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Original Article

RANSE-based simulation and analysis of scale effects on open-water performance of the PPTC-II benchmark propeller

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Abstract

This paper presents our numerical study of the scale effects on a tip-rake propeller, the PPTC-II, based on the RANS simulations using software FLUENT 6.3. The low *Re* option in SST k–ω model is adopted at model scale, together with fine prism grids to resolve the viscous sub-layer. At full scale, standard wall function is adopted. The scale-effect corrections yielded by our RANS simulations are compared with those obtained from the ITTC method. To explain the CFD results, an analysis of sectional forces is performed. To investigate how the tip rake influences propeller scale effects, the geometry of PPTC-II is modified by removing the tip rake only, and the RANS-predicted scale effects for the modified propeller, PPTC-II-m, are compared with those for the PPTC-II. The study indicates that the scale effect on propeller thrust can be as important as that on the torque; somehow the RANS- and ITTC-based predictions for full-scale efficiency agree quite well; the tip-rake reduces tip loading and tip vortex strength, and brings about large differences in the scale effects as compared with the propeller without tip-rake.

Keywords: Propeller; Tip rake; Open water; Scale effect; RANSE.

1. Introduction

Theoretically, the scale effects on propeller open water performance need to be corrected for when predicting the powering performance of a ship. The empirical formulae in the 1978 ITTC Performance Prediction Method [1] (referred to as the ITTC method hereinafter) have been widely used for the correction. In the ITTC method the amounts