The Study of Tip Vortex Flow and Cavitation Inception on an Elliptical Hydrofoil*

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ABSTRACT

Tip vortex cavitation (TVC) is an important cavitation phenomenon in marine propeller. The prediction of tip vortex cavitation inception is hot topics consistently both in engineering application and mechanism research. In this paper some recent experiment results on tip vortex cavitation are presented. The tests were carried out in Cavitation Mechanism Tunnel of China Ship Scientific Research Center. One of the features of the tunnel is the air content and nuclei distributions can be controlled independently. LDV was adopted to obtain the information of tip vortex flow field, such as the vortex core radius, circulation as well as the velocity fluctuation around the vortex core. High speed video observation and acoustic measurement method are used to determine the incipient cavitation (desinent cavitation). The relations among the cavitation inception index and Reynolds number, lift coefficient, pressure fluctuation in the core, air content of test water and nuclei distribution, were analyzed. A new prediction formula for tip vortex cavitation inception is proposed.

Keywords

Tip vortex flow, cavitation inception, scale effect

1 INTRODUCTION

For the designer of naval and merchant ships cavitation is always a major concern because it induces hydrodynamic noise and vibration of marine propellers, as well as the potential of cavitation erosion. Among various kinds of cavitation tip vortex cavitation (TVC) begins in tip vortices and appears at lower ship speed than other forms of cavitation in the most cases. Therefore, prediction of tip vortex cavitation inception is very important to develop high performance and quiet propellers. However, up to now the full scale prediction of tip vortex cavitation inception still meets some difficulties as it has strong dependencies on Reynolds number and water quality. The mechanism of these effects is also not well understood.

Many researchers has been studied the effect of Reynolds number on tip vortex cavitation inception[1-5]. McCormick [1] found that cavitation inception number decreased with a power of Reynolds number, Re^n, and suggested n=0.35. But the different values of n were proposed by other researchers [2-4]. In the paper of Shen et.al.,[2] new scaling formula based on friction factors of boundary layers showed that the "n" is a function of Reynolds number.

The effect of water quality, especially the nuclei distribution on tip vortex cavitation inception also was studied by various researchers [5-8]. The 21st ITTC cavitation committee [5] showed the strong influences of nuclei distributions on tip vortex cavitation inception. Briancon-Marjollet and Merle [7] carried out a series of experiments on tip vortex cavitation with an elliptical hydrofoil. They showed that McCormick's scaling formula is applicable when tensile strength of water is taken into account. Nagaya et.al [9] studied experimentally the effect of Reynolds number and water quality on tip vortex cavitation with some elliptical hydrofoils of various chord lengths. They found the values of n to be $0.2 < n < 0.4$ for α=4deg but in the case of large angle of attack α=10 deg, the value of n showed larger scatter.

Franc and Michel [10] describes the mechanism of TVC inception in their textbook. In a classical wing theory, the circulation distribution along spanwise direction makes a vorticity sheet from a hydrofoil trailing edge and then the vorticity is eventually rolled-up around a primary tip vortex from a hydrofoil tip. In other words, the circulation around a primary tip vortex increases gradually in downstream. Moreover, the line vortex from a hydrofoil has a viscous core at its center. Fundamentally, the thickness of this viscous core is governed by a boundary layer thickness on a foil tip. Those two parameters, circulation strength and a viscous core size, govern a minimum static pressure in a vortex core.

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In the present study, an elliptical hydrofoil was tested in cavitation tunnel. LDV was adopted to obtain the information of tip vortex flow field. High speed video observation and acoustic measurement method are used to determine the desinent cavitation with different attack angles, different incoming flow velocities, different air content and different nuclei distributions. Nuclei distributions were measured by interferometric laser imaging system.

2 EXPERIMENTAL SETUP

Experiments were conducted in cavitation mechanism tunnel of China Ship Scientific Research Center (CSSRC) as shown in Fig.1. The tunnel has two exchangeable test sections of circular and square respectively. In present study the test section with a square cross section was used. The size of test section is 1600mm (L) × 225mm (W) × 225mm (H) and maximum incoming velocity can be up to 25m/s. The contraction ratio is 12.61 and the turbulence level of incoming flow is less than 0.5%.

