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A Simplified Method to Assess Cavitation Erosion on Marine Propellers and Its Application to Blade Section Design

Zhibo Zeng [1]*, Ziying Xiong [1], Zhengqing Dong [1] and Gongzheng Xin [1]
[1]National Key Laboratory on Ship Vibration & Noise, China Ship Scientific Research Center, Wuxi214082, China

Abstract: The paper presents a simplified method to assess cavitation erosion on marine propellers in a non-uniform wake field. It is realized by considering two-dimensional cavitation transition from sheet cavitation to cloud cavitation on each blade section with specified pressure distribution by Eppler method. Two dominant parameters: cavity thickness and adverse pressure gradient on a two-dimensional blade section in quasi-steady condition have been simplified with only a limited number of non-dimensional parameters, which results in a feasible way to assess the risk of cavitation erosion on a propeller blade passing a wake peak. Application of the method to blade section design of propeller shows to be effective. Extensive tests in a towing tank and a large cavitation channel in China(CLCC) validated the risk aversion of cavitation erosion with the very close open water efficiency.

Keywords: Cavitation erosion; cavity thickness; adverse pressure gradient, blade section.

1. Introduction

Cavitation is a key factor in marine propeller design for it brings about adverse effects such as erosion, vibration and noise. Traditionally the objective of propeller design for commercial ships was to obtain maximum efficiency, the resulting propeller has a distribution of high load and short chord length in the outer radial region, so that cavitation is unavoidable when the propeller is working in behind condition. It is necessary to assess the risk of cavitation erosion during the propeller optimization, however the available prediction on propeller cavitation and then assess the erosion is a challenge[1,2,3].

The origin of the erosion is cloud cavitation which forms in the leading edge of the blade section from the sheet cavitation. A propeller design method for maximum cavitation inception speed or minimum pressure fluctuations has been developed [4,5]. In case of cavitation inception calculation of the cavity can be avoided and an objective of the non-cavitating pressure distribution can be formulated: the minimum pressure on the blades during one revolution remains above the vapor pressure. In case of cavitation pressure fluctuation calculation of the cavity can be minimized and an objective can be formulated: the cavity volume variations related to the non-cavitating pressure distribution on the blades during one revolution remain in a lowest level. The question arises if a similar approach is possible to sustain cavitation stability for minimum risk of erosion. This also requires that the propeller is considered operating in a wake field and the onset of cavitation unstable behavior should be assessed.

Many efforts have been made to investigate the onset of cavitation unstable behavior and the corresponding control measures. Kawanami, Kato, et al.[6] investigated the generation mechanism of cloud cavitation with an obstacle fitted on the surface, they found it is the re-entrant jet that gives rise to the cloud cavitation. Franc[7] concluded the onset of partial cavity instability requires two main conditions: the large enough adverse pressure gradient at the closure of the cavity favorable to the development of the re-entrant jet and the thick enough cavity to limit the interaction between the re-entrant jet and the cavity interface. Duttweiler &Brennen [8] conducted experiments in cavitation tunnel to explore the onset of propeller cavity instability by two dimensionless parameters: the cavitation

*Corresponding Author: Zhibo Zeng, zbzeng80@163.com

number and the advance ratio. Keil, Pelz& Buttenbender[9] found the transition from sheet to cloud cavitation depends on both cavitation number and Reynolds number. On the basis of the mechanisms several measures have been developed to control the transition from sheet to cloud cavitation. Fujii, Kawakami, et al.[10] showed that foil thickness affects the strength of partial cavity oscillations. Amromin[11] designed a new hydrofoil by tuning the local pressure gradient in the region of cavity closure and analyzed the reduction of cavity oscillations in gust flows compared to conventional blade sections. Che, Chu, et al.[12] enhanced the control on cavitation dynamics by reduction in the height of the micro vortex generators installed close to the leading edge of a quasi-two-dimensional NACA0015 hydrofoil, especially with respect to the penetration depth of the re-entrant jet.

Since for a propeller in a wake, the relation between the dominant parameters of erosion and the working condition is nonlinear, the assessment has to be done many times while changing the propeller geometry. The simplified method in this paper includes the cavity thickness and the adverse pressure gradient in a wake. This approach is a continuation of the prediction procedure for sheet cavity volume by the first author[5], so some elements are re-used.

