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CFD analysis of cloud cavitation on three tip-modified propellers with systematically varied tip geometry

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Abstract. The blade tip loading is often reduced as an effort to restrain sheet and tip vortex cavitation in the design of marine propellers. This CFD analysis demonstrates that an excessive reduction of the tip loading can cause cloud cavitation responsible for much of noise and surface erosion. Detached eddy simulations (DES) are made for cavitating flows on three tip-modified propellers, of which one is a reference propeller having an experimental result from a cavitation tunnel test with a hull model, and the other two are modified from the reference propeller by altering the blade tip loading. DES results have been validated against the experiment in terms of sheet and cloud cavitation. In DES, non-uniform hull wake is modelled by using the inlet flow and momentum sources instead of including a hull model. A 4-bladed Kappel propeller with a smooth tip bending towards the suction side is used as the reference propeller. For the reference propeller, sheet cavitation extends over a whole chord length in the hull wake peak. As the blade gets out of the wake peak, the rear part of sheet cavity is detached in a form of cloud cavitation. For the reference propeller, the tip pitch reduction from the maximum is about 35%. When decreasing the tip pitch reduction to 10%, tip vortex cavitation is formed and cloud cavitation is significantly weakened. When increasing the tip pitch reduction to 60%, sheet cavitation slightly moves to inner radii and cloud cavitation grows larger.

1. Introduction

The mechanism of cloud cavitation on a hydrofoil is that the rear part of a sheet cavity is detached in a form of cloud cavitation by a re-entrant jet, when sheet cavitation is chordwisely extended more than a certain length [2]. Cloud cavitation can also be produced by a periodic flow disturbance on an oscillating hydrofoil [3]. Sheet cavitation builds up with an increase of the incident angle. As the incident angle decreases, a froth cloud is ejected from the downstream edge of the sheet cavity with the sheet cavity collapsing. The periodic inflow fluctuation on a hydrofoil resembles non-uniform hull wake on a ship propeller.

As the smooth interface of a sheet cavity grows instable by turbulent eddies, it breaks down into a microbubble cloud. As the cloud cavitation flows downstream, collapse of a single microbubble may initiate cascade implosions of collective microbubbles emitting shock waves with high energy concentration [4]. Cloud cavitation is associated with intense noise generation and surface erosion, hence the prevention of cloud cavitation is of major importance in the marine propeller design.

A marine propeller showing extensive sheet cavitation and cloud cavitation in a cavitation tunnel test is selected as a reference propeller for research. A cavitation simulation for the reference propeller with hull wake has been validated against the experimental result in terms of cavitation variation along the blade position [1]. Two other propellers are modified from the reference propeller by altering the blade tip loading. By comparing DES results for three propellers, the influence of the tip loading on cloud cavitation is investigated.

2. Propeller models

As a part of efforts to improve propulsive efficiency in ship operations, several kinds of tip-modified propellers have been introduced to reduce energy loss from tip vortices [5]. Due to tip bending, variation patterns from sheet cavitation to tip vortex cavitation on tip-modified propellers are different from conventional propellers. The reference propeller taken for research is a Kappel propeller which features a smooth tip bending towards the suction side. It is a 4-bladed propeller with a low area ratio of Ae/Ao=0.38, where Ae is the expanded blade area and Ao is the propeller disk area. A cavitation tunnel test conducted with a complete hull model at SSPA shows a large extent of sheet cavitation and detachment of sheet cavity in a form of cloud cavitation.

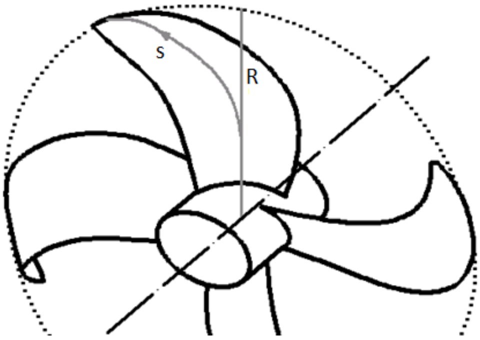

Figure 1. Orthogonal mid-chord locus of Kappel propeller

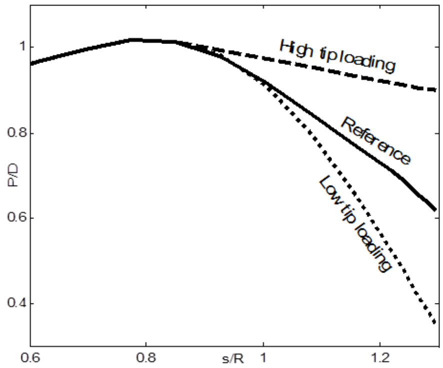

Figure 2. Pitch ratio P/D as a function of relative mid-chord length s/R

Figure 3. Computational mesh around the reference propeller and rudder

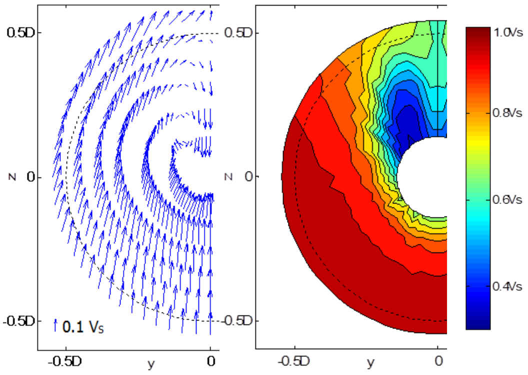

Figure 4. Transverse (left) and axial (right) velocity components of hull wake extracted from a bare hull simulation [1]

