CAV2021
11th International Symposium on Cavitation
May 10-13, 2021, Daejon, Korea

Tip Vortex Cavitation Suppression by Tip Modification of a Ship Propeller

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Abstract: It is often necessary to delay cavitation inception on marine propellers for reducing hull pressure fluctuations and underwater radiated noise. The blade tip geometry of a twin-screw ship propeller is modified by CFD-based optimization for delaying the inception of tip vortex cavitation (TVC), which is usually the first cavitation type observed at the lowest inception speed. About 400 tip-modified blade designs are considered in the optimization and two steady RANS simulations are made on each design with simplified hull wake models corresponding to the blade positions of maximum and average thrust for estimating tip vortex strength and propulsive efficiency, respectively. After the optimization, unsteady simulations are made on the baseline and optimized blade designs by DES with modelling cavitation and full hull wake for assessing the increase of the TVC inception speed. CFD with the simplified and full hull wake models is validated against cavitation tunnel test results. The CFD result shows a substantial reduction of TVC and over 1% efficiency gain for the optimized tip-modified design. The CFD-based optimization of the blade tip geometry is demonstrated to be an effective way for delaying TVC inception and improving propulsive efficiency.

Keywords: tip vortex cavitation; cavitation inception; ship propeller; hull wake; DES

1. Introduction

Since cavitation-induced hull pressure fluctuations are 5 to 15 times greater than in non-cavitating flow conditions [1], it is often necessary to delay cavitation inception on marine propellers for satisfying requirements of ship design related to passenger comfort, cargo safety and special-purpose vessel operation. A number of means have been researched for suppressing TVC [2], which is often the first cavitation type observed at the lowest inception speed. It is important to suppress TVC for mitigating underwater radiated noise, of which harmful impact on marine life is highlighted in these days [3], because ship propellers are often the strongest underwater noise source and TVC can travel far downstream. By CFD-based optimization, a conventional four-bladed propeller of a twin-screw ship is modified to have smoothly curved geometry at the blade tip for delaying TVC inception, while at the same time improving propulsive efficiency.

2. CFD Setup

In the optimization phase, steady simulations are made on a single blade in a quarter-cylinder domain with periodic boundary conditions on the sides by an incompressible RANS solver with k-ω SST turbulence model. At the end of the optimization, unsteady simulations are made on all propeller blades in a cylindrical domain by a DES solver with the volume-of-fluid method and an interphase mass transfer model based on the asymptotic Rayleigh-Plesset equation for modelling cavitating flows. The CFD

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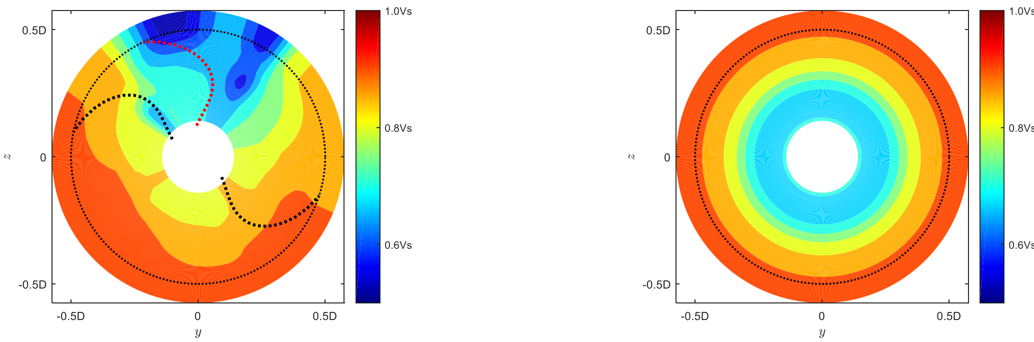
approaches have been validated against experiment results for open-water propeller performance and various types of propeller cavitation, and the setup details are described in [4, 5].

A hull wake model simplified to be circumferentially uniform and to radially vary for representing a specific blade position is applied to the inlet of steady simulations, whereas a full wake model is applied to the propeller inflow by using a velocity inlet boundary condition for axial wake and momentum sources for transverse wake in DES [6] (See Figure 1). While propeller rotation is modelled by the rigid-body motion and the sliding grid in DES, the moving reference frame is adopted in steady simulations. A steady simulation with the simplified wake model takes about 1/60 of the computational time of an unsteady one with the full wake model.