2. Cavity thickness and pressure gradient prediction

The risk assessment on cavitation erosion for a propeller blade is simplified by considering two-dimensional cavitation on each blade section, which is realized by the dominant parameters: the cavity thickness and the adverse pressure gradient at the closure of cavity. When a section passes a wake peak the cavitation will experience inception, development and disappearance with the rotating propeller blade position θ. The cavity area V_c, length L_c on a section can be calculated using CFD, then the mean thickness of cavity can be calculated by $T_c = V_c/L_c$ and the adverse pressure gradient at the closure can be interpolated from the fully wetted pressure distribution. But to carry out such a cavitation calculation on each section in a range of blade positions requires considerable computing time and this makes optimization impossible. Therefore an approximate method was developed to calculate the cavity thickness variations on the blades.

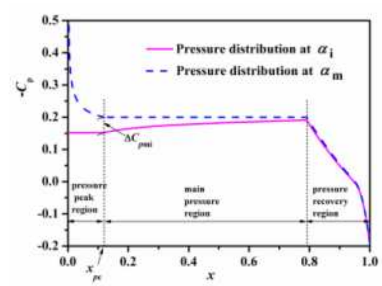


Figure 1. Pressure distributions on suction side of section

Usually a change in section geometry causes a corresponding change in cavity thickness at a given condition. The shape of sheet cavity on the suction side of a foil depends only on the non-cavitating pressure distribution in fully wetted condition in that region. The dominant parameters for the pressure distribution is the pressure difference: ΔC_{pmi} at the cross point: x_{pc} as shown in Fig.1, there α_i is the ideal angle of attack corresponding to α_2 in Eppler method, and α_m is the mean angle of attack corresponding to α_1 in Eppler method. The cavitation area and length on a foil can be described by the power functions:

$$\text{cavity length:} L_c = \frac{A}{\sigma^{*m}}, [A, \quad m] = f(\Delta C_{pmi}, \quad x_{pc}) \tag{1}$$

$$\text{cavity area:} \frac{V_c}{\alpha - \alpha_i} = \frac{B}{\sigma^{*n}}, [B, \quad n] = g(\Delta C_{pmi}, \quad x_{pc}) \tag{2}$$

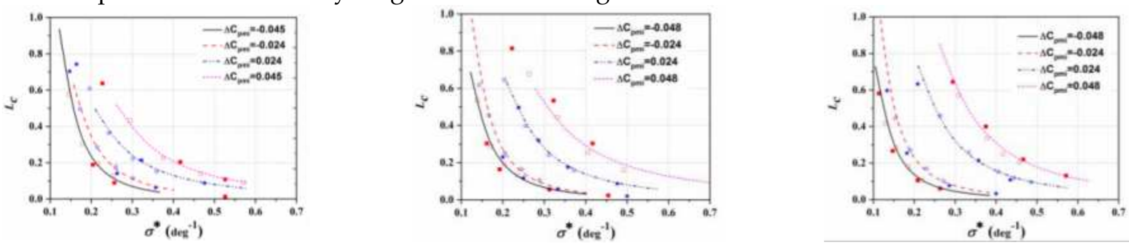
where A and m , B and n are the coefficients, a non-dimensional condition parameter,

$$\sigma^* = (\sigma + C_{pm})/(\alpha - \alpha_c(\sigma)) \tag{3}$$

allows for the operating curve of a section in a wake, there C_{pm} is the mean pressure extracted from the main pressure region at the mean angle of attack α_m, the cavitation inception angle of attack $\alpha_c(\sigma)$ is determined from the cavitation bucket of the section by interpolation.

*Corresponding Author: Zhibo Zeng, zbzeng80@163.com

In previous paper [5] by the first author, a regression method has been developed to predict the cavity area on the section from its pressure distribution in equation (2). In this paper a similar regression method is developed to predict the cavity length also from its pressure distribution in equation (1). A database of pre-calculated cavity length is shown in Fig.2.