Figure 1. Cavitation mechanism tunnel in CSSRC

The tunnel is constructed with stainless steel and holds about 80 m3 of water. There are some water quality control systems in the tunnel. Filtration system can wipe off the solid particles up to 10 micron and improve the transparency of the water. Fast degassing device using the ideal of “diffusion nuclei” can control the air content of water. The tunnel also equipped a nuclei seeding system to simulate the nuclei distributions. The nuclei were seeded by injection array of supersaturation water that contains 7 x 7 injectors installed in the upstream of test section as shown in Fig. 2. The large degassing tank is installed following the diffuser and the free gas created in the test section will be escaped from the free surface of the tank through the several rows of screens and honeycombs inside the tank.

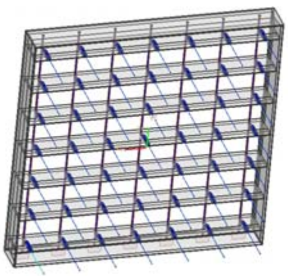

Figure 2. Sketch diagram of injection array in nuclei seeding system

The elliptic hydrofoil with section NACA 66_2-415 was chosen as test model shown in Fig.3. The maximum chord and half span of the model are 94.2mm and 112.5mm respectively. The model was installed in the horizontal centre of test section while the suction surface of hydrofoil is in the bottom and the tip of the elliptic hydrofoil is in the centreline of test section. A mechanism was designed to support the model and adjust the attack angle of the hydrofoil with precision 0.1^{o}. A high-speed video (HSV) camera, Photron APX with resolution 2048 ×2048 pixels and 3000fps, was set in the bottom of test section to visualize the inception and development of tip vortex cavitation, while a LED lamp as the source of light. A hydrophone of B&K 8103 was installed in side window with a cup filled with water. The arrangement of the experiment was shown in Fig.4.

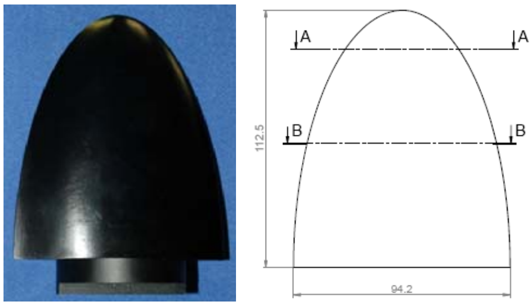

Figure 3. Elliptic hydrofoil NACA66_2-415

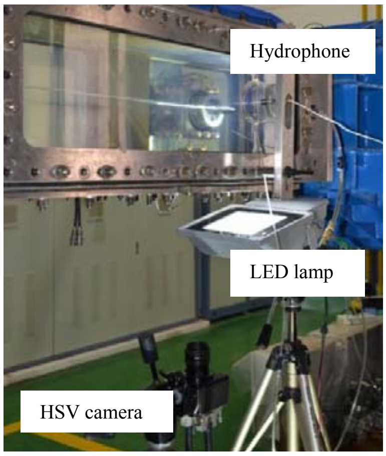

Figure 4. Set-up of the experiments

The air content of water was measured by dissolved oxygen meter and expressed as DO, which is the relative dissolved oxygen to the saturation case. Nuclei distribution was measured by interferometric laser imaging method. The fundamental principle of the method is when laser sheet goes through the gas bubble in water the interference pattern is formed by scattering lights of incident light on the bubble surface and circular image with fringes show on the defocused plane of camera, as shown in Fig.5. The numbers and diameters of nuclei can be obtained by counting the number of circular images and fringes respectively in the each bubble images. Interferometric laser imaging system includes laser, lens and CCD camera. The laser type is Quantel Twins Brilliant B and laser sheet is produced by cylindrical lens with -15mm focus and convex lens with 500mm focus. CCD camera type is TSI630159 and lens is Nikon AF Nikkor 50mm f/1.8D with 1600×1200pixel resolution.

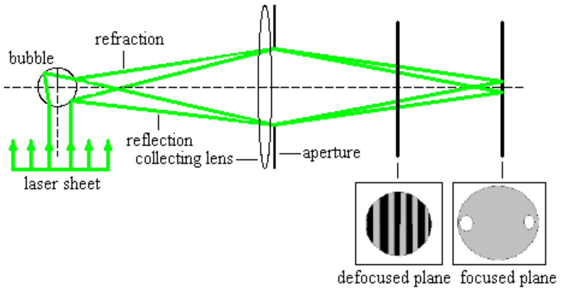

Figure 5. Sketch principle of interferometric laser imaging

3 FEATURES OF TIP VORTEX FLOWS

LDV was used to measure the vortex flow field downstream the tip of the hydrofoil model. The positions of vortex centres were estimated by very weak vortex caviation first. The velocity distributions along the vertical direction including the vortex centre were measured. Fig.6 shows an example of the measurement results. The axial velocities are presented by black dots while the tangential velocities are shown by red ones. Form the result the vortex core radius and velocity circulation around the vortex can be estimated.

