Numerical Analysis of Tip Cavitation on Marine Propeller with Wake Alignment Using a Simple Surface Panel Method "SQCM"

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Abstract. This paper presents the calculation method of tip cavitation with wake alignment. Tip cavitation consists of tip vortex cavitation and tip super cavitation which means the undeveloped and local super cavitation around blade tip. The feature of this study is that the method applies the wake alignment model in order to express the realistic phenomena of tip cavitation and predict the pressure fluctuation more accurately. In the present method, the wake sheet is deformed according to the induced velocity vector on the vortex lines. The singularity of the potential vortex can be removed by using the Rankine Vortex model. This paper shows the calculated results regarding cavitation pattern, pressure fluctuation etc. comparing with published experimental data and calculated results without wake alignment.

1. Introduction

The unsteady cavitation on marine propeller produces the considerable pressure fluctuation on ship stern, which causes the hull vibration and structural damage. Therefore, it is very important to predict the pressure fluctuation in the propeller design stage and theoretical prediction methods are indispensable for the practicality. We presented the calculation method of propeller sheet cavitation using a simple surface panel method "SQCM" which was developed by Kyushu University (Ando et al. 1998) and we obtained reasonable results regarding not only cavitation pattern but also cavity volume (Kanemaru et al. 2009). The method was extended to the calculation method of pressure fluctuation on ship stern (Kanemaru et al. 2011). Furthermore, we developed the calculation method of tip vortex cavitation and tip super cavitation which are important for the higher order frequency components prediction of the pressure fluctuation (Kanemaru et al. 2015). We named these two types cavitations 'tip cavitation' in the above mentioned paper.

Our previous methods apply the geometrical pitch model for the wake sheet arrangement. However, wake alignment is important to express the complicated phenomena of tip cavitation and obtain more accurate prediction of pressure fluctuation. In this study, we apply the wake alignment model using the induced velocity vector on the wake sheet.

2. Calculation Method

2.1. Outline of SQCM

SQCM (Source and QCM) uses source distributions (Hess and Smith 1964) on the propeller blade surface and discrete vortex distributions arranged on the mean camber surface according to QCM

(Quasi-Continuous vortex lattice Method) (Lan 1974), which is well known as one of lifting surface methods. The formulation of SQCM is described in the papers (Ando et al. 1998, Kanemaru et al. 2009). We applied SQCM to the calculation methods of unsteady propeller sheet cavitation which is based on the free streamline theory (Kanemaru et al. 2009). Also the method was expanded to the calculation method of pressure fluctuation induced by the calculated sheet cavitation (Kanemaru et al. 2011).

2.2. Tip Cavitation

Although the excitation by the sheet cavitation is predominant in the fluctuating pressure, tip cavitation should be considered for the accurate prediction including higher order frequency components in case that these components causes serious problem. Regarding tip vortex cavitation, several theoretical model were presented by Lee et al. (2004) and Szantyr (2007). We referred these studies in our tip vortex cavitation model. In calculation models, tip vortex cavitation means the cavitation around tip vortex line which is a free vortex arranged at the most tip side on the wake sheet. On the other hand, local and unstable tip super cavitation which exists between the trailing edge and the developed tip vortex cavitation should be considered for more accurate prediction method of pressure fluctuation. We treated these cavitation as 'tip super cavitation' and presented the practical calculation model. These details are shown in the paper (Kanemaru et al. 2015).

2.3. Wake alignment

In the calculation of panel method or lifting surface method, the wake sheet has to be arranged in advance. Generally, liner wake model based on the theoretical or empirical model. Our previous works 2.1 and 2.2 apply the geometrical pitch model using the blade geometry and the model gives reasonable results regarding thrust and torque at the design point. However, in the actual phenomena, the wake sheet geometry is formed by the velocity vector in the slipstream. In the case of tip cavitation calculation, wake alignment should be considered because the calculated cavity is affected by the wake sheet and the pressure fluctuation is very sensitive to the cavity shape and volume.