Two other propellers are modified from the reference by altering the blade tip pitch. For the reference propeller, the tip pitch reduction from the maximum is about 35%. The maximum pitch is at a relative mid-chord length of s/R≈0.80, i.e. a relative radius of r/R≈0.75. Two propellers are designed by modifying the tip pitch reduction to 10% and 60%, respectively. As shown in figure 2, the pitch drops from the same maximum with a different rate for three propellers and the one with the small reduction will have a higher loading than the reference propeller and the one with the larger reduction will have a lower loading. Since the lifting surface in the tip region of the tip-modified propeller is not on cylindrical surfaces, the angle of incidence to the blade sections is determined by the pitch angle and the vertical angle of aperture of the surface relative to the onset flow.

3. Cavitation simulation

Cavitation simulations are made by DES with the k-ω SST turbulence model. Unsteady computations are performed with a time step corresponding to 1° propeller rotation. A cylindrical domain is used with an inner rotating domain around a propeller model with a diameter of D=250 mm. The propeller rotation is simulated by rigid body motion with a sliding mesh.

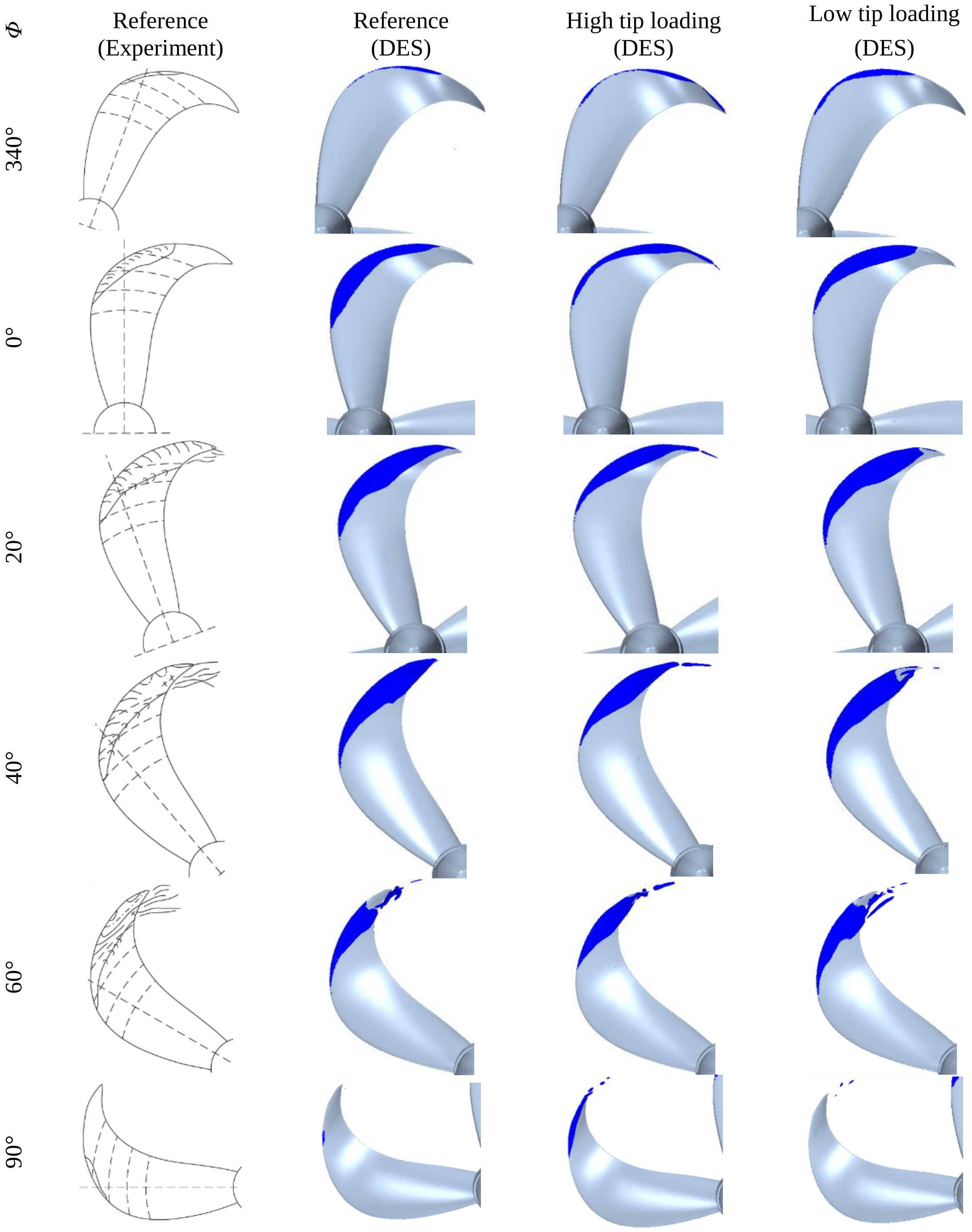

Figure 5. Cavitation for three propellers with different tip loadings

A hexahedral mesh trimmed by propeller and rudder models is generated with prism layers resulting mostly in a dimensionless first-cell height of $y^+<2$ (See figure 3). Mesh generation, computation and post-processing are made using the commercial CFD solver StarCCM+. Cavitation is modeled by the Volume-of-Fluid (VOF) and a vapor transport equation based on the Rayleigh-Plesset equation. The force of gravity is applied to take into account hydrostatic pressure.

Simulations are made in the same model-scale condition as the cavitation tunnel test: ship speed V_S=4.5 m/s, rotating speed N=24.0 rps and cavitation number σ_N=3.8. Instead of including a hull model, a wake field extracted from a bare hull simulation is applied as a propeller inflow by using the inlet boundary condition and momentum source [1]. Since hull wake of a single-screw ship is almost symmetric with respect to the vertical centerline, only half of the wake field is presented in figure 4. The rotating speed of two modified propellers is adjusted by $\Delta N\approx\pm0.5$ rps to reach the same thrust T with a difference of $\Delta T\leq1\%$ as the reference. The propeller loadings are as follows: reference- K_T=0.213 (experiment), 0.215 (DES), high tip loading- K_T=0.225 (DES) and low tip loading- K_T=0.206 (DES), where $K_T=T/(\rho\cdot N^2\cdot D^4)$. The efficiency η of the high tip-loading propeller is 0.5% lower than the reference probably due to an energy loss from an increased tip vortex, where $\eta=T\cdot V_A/(2\cdot\pi\cdot N\cdot Q)$ and Q is the propeller torque and V_A is the propeller advance speed. η of the low tip-loading propeller is close to that of the reference with a difference of less than 0.1%.

