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The effect of water quality on tip vortex cavitation inception *

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Abstract: The inception of tip vortex cavitation is very sensitive to water quality. In order to quantify the effect of water quality on the inception of tip vortex cavitation, we develop a motion model to describe the migration and growth of nuclei in water. An analytical solution of migration of nuclei in a vortex flow is obtained so that the capture times of various nuclei can be given out directly. A criterion is built to determine the critical nucleus in a certain nuclei spectra distribution. Tensile strength of the critical nucleus is used to quantify the effect of water quality and correct the tip vortex cavitation inception number. Finally this change of cavitation inception number is compared with experimental results to validate our model.

Key words: Water quality, cavitation inception, capture time, tensile strength

Introduction

Tip vortex cavitation is one of important cavitation types on marine propeller and hydraulic machinery. Compared with the wet flow, tip vortex cavitation can cause significant noise and extra vibration[1-3]. Trying to accurately predict the occurrence of tip vortex cavitation (TVC), many researchers studied the effects of flow parameters on the inception of TVC, and proposed a classic formula to predict the inception cavitation number. However, the inception of TVC is very sensitive to the water quality, leading to the big uncertainty in predicting the inception. Up to now, the quantitative effect of water quality on the inception of TVC is still unclear. Trying to avoid the occurrence of tip vortex cavitation, accurate prediction of tip vortex cavitaion inception is a pressing need in engineering.

Previously, Ardnt et al.[4], Stinebring et al.[5] and Fruman and Dugue[6] studied the features of the flow field around the tips of 3-D hydrofoils. Flows of tip vortex cavitation were observed and measured including inception cavitation number at various angles of attack and Reynolds number. Before the appearance of cavitation, some kinds of ideal vortex models such as Rankine vortex can describe the vortical flows with two main parameters, vortex intensity and vortex core radius. They[7,8] found that strengths of tip vortex mainly depend on circulation and have a positive correlation with lift coefficient of foils. They also found vortex core radius of tip vortex is in connection with thickness of boundary layer of foils which is related to the Reynolds number. Tip vortex cavitation often occurs at vortex center firstly, so vortex model can provide lowest pressure at vortex center to determine whether it has reached the critical condition for cavitation. On the basis of these studies, a prediction model of inception of tip vortex cavitation is established[9]

$$\sigma_i = KC_L^2 Re^m \tag{1}$$

where σ_i is tip vortex cavitation inception number, K is an empirical coefficient, C_L is lift coefficient,

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Re is Reynolds number and $m = 0.4$. Apparently this prediction model can judge theoretically whether tip vortex cavitation occurs, for which tip vortex cavitation inception index can be derived from flow parameters directly. On the other hand, this prediction model is also the theoretical basis to extrapolate results of model experiments to full-scale. However, this prediction model is found in many following studies[10,11] to be short of universality.

Up to now, researchers agree that water quality also has an important effect on tip vortex cavitation inception[1,12]. In most cases, lowest pressure in water reaching the saturated vapor pressure will not immediately lead to cavitation. The critical pressure for tip vortex cavitation is always lower than saturated vapor pressure especially when the size of free stream nuclei is small. As we know, for cavitation experiments in tunnels the content must be depressurized and from which most gas be eliminated first, and the size of nuclei in water must be small. Actually hydrofoils work in natural water, such as sea, containing a great number of nuclei. Obviously, a significant difference of water quality exists between these two conditions. The effect of water quality should be evaluated accurately to avoid dilemma of extrapolation of model experiments to full-scale. But the effect of water quality has been expressed in the providing prediction model since this model considers the vortical flows only. Unfortunately there is a lack of appropriate methods to quantitatively evaluate the effect of water quality until today[13]. Even though macro cavitation model is widely used in the study of many cavitation phenomena, it is not suitable for tip vortex cavitation inception due to the effect of water quality had not been considered by all existing cavitation model[14-16]. Therefore, it is urgent to develop a theory and model suitable for prediction of tip vortex cavitation inception.

Presently experimental and numerical methods in addition to theory of bubble dynamics can be employed to study nuclei. In the experiments, to get nuclei population requires accurate measuring technology, such as holography, laser interferometric imaging[17] and a Venturi approach. In general, these methods enable us to count smallest nuclei in micron scale. Based on bubble dynamics, critical pressure below which a nucleus will grow explosively of every nucleus can be obtained. For water with nuclei in only one size, it means the effect of water quality can be quantified by tensile strength of a nucleus. According to nuclei spectrum, nuclei distribute in a large scale range with different population in real water. In recent years, Hsiao and Chahine[18,19], park et al.[20] numerically studied the movement of nuclei in vortical flows. Zhang et al.[21] summarized these researches. In order to promote further understanding of the characteristic of motion of nuclei, Zhang et al.[21], Oweis et al.[22], Cui et al.[23], have performed theoretical analysis and numerical simulation for trajectory and capture time of nuclei in ideal vortex models. Outside the vortex core, Oweis got the capture time of nuclei analytically ignoring radial acceleration. The results differ a lot from simulations. Inside the vortex core, Zhang et al. got the capture time of nuclei in the vortex core. Even though their results have a satisfying agreement compared with simulation, the form of solution is complicated. A complete and concise theory to describe the motion of nuclei in the whole vortex still lacks.

In the present work, firstly we have a theoretical analysis of motion of nuclei in an ideal vortex-Rankine vortex. By simplification, a complete and concise solution for the positions of nuclei in the vortex changes over time is presented. In other words, capture time of every nucleus can be calculated from the solution directly. Numerical simulation is employed to validate the effectiveness. According to the experimental data[24] provided by our cooperator, China Ship Scientific Research Center, we can get vortex circulation Γ and vortex core size r_c to describe the vortical flow by Rankine vortex model. Nuclei are distributed in this flow based on nuclei spectrum measured in the experiment. Now we can get the capture time of these nuclei quickly with theoretical solution. The nucleus that will grow explosively first is selected according to certain filter condition. Further, tensile strength of this nucleus will be used to quantify the effect of water quality and correct the tip vortex cavitation inception number. Finally we compare this change of cavitation inception number with experimental results to validate the whole procedure.

1. Mathematical model

1.1 *Rankine vortex model*

The ideal Rankine vortex model with vortex circulation Γ and vortex core size r_c describes the vortical flow, i.e., tangential velocity and pressure are as follows:

$$u_\theta = \frac{\Gamma}{2\pi r_c^2} r \ (r \le r_c) \tag{2a}$$

$$u_\theta = \frac{\Gamma}{2\pi r} r \ (r > r_c) \tag{2b}$$

$$p(r) = p_\infty - \frac{\rho\Gamma^2}{4\pi^2 r_c^2} + \frac{\rho\Gamma^2 r^2}{4\pi^2 r_c^4} \quad (r \le r_c) \tag{3a}$$

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