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The Numerical Study of the Cavitation flow of the propeller in the wake of the ice block

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Abstract: To investigate the influence of the ice on the cavitation flow around the propulsion, a four-blade propeller operating in water tunnel with an ice block located upstream is simulated by the RANS solver. The careful research is done to investigate the shape and the periodical development of the propeller cavity. The results shows that the existence of the ice increases the non-uniformity of the propeller inflow and induces the oscillation of the cavitation volume. The ice block would also decrease the pitch angle of the tip vortex and cause the bending deformation of the hub vortex. Besides, the cavitation flow of the backward rotating propeller in the wake of the ice, which is an important operation condition to the double action icebreaker, is also numerical studied.

Keywords: ice block; ice-propeller interaction; cavitation flow; vortex

1. Introduction

With the continued melting of the polar ice caps, it is possible to open the Arctic sea routes, which could cause a reduction in shipping distance and cost between East Asia and Europe. And the research of icebreaker and high ice-class vessels is on the rise.

The loading regimes between the propeller and ice includes the contact loads associated with milling the ice, loads resulting from ice impact, and noncontact hydrodynamic loads caused by the ice blockage [1]. Bose [2] modifies a 3-D panel method code from NASA, called PMARC, to evaluate the hydrodynamic load fluctuation between a milled ice block and the propeller blade leading edge profile. Wang et al. [3] apply the overlapping grid method to solve the ice-propeller interaction in a viscous flow field with the commercial software STAR-CCM+. Heydari et al. [4] combine the Eulerian CFD solver, Lagrangian Discrete Element Method (DEM) solver and Multi Body Dynamic methods to study the interaction of ice structures with an operating propeller.

The aim of the present work is to expand the previous studies for further investigation of the ice blockage effect on the propeller performance. A four-blade ice-class propeller at various gap distance between the ice and propeller is simulated by the RANS solver. The numerical analysis is focused on the influence of the ice on the hydrodynamic loads and the pressure and vortex structure. The cavitation on the blades is also studied in detail and compared at different ice-propeller proximity.

2. Materials and Methods

2.1. Mathematical Equation

In the present work, the Homogeneous Equilibrium Flow Model (HEFM) is applied to model the cavitation flow. The eddy viscosity assumption is introduced to model the Reynolds stress tensor, and the eddy viscosity is calculated by SST k-ω turbulence model. The standard wall function is also applied near

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the wall. The Schnerr-Sauer cavitation model is used in the simulation to describe the mass transfer due to evaporation and condensation in the ice-propeller flow.

2.2. Propeller and Ice Geometry

The ice-class propeller designed by the China Ship Scientific Research Center (CSSRC) has four blades rotating clockwise when seen from the stern. The propeller diameter in full scale is 7.0 m with a hub ratio of 0.21 and blade area ratio of 0.75. The numerical simulation is conducted with the scale ratio of 1/28, which is the same as the open water test carried out in the CSSRC Cavitation Tunnel.

As shown in Figure1, the cylindrical coordinate system is located at the center of propeller, with z pointing toward the suction side (upstream), φ to starboard and r upward. The axis of rotation is aligned with the z axis. The initial position of the key blade, the blade in red, is at 12 o'clock direction (φ=0°). The ice is modeled by a rigid rectangle with 1.72D×D×0.5D, where D is the diameter of the propeller. The gap between the ice and the propeller plane is expressed as m, while the distance of the ice and the rotation axis is expressed as s.

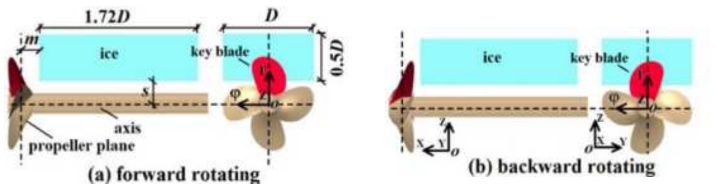

Figure 1. Position of the propeller and the ice

2.3. Computational domain and grids

Fig.3 illustrates an overview of the computational domain. The domain is defined as a 24D long circular cylinder with a radius of 1.6D, which is the radius of the CSSRC Cavitation Tunnel. Boundary conditions consist of the velocity boundary condition for the inlet, pressure boundary condition for the outlet and no-slip wall on the propeller, the ice block and the outward flow field. The ice block is located at the upstream of the propeller to investigate the blockage effect. All the simulations are conducted for the propeller rotating at constant velocity n=35 rev/s. The time step is equivalent to 1° of propeller rotation, and the iteration number in one time step is 30.