In figure 5, the variation of cavitation for three propellers is summarized only for blade positions of $\varphi\approx$340-90°, because cavitation on the reference propeller is suppressed at other blade positions. An isosurface of 10% vapor fraction is taken as a cavitation interface. As the blade enters a high wake region at $\varphi\approx$340°, leading-edge sheet cavitation starts. Sheet cavitation is gradually developed at $\varphi\approx$340-40°. At $\varphi\approx$40°, it is extended over the whole chord length at $r/R\approx$0.9-1.0. While the rear part of the sheet cavity is detached in a form of cloud cavitation in the experiment at $\varphi\approx$60°, unstable sporadic large-scale structure of cloud cavitation is reproduced by DES, but microbubbles are not captured, because the computation grid of $\Delta x\approx$0.5 mm is larger than microbubble scales.

DES for the high tip-loading propeller shows that sheet cavity is extended to the tip and tip vortex cavitation occurs without detachment of a sheet cavity. For the low tip-loading propeller, the sheet cavity is detached earlier and cloud cavitation is more intense than for the reference, as shown at $\varphi\approx$40° in figure 5. Since the blade loading is distributed more to the tip region for the high tip-loading propeller, overall sheet cavitation is lessened at $\varphi\approx$0-40°. In contrast, the blade loading is concentrated on the maximum pitch region for the low tip-loading propeller and hence sheet cavitation becomes more extensive.

4. Conclusion

DES is made for cavitating flows on three propellers with different tip loadings. The DES result indicates that high unloading of a blade tip can cause or intensify cloud cavitation for propellers accompanying extensive sheet cavitation. Cloud cavitation can be prevented or reduced by increasing tip loading and so distributing blade loads more evenly from the maximum pitch region to the tip. Since high tip loading can, on the other hand, bring up tip vortex cavitation and propulsive efficiency loss from the tip vortex, an appropriate balance of the tip load distribution is required in the marine propeller design.

References

[1] Shin K W, Regener P B and Andersen P 2015 *Proc. SMP'15* (Austin)
[2] de Lange D F, de Bruin G J and van Wijngaarden L 1994 *Bubble Dynamics and Interface Phenomena* (Netherlands: Springer) p 241-246
[3] Reisman G E, McKenney E A and Brennen C E 1994 *Proc. 21th Symp. on Naval Hydrodynamics* (Santa Barbara)
[4] van Terwisga T J C, Fitzsimmons P A, Ziru L and Foeth E J 2009 *Proc. CAV2009* (Ann Arbor)
[5] Andersen P, Friesch J, Kappel J J, Lundegaard L and Patience G 2005 *J. Marine Tech.* **42** 3
[6] Dang J 2004 *J. Int. Shipbuild. Progr.* **51** 4 353-376