(a) (b)

Figure 1. Axial hull wake models: (a) Full model in DES; (b) Simplified model for φ = 314° in steady RANS simulations

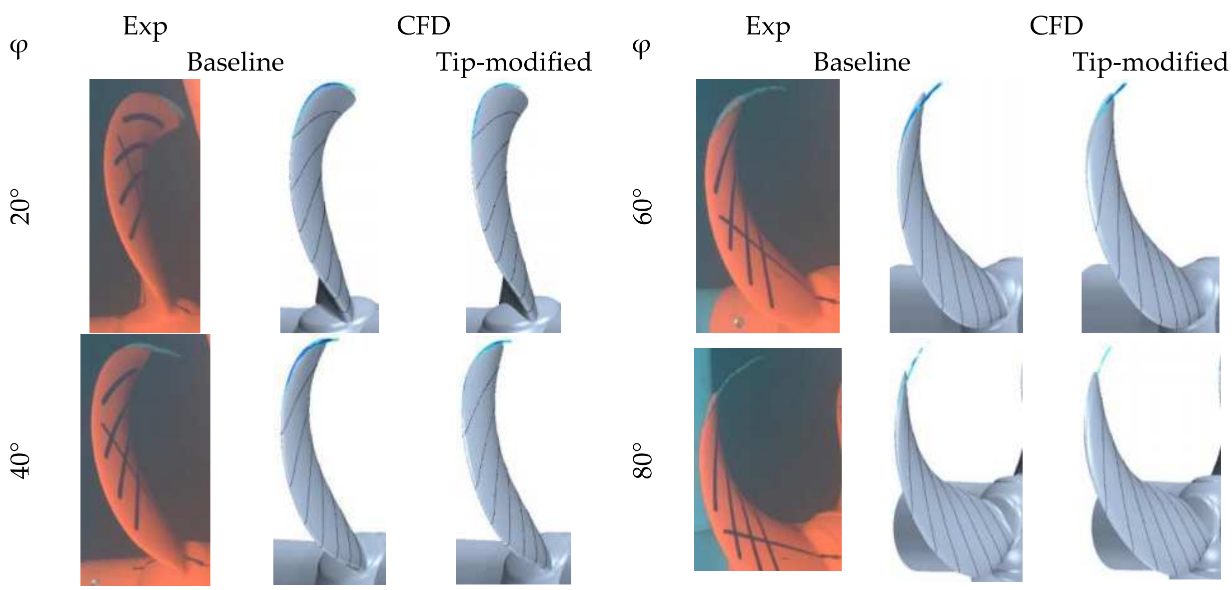


Figure 2. Cavitation patterns on the suction side of the blade in the cavitation tunnel test and CFD with the full hull wake model: CFD cavity interfaces in light and dark blue colors are defined by iso-surfaces of 10% and 50% vapor volume fractions, respectively

3. CFD Results

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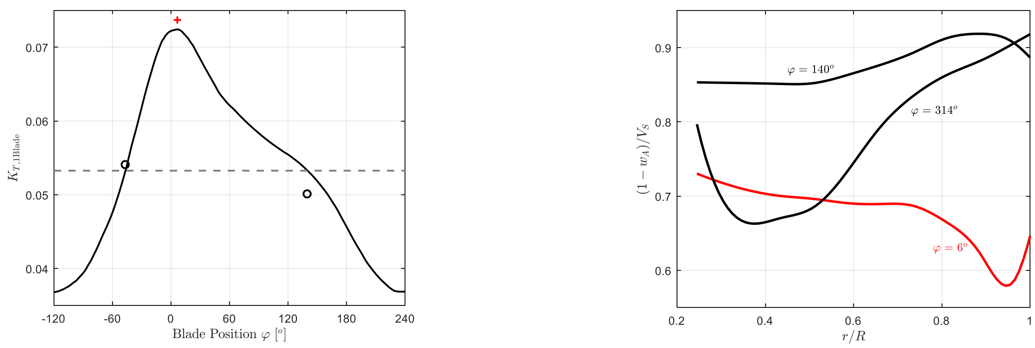
3.1. Validation of CFD with a full hull wake model

DES with the full hull wake model is made on the baseline design with a straight upright tip at the TVC inception speed obtained from experiments, which have been conducted in the large cavitation tunnel of SSPA including a hull model. Cavitation patterns are compared between CFD and the experimental results in Figure 2. The blade position of φ ≈ 5° where TVC starts in CFD is earlier than φ ≈ 10° in the experiment. TVC is formed from the leading edge of the tip and extended to a little distance from the tip end in both the experiment and CFD. TVC is weakened to be intermittent near the tip end at φ ≈ 90 – 210° in the experiment, whereas weak TVC disconnected from the tip is formed at φ ≈ 90 – 105° and no TVC is shown after φ ≈ 105° in CFD.