3. Results

Fig. 2 gives the time history of the thrust and torque coefficient of the propeller in two revolutions with different ice-blade gap. T0 is the period that the propeller shaft rotates one cycle. It is shown that the hydrodynamic load fluctuates due to the influence of the ice, and the amplitude of oscillation increases as the ice getting close to the propeller. The torque coefficient oscillates with the frequency about 4/T0, which is the blade frequency of this four-blade propeller. The frequency of the thrust coefficient is also dominated by the blade frequency, while it combine some high frequency components. The time average value of Kt, Kq and η0 suggests that the blocking ice would increase the thrust and torque significantly, but reduced the efficiency.

Fig. 3 demonstrates the variation of the hydrodynamic force on the key blade. The initial position of the key blade could be seen in Fig. 1. Fig. 3 indicates that the thrust and torque raises when the blade gets close to the ice (φ=180° to 0°), and drops with the blade moving away from the ice (φ=0° to -180°). The high frequency fluctuation of the hydrodynamic loads would be enhanced during φ from 60° to -60°, when the key blade is sweeping across the ice. Fig. 3 also shows that the thrust and torque of the blade is much larger with small gap between the ice and blade.

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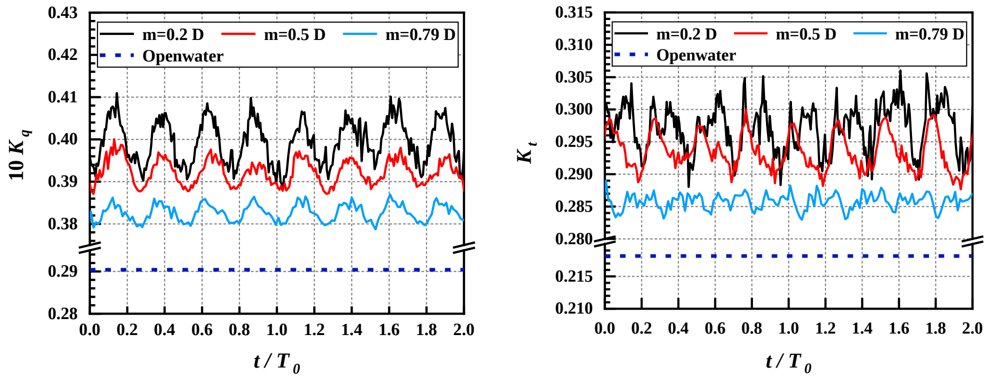

Figure 2. Time history of the thrust and torque coefficient (J=0.45) with different distance between ice and propeller

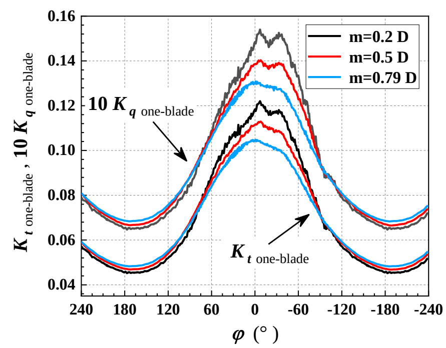

Figure 3. Variation of thrust and torque coefficient for the key blade

The instantaneous pressure distribution on the propeller is shown in Fig. 4. With the effect of the ice, the local high pressure region near the leading edge at pressure side and the trailing edge at suction side is enlarged. The pressure on the blade tip at the suction side would drop to the saturated vapor pressure of water. And the cavitation phenomenon would occur at that region, which is not found in the open water condition. The evolution of the cavity area on the key blade (the blade in red) is displayed in Fig. 5 with the cavity shape presented by the isosurface of the vapor volume fraction α_v=0.5. It shows that the cavity would incept at phase φ=90° and collapse at phase φ=-90°, but the collapse rate of the sheet cavity is quicker than the growth rate. Two peaks would appear in the range of phase φ=40° to -40°.