In this study, we try to deform the wake sheet according to the induced velocities at the node of the ring vortex defined by SQCM as follows:

$$\vec{W}_{\mu\ell} = \vec{W}_{\mu\ell-1} + \vec{V}_{I\mu\ell-1} \cdot \Delta t + \vec{V}_{S\mu\ell-1} \cdot \Delta t \tag{1}$$

Here, $\vec{W}_{\mu\ell}(x_{\mu\ell}, y_{\mu\ell}, z_{\mu\ell})$ is the position vector at the control point (**Figure 1**), $\vec{V}_{I\mu\ell}(\vec{V}_{Ix}, \vec{V}_{Iy}, \vec{V}_{Iz})$ is the inflow velocity vector and $\vec{V}_{S\mu\ell}(\vec{V}_{Sx\mu\ell}, \vec{V}_{Sy\mu\ell}, \vec{V}_{Sz\mu\ell})$ is the induced velocity vector by the singularities. And Δt is the time step size. This method is based on our paper (Kanemaru et al. 2007). The paper calculates the induced velocity vector at the center of ring vortex in order to avoid the singularity by the Biot-Savart law. But in this study, the velocity vector is calculated at the node of ring vortex by applying the Rankine Vortex model which treats the flow near the vortex segment as the solid body (Kanemaru et al. 2011). It is not important to calculate the wake sheet deformation in far area from trailing edge (T.E). The present method is performed from T.E. to 45 degree position from T.E. (**Figure 2**) considering both the accuracy and the practicality.

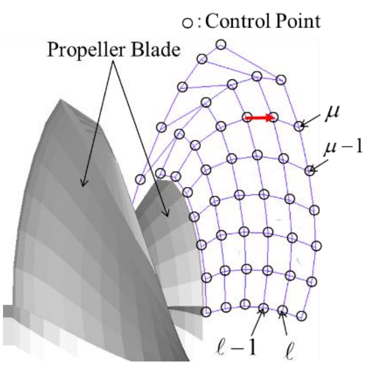

Figure 1 Control point on wake sheet

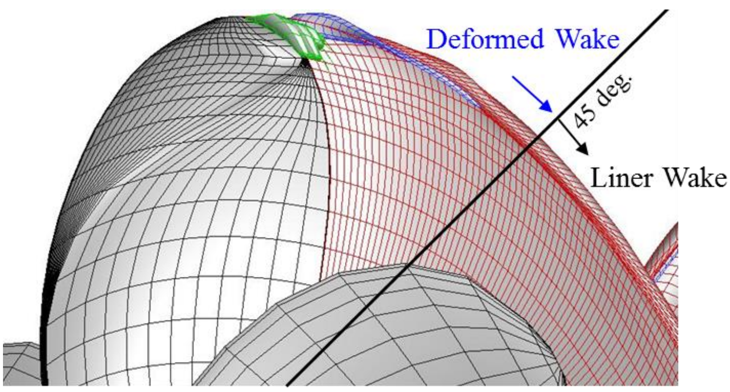

Figure 2 Deformed wake sheet

3. Calculated Results

3.1. Calculation of Cavitation

Seiun-Maru-I conventional propeller (CP) and highly skewed propeller (HSP) are adopted in order to compare with the experimental data at SRI (Kudo et al. 1989). The validation of sheet cavitation model is presented in our paper (Kanemaru et al. 2009). The detail of the calculation conditions and definitions are same to the paper.

Figure 3 shows the calculated cavitation patterns at each angular position. It can be seen that the tip cavitation occurs when the blade passes the high loading position. Owing to the wake alignment, the twisting of tip vortex cavitation by the tip vortex roll up can be seen.

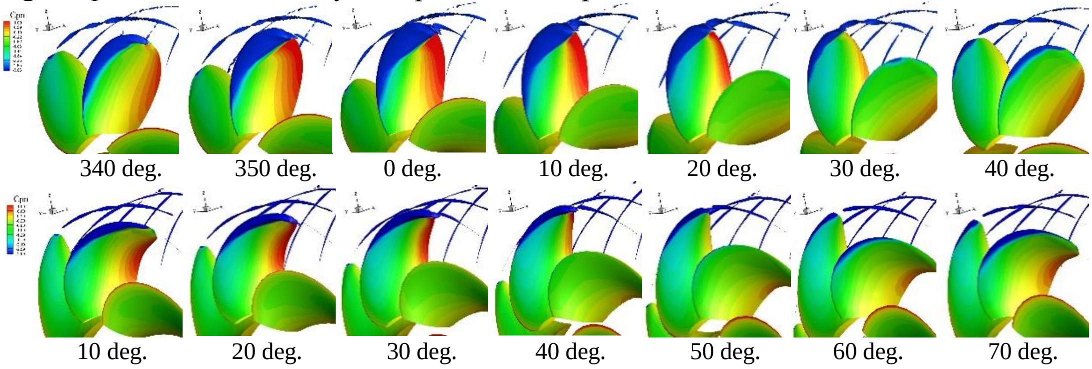

Figure 3 Cavitation patterns

(Upper: CP (K_T =0.207, σ_n=3.06) , Lower: HSP (K_T =0.201, σ_n=2.99))