To compare the effect of incoming flows on the vortex structures, two incoming velocities, 5m/s and 13m/s, were measured by LDV. Ten velocity distributions like Fig.6 along the flow direction were obtained in each incoming flow. The vortex core radius and velocity circulation around the vortex were estimated as shown in Fig.7 and 8 respectively.

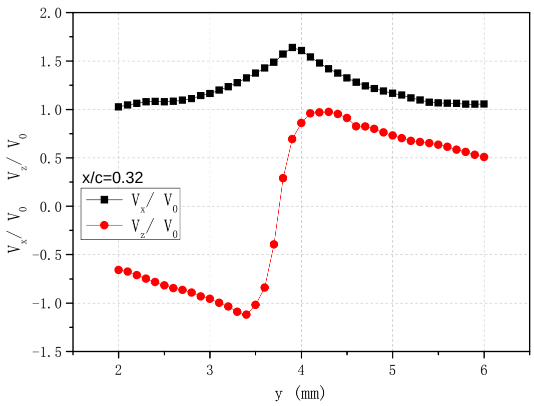

Figure 6: Velocities distribution around the tip vortex (Vo=13m/s, x/c=0.32)

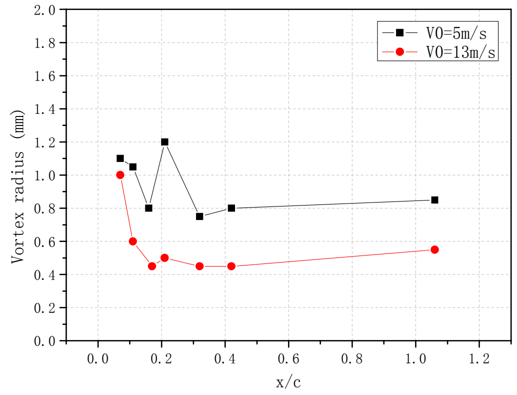

Figure 7. Vortex radius vs downstream distance from tip point

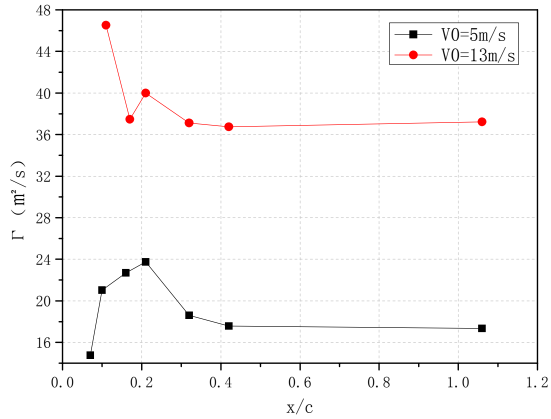

Figure 8: Velocity circulation vs downstream distance from tip point

The results propose there is a tip vortex formation range just downstream the tip point, where the vortex radius and circulation present somewhat oscillation. For the lower velocity the vortex formation distance is longer than the case of higher velocity. But in the both cases the tip vortex can be keep quite long with consistent vortex radius and circulation. Generally, the radius is larger and the circulation is smaller with the lower incoming speed, which means in higher incoming velocity the vortex intensity is larger and the core pressure is lower than the case of lower incoming velocity. Form the view of tip vortex cavitation inception in the lower incoming velocity the nuclei have loner time to development to cavitation but easy to form the gaseous cavitation, while in the case of higher velocity the lower pressure in the vortex can easier to induce the vapour cavitation.

Pressure fluctuation is considered an important factor to influent the cavitation inception. As pressure fluctuation is difficult to obtain from the experiment in this moment, velocity fluctuation is analyzed form the LDV measurement results. Turbulent fluctuation intensity is chosen to present the velocity fluctuation, it's defined as:

$$k = \frac{1}{2}\left(V_x'^2 + V_z'^2\right)$$

Fig. 9 shows the results of turbulent fluctuation intensity around the vortex core with different section of flow positions in two incoming velocities. It can be seen that the fluctuation intensity in the vortex core for the higher incoming velocity is much larger than the lower incoming velocity. The results are suggested that the pressure fluctuation should be considered in the tip vortex cavitation inception, especially in the case of high velocity.