(**a**) (**b**)

Figure 3. (a) Single-blade thrust coefficient with respect to φ: Solid line – CFD with the full hull wake model, + and o marks – CFD with the simplified hull wake models at φ = 6°, 140°, 314°; (b) Axial hull wake distributions along the mid-chord locus

3.2. Validation of CFD with a simplified hull wake model

In Figure 3(a), CFD with the full hull wake model shows the highest single-blade thrust at φ = 6° and the mean thrust at φ = 140°, 314°. Three simplified hull wake models are prepared based on axial wake distributions along the mid-chord locus taken at φ = 6°, 140°, 314° as shown in Figure 3(b). The mid-chord loci at the three blade positions are marked in Figure 1(a). CFD with the simplified wake models of φ = 6°, 314° shows single-blade thrust close to those from CFD with the full wake model with differences smaller than 2%, whereas the difference at the other mean-thrust position of φ = 140° is 6.4% as shown in Figure 3(a).

(**a**) (**b**) (**c**)

Figure 4. Cavitation at φ = 40°: (a) experiment; (b) CFD with the full hull wake model; (c) tip vortex defined by the iso-surface of Q = $2.7 \cdot 10^7$ in CFD with the simplified hull wake model of φ = 6°

CFD with the simplified wake models of φ = 6°, 314° is adopted in the following optimization for estimating tip vortex strength and propulsive efficiency, respectively. CFD with the full wake model shows the maximum cavity volume $V_{Cav,Max}$ at φ = 35°, which is later than the blade position of φ = 6° with the maximum thrust, as it takes a certain time for the cavity to build up. The tip vortex volume V_{TV} defined by a Q-criterion iso-surface in CFD with the simplified wake model of φ = 6° is made to be equal to $V_{Cav,Max}$ from full-wake CFD by iteratively adjusting the Q-criterion value, as shown in Figure 4.

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3.3. Optimization of blade tip geometry

The parameterized tip geometry is optimized for maximizing an objective function consisting of the tip vortex volume reduction -ΔV_{TV} and the efficiency gain $\Delta\eta$. About 400 tip-modified blade designs are considered and two CFD simulations with the simplified wake models of φ = 6°, 314° are made on each design.

The results in Figure 5 shows that an approximate Pareto front is formed at the bottom right hand corner, as the maximum possible efficiency gain is smaller for a larger reduction of V_{TV}. The designs with a tip bent backward marked by black dots show tip vortex reductions and positive efficiency gains. The highest efficiency gain is $\Delta\eta$ = 1.3% with ΔV_{TV} = -7.7% and the largest reduction of the tip vortex volume is ΔV_{TV} = -32.8% with $\Delta\eta$ = 0.9%. A tip-modified blade design showing $\Delta\eta$ = 1.1% and ΔV_{TV} = -25.1% is selected as the final one with more weight on -ΔV_{TV}.

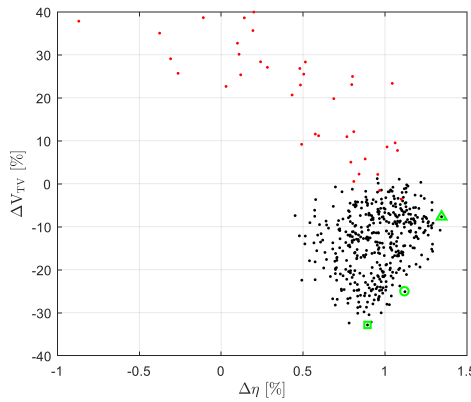

Figure 5. Efficiency gain and tip vortex volume change for tip-modified blade designs: black dot – backward bent tip, red dot – forward bent tip, o mark – final chosen design, □ mark – design showing the largest reduction of V_{TV}, Δ mark – design showing the largest efficiency gain

CFD with the full wake model is made on the final tip-modified design. The comparison of CFD cavitation patterns in Figure 2 shows that the overall TVC is significantly reduced for the tip-modified design compared to the baseline. $V_{Cav,Max}$ for the tip-modified design is reduced by 30.2%, which is larger than the tip vortex volume reduction in CFD with the simplified wake model. When CFD is repeated on the tip-modified design at 4% higher inflow speed, $V_{Cav,Max}$ is slightly lower than that for the baseline.

4. Conclusions

CFD with a simplified hull wake model is an effective way of optimizing the blade tip geometry for delaying the TVC inception and improving the propulsive efficiency. CFD with modeling full hull wake and cavitation shows over 4% increase of the TVC inception speed for the optimized tip design over the baseline.

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