3.2. Calculation of Pressure Fluctuation

Figure 4 shows the fluctuating pressure on the point where is right over the propeller (Kanemaru et al. 2009). The fluctuating pressure K_p consists of three components as:

$$K_p = K_{pShC} + K_{pTVC} + K_{pTSC} \qquad (2)$$

Here K_{pShC} is the result by the sheet cavitation model only which includes the components of lift and blade thickness. K_{pTVC} and K_{pTSC} are the components of tip vortex cavitation and tip super cavitation. K_{pTVC} is very small because the tip vortex cavitation model is applied from the confluence point of free vortices which form the tip vortex. On the other hand, K_{pTSC} has large fluctuation in results of both CP and HSP. The difference between w/ and w/o wake alignment can be seen in K_{pTSC} of both CP and HSP.

Figure 5 shows the amplitude of pressure fluctuation at the same point of **Figure 4**. In these figures, the components from 1st order blade frequency to 4th one are shown and compared with the experimental data (Kurobe et al. 1983) and the calculated results w/o wake alignment. Overall, the difference of the amplitudes by the present method and the method w/o wake alignment is not so large. However the higher order frequency components by the present method are larger than those by the method w/o wake alignment and these results are closer to the experimental data. This denotes that the treatment of wake alignment is important for accurate prediction method of pressure fluctuation.

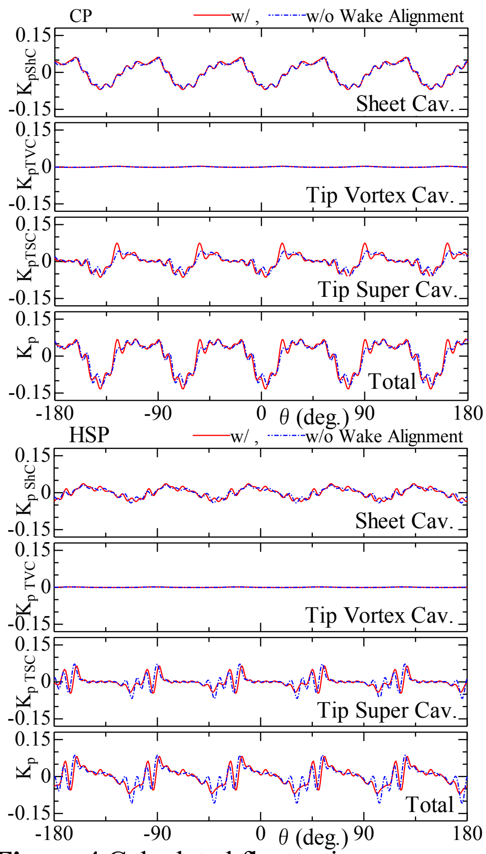

Figure 4 Calculated fluctuating pressure (Upper: CP, Lower: HSP)

4. Conclusion

The amplitudes of pressure fluctuation by the present method are closer to the experimental data comparing with the results by the method w/o wake alignment regarding the higher order frequency components. The present study shows that the exact treatment of cavitation around tip might contribute to the accuracy of prediction method. To develop more realistic model is one of our future works.

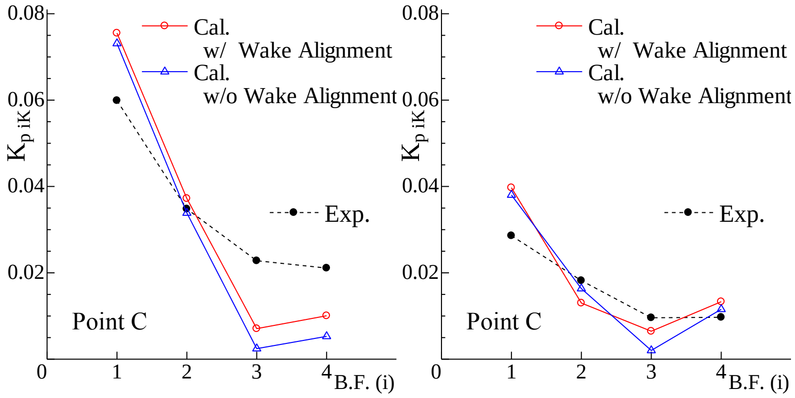

Figure 5 Amplitude of pressure fluctuation (Left: CP, Right: HSP)

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