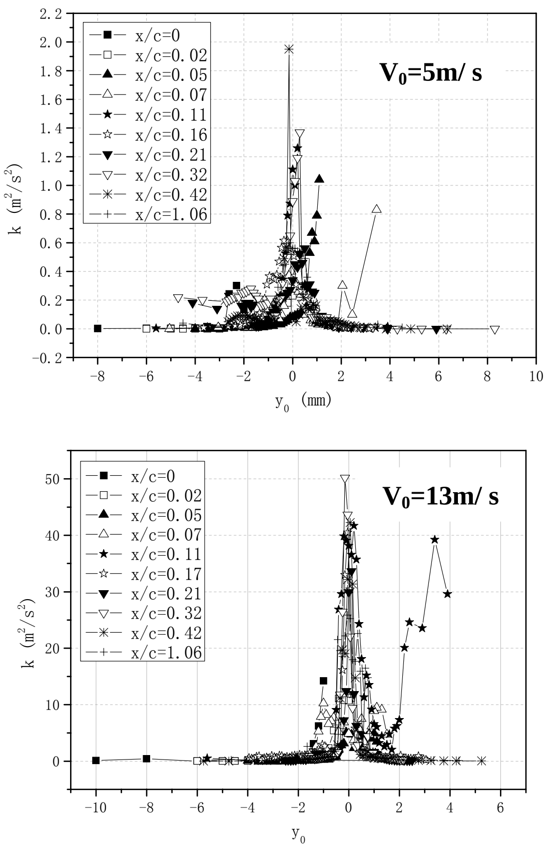

Figure 9: Turbulent fluctuation intensity around the tip vortex

4 CAVITATION INCEPTION OF TIP VORTEX

In the present study desinent cavitation index was used to study the tip vortex cavitation inception. In the experiments development of TVC was achieved first in each incoming velocity then increase the pressure of the tunnel gradually until the cavitation disappeared. The desinent cavitation was mainly determined by observation with high-speed video camera and complementally with acoustical measurement.

4.1 Two Forms of Tip Vortex Cavitation Inception

Generally cavitation inception occurs when a bubble is trapped in to the low-pressure region located in the center of the vortex from the tip of a hydrofoil. Two forms of tip vortex cavitation inception were observed in our experiments based on different flow conditions and water qualities, as shown in Fig .10 and 11.

In the case of high incoming velocity and large attack angle of hydrofoil, cavitation often appeared suddenly in the vortex core just downstream of tip point and shows as cavitation line (see Fig.10). But in the case of low incoming velocity and small attack angle of hydrofoil, there often showed the single bubble cavitating in the cortex core (see Fig.11). It should be pointed out that the dots in the Fig.11 was just one bubble in time series demonstrated one bubble travels from upstream to downstream and cavitates in the location showed in ①. The results proposed the nuclei population might be stronger effect for the case of low incoming velocity and small attack angle of hydrofoil. In this case the uncertainty of tip vortex cavitation inception may increase.

