NACA16012) was selected to be calculated for the relatively simple cloud cavitation structure on it as mentioned above. In the calculation, mixture model was employed to simulate multiphase flow, considering the mixture is composed of water and vapour with non-slip velocity. Large eddy simulation was introduced to model the turbulent flow.

Figure 5 gives numerical results of cloud cavitation evolution around the 3D twisted hydrofoil at $\sigma = 1.0$ with $V = 14\text{ m/s}$ and chord length $c = 0.1\text{ m}$. Left one shows the isosurface of volume fraction 0.1 and right one shows the corresponding isosurface of Q criterion, $Q=2.5 \times 10^5$. It can be seen that the calculation result is quite similar to the experimental appearance (seen in Figure1), showing that numerical methods employed in this work can capture the main features of cloud cavitation. Furthermore, the vapor structures coincide well with vortex structures distinguished by Q criterion, illuminating that cloud cavitation evolution is related to vortex structures, and the development of this cavitation cloud might be dominated by the U-shaped vortex.

To estimate the strength of vortex of the U-shaped vortex structure we simply calculated it from velocity field in the middle span. Then velocity circulation $\Gamma$ around the U-shaped vortex section is obtained which denotes the strength of this U-shaped vortex, shown in Figure 6. It can be seen that the strength of U-shaped vortex damps when convected downstream which matches well with the experimental observation that the U-shaped structure disappears downstream. Though numerical dissipation may play a role in this process, it is a reflection of inherent physical principle that the vortex dissipate due to viscosity during transportation.

Figure 6. Normalized vortex strength (velocity circulation) in a cycle
To establish a relationship between the flow parameters and the vortex strength, an attempt was taken considering the free-stream velocity $U$ and maximum length of sheet cavitation $L_{max}$. Then we can acquire the maximum vortex strength $\Gamma_{\text{theoretical}}$ evaluated by the hypothesis that cloud cavitation is a result of sheet cavitation shedding in which re-entrant flow beneath the cavity sheet plays a critical role. Based on Pham et al.’s (1999) research, velocity of re-entrant jet beneath the cavity is the same order of magnitude as the free-stream. With the suppose that velocity on the surface of sheet cavity is equal to the incoming flow, the maximum vortex strength of U-shaped structure can be written as,

$$\Gamma_{\text{theoretical}} = 2VL_{\text{max}}$$

Compare the velocity circulation calculated numerically at the instance of maximum sheet length with this theoretical value, it is found that they are in the same magnitude order which numerically confirms that maximum vortex strength could be assessed by free-stream velocity and maximum length of sheet cavity qualitatively. The data in Figure 6 is normalized with free-stream velocity $V$ and chord length $c$. According to this result, it might be possible to evaluate the maximum vortex strength with incoming flow velocity and maximum cavity length. This provides probability to assess the erosion intensity in a vortex approach with some other parameters.

4. Conclusions

Cloud cavitation is a complicated cavitation type that exhibits strong instability and unsteadiness, which can bring a series of erosive effects. However its generation and evolution mechanism is still not clear at present. In this article our emphasis was put on the developing process of LSCC with experimental and numerical approaches, attempting to achieve some universal mechanisms. Firstly LSCC on diverse models was observed by HSC in experiment, then numerical analysis was conducted on a NACA16012 3D twisted hydrofoil. Some suggestions can be obtained from our present investigation:

(1) LSCC evolution is related to vortex structures which generally appear in U-shaped forms. It is convinced in the experiment that U-shaped structures existed in large scale cloud cavitating flow may be a general phenomenon despite the models and flow conditions. The evolution of cavitation cloud is governed by this kind of U-shaped vortex structures.

(2) Maximum strength of U-shaped vortex might be evaluated from the flow parameters. Vortex strength in a cycle was obtained from numerical calculation showing that its maximum value corresponds to that evaluated by theoretical analysis which can provide an access to assess the maximum vortex strength.

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