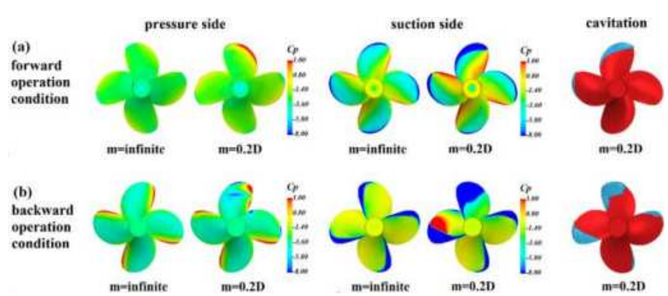

Figure 4. Pressure contour on propeller at phase φ=0°

The vorticity on the plane z=0 and the iso-surface of the second invariant of the velocity gradient tensor (Fig. 7, 8) shows the complicated interaction of the tip, hub and blade passage vortex in the upper side of propeller axis. The tip vortex would break earlier in ice wake than in open water condition. The pitch angle

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of the tip vortex close to the ice is also decreased by the blockage effect with the reduction of the axial velocity. Considering the case with gap distance m=0.2D, the vortex on the ice is stretched towards the rotating blade. And the deformation of the hub vortex induced by the blade passage vortex is quite obvious.

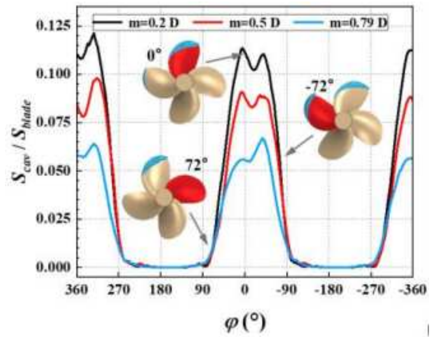

Figure 5. Development of the cavity on the key blade

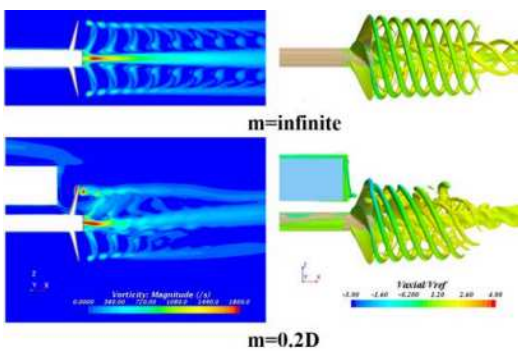

Figure 6. Vortex structure at phase φ=0° of the forward operation condition (Q=5000 1/s2).

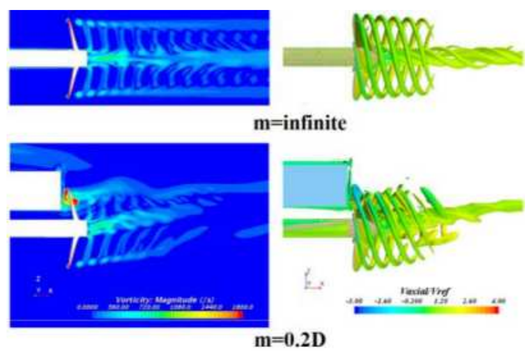

Figure 7. Vortex structure at phase φ=0° of the backward operation condition (Q=5000 1/s2).

4. Conclusions

The blockage effect of the ice on the four-blade propeller is numerically studied by the RANS solver The performance of the propeller is investigated for fixed ice-propeller proximity condition including m=0.79D, 0.5D and 0.2D, on the advance coefficient J=0.45 and the rotating cavitation number σr is about 4.0. The results show that the ice would cause the periodic oscillation of thrust and torque. The ice would reduce the pressure on the tip of the suction side leading to the cavitation, And the cavitation would become more severe at small blockage proximity. The existence of the ice would also increase the nonuniformity of the propeller inflow and speed the diffusion of the tip vortex. The reduction of the axial velocity in ice wake would bring about the decrease of the tip vortex pitch angle and the bending deformation of the hub vortex.

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