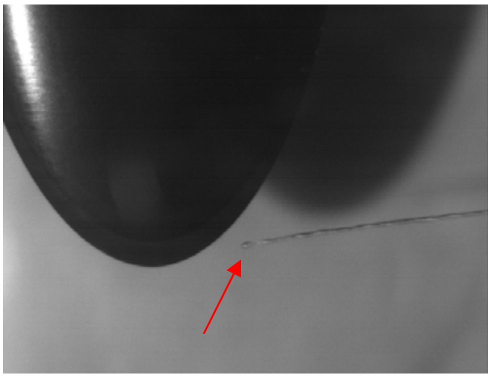

Figure 10: Form of tip vortex cavitation inception in high incoming velocity

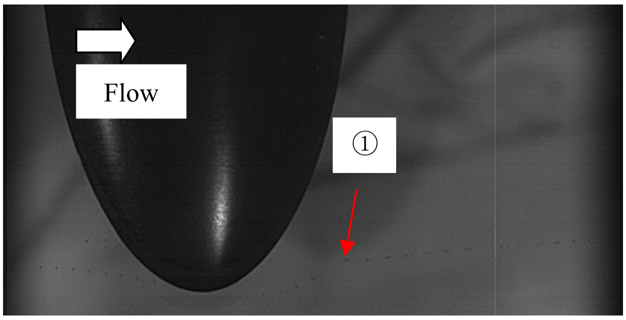

Figure 11: Form of tip vortex cavitation inception in low incoming velocity

4.2 Effect of Reynolds Number

The effect of Reynolds number was tested in attack angle θ=7° with different incoming velocities and different air contents. The results show in Fig.12, where DO presents the relative air content measured by dissolved oxygen meter. The results show that Reynolds number has great effect on tip vortex cavitation inception when the air content of water is higher, especially in the lower Reynolds number. The tendency of the effect of Reynolds number is totally different with different air contents. In the case of very low air content the TVC inception almost not affected by the Reynolds number. In the medium air content the influence of Reynolds number approximately obey the McCormick’s law but the index number should be smaller than McCormick’s formula. However, in the case of high air content the cavitation inception index even decrease with the increase of Reynolds number.

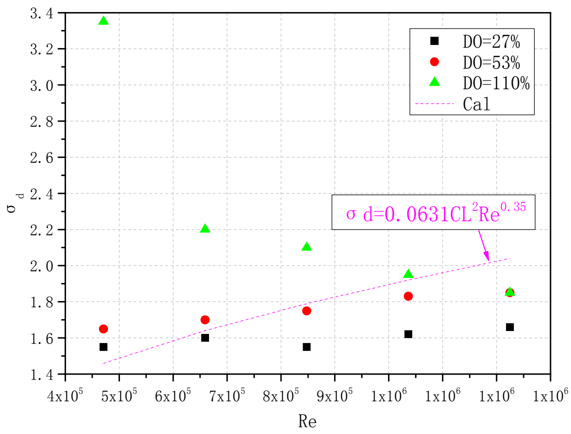

Figure 12: Effect of Reynolds Number on TVC inception

4.3 Effect of Lift Coefficient

In present study the TVC inceptions in different attack angles were tested. To establish the relation between the lift coefficient of the hydrofoil and its TVC inception the lift measurements in different attack angles were taken first. A balance with 3 components force was used, which the measuring range of lift is 500N with precision 0.2. The results show good linear relation between lift coefficient and attack angle as shown in Fig.13.

The effect of lift coefficient was tested in the case of incoming velocity 13m/s (Re=1.22×106) with different air contents and the results show in Fig.14. It can be seen that the tip vortex cavitation inception number is increase with the lift coefficient, and roughly shows square law. But the TVC inception number is larger in the higher air content than the lower one.

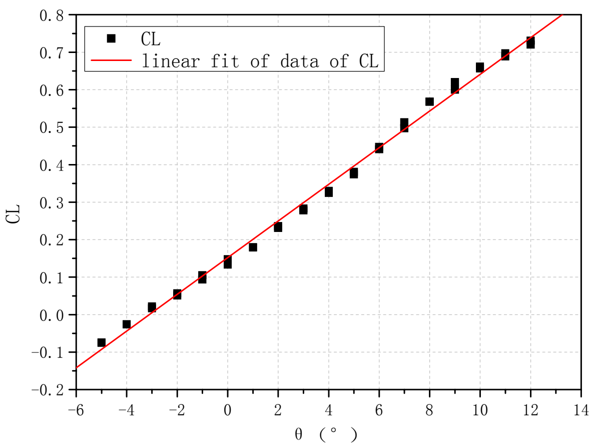

Figure 13: Measurement results of lift coefficient

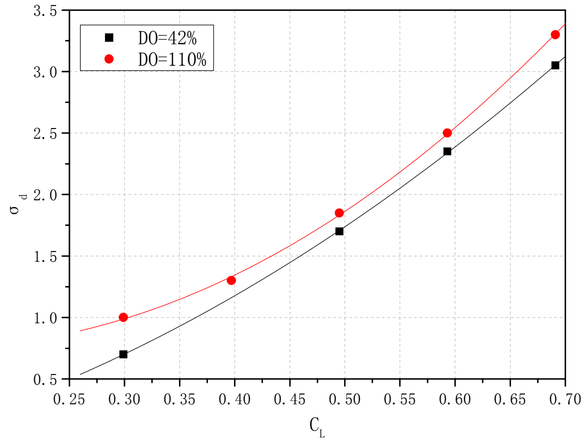

Figure 14: Effect of lift coefficient on TVC inception

4.4 Effect of water quality

Both the effect of air contents and nuclei populations on the tip vortex cavitation inception were studied experimentally. From the results shown in Fig.12 we can analyze the effect of air content on TVC inception. Generally the TVC inception number is increase with the increase of the air content, but the influence is weaker with the increase of Reynolds number. The reason may be that in the low velocity and high air content, there are more nuclei have longer time to travel in the low pressure and more influence of diffusion of dissolved air in water, so these nuclei is much more easy to developed to cavitation.