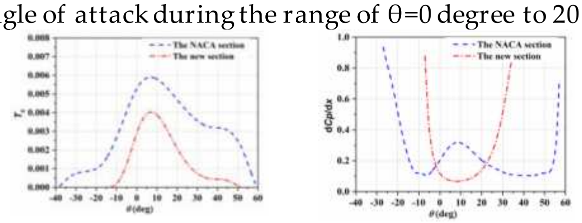
(a) (b) (c)

Figure 2. The database of pre-calculated cavity length related with a series of pressure distributions on two-dimensional section:(a) x_{pc}=0.017; (b) x_{pc} =0.067; (c) x_{pc} =0.110 ("■and□" denote a variation of σ with αunchanged; "★ and ☆"denote a variation of α with σ constant)

So the cavity area and length are found from its pressure distribution in fully wetted condition instead of from the angle of attack and the section geometry using the pre-calculated database. When a section, its geometry prescribed by the Eppler parameters, passes a wake peak, the non-dimensional condition parameterσ^*can be calculated. On each section the development of the cavity area V_c and length L_c with the blade position θ can then be predicted from equation (1) and (2), then the mean thickness of the cavity and the adverse pressure gradient (fully wetted pressure distribution) at the cavity closure point can be determined.

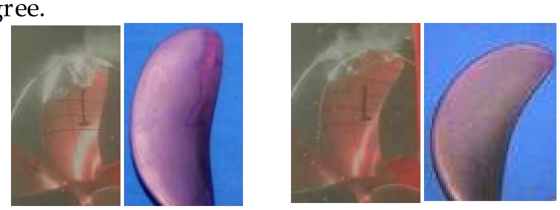
3. Application to bade section design and validation

The method was applied to blade section design for a bulk cargo ship, where only one section at r/R=0.8 was optimized. Fig.3 shows the comparison of the two dominant parameters of erosion between a traditional NACA section and an optimized section. It can be seen that the new section has much smaller mean thickness with the blade position θ and the adverse pressure gradient dCp/dx at the cavity closure on the new section is significantly reduced when the cavitation develops fully around the maximum angle of attack during the range of θ=0 degree to 20 degree.



(a) (b)

Figure 3. Comparisons of the two dominant parameters :(a) the mean cavity thickness, (b) the adverse pressure gradient



(a) (b)

Figure 4. Comparisons of cavity extent and erosion: (a)the NACA propeller, (b) the optimized propeller

With the NACA and optimized two-dimensional sections, two propellers has been designed in a similar way as was done for the optimization of the maximum inception speed and the minimum pressure fluctuations[4,5]. The open water performance test and the cavitation test in behind condition for both propellers were carried out in the towing tank and in the large cavitation channel of CSSRC in Wuxi, China. The test results show that the loads and efficiency are very close. The cavitation behavior on the new propeller is significantly different from the NACA propeller, the cavity extent and length at each radius is reduced at the 10 degree blade angle position as shown in Fig.4. The shedding cloud cavitation can be seen from the NACA propeller at about 30 degree blade position, which causes the definite erosion

*Corresponding Author: Zhibo Zeng, zbzeng80@163.com

on the blade from the paint test as shown in Fig.4. In contrast there is no obvious cloud cavitation flow on the new propeller blade below 0.9R, which is consistent with the paint test. However in the tip region exists a little bit erosion, which is related to the complex vortex cavitation flow in this region.

4. Conclusions

A practical method using blade sections to assess the risk of cavitation erosion on propellers is shown to be effective, the criterion is simplified by the two dominant parameters: the sheet cavity thickness and the adverse pressure gradient at the closure. In the simplified method the calculation of two-dimensional cavity area and length on a blade section during a revolution was made so efficient that it could be used to assess the mean cavity thickness. This was done by making a database of pre-calculated cases.

Cavity thickness and adverse pressure gradient on a propeller blade in a wake can be fast predicted in a quasi-steady way, this is restricted on the blade below 0.9R radius. On the other hand, strong 3D effect of cavitation flow is another important factor especially when the re-entrant jet has been generated, propeller skew and rake should be considered in combination with the present method.

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*Corresponding Author: Zhibo Zeng, zbzeng80@163.com