The effect of nuclei populations on the TVC inception was tested under three nuclei seeding conditions and compared with no nuclei seeding case. The nuclei measurement results showed the density of nuclei were 384.7 N/cm3, 520.3 N/cm3 and 615.5 N/cm3 respectively in the three seeding conditions and the sizes of nuclei mainly in the range of 30-60μm (see Fig.15). TVC Inception tests were taken in the air content D0=53% with different incoming velocities and the results shown in Fig.16. It can be seen that the TVC inception numbers are increase with the increase of nuclei density.

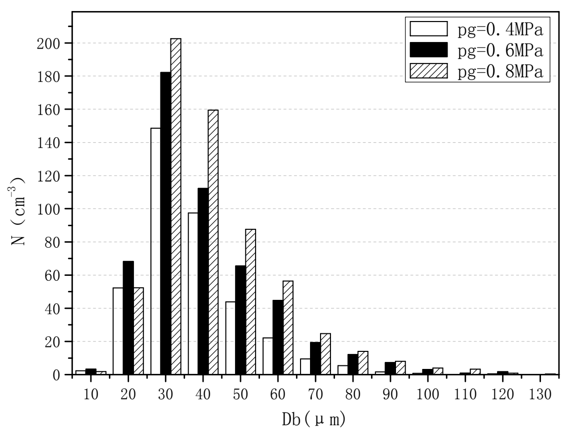

Figure 15: Nuclei spectrum in the three seeding conditions

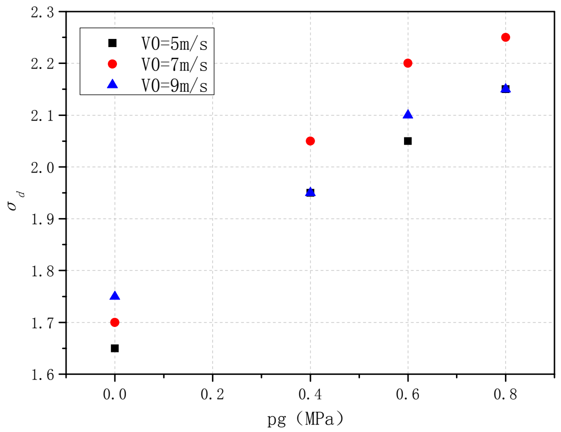

Figure 16: Effect of nuclei population on TVC inception

4.5 New prediction formula for tip vortex cavitation inception

Based on the view of tip vortex cavitation inception mechanism and the experiment results in present study there are three main factors to control the TVC inception, which are the mean pressure of vortex core, pressure fluctuation around the vortex core and the water quality. From the dimension analysis the following formula to predict the tip vortex cavitation inception was proposed.

$$\sigma_d = AC_L^2 \mathrm{Re}^m + B\mathrm{Re}^n + C\left[DO/Fr\right]^k$$

where the A, B, C, and m, n, k are the empirical constants. The three terms of this new formula are expected to present the effects of mean pressure of vortex core, pressure fluctuation around the vortex core and the water quality respectively. Considering the effect of nuclei populations is quite difficult to give a quantitative expression at this moment and it is also difficult to obtain in most of the application, only relative air content is involved in the formula.

The empirical constants in the new formula were obtained based on the present test data and an approximate relation for tip vortex cavitation inception can be proposed as:

$$\sigma_d = 0.042C_L^2 \mathrm{Re}^{0.35} + 0.012\mathrm{Re}^{0.25} + 80\left[DO/Fr\right]^{2.4}$$

5 CONCLUSIONS

The scale effect of tip vortex cavitation inception is very important but also difficult problem. It has been studied by many researchers for many years. In present paper we studied the effect of various factors on TVC inception, including Reynolds number, lift coefficient, air content of test water and nuclei distribution, also considered the influence of pressure fluctuation in the core. A new formula of scale effect to predict the tip vortex cavitation inception was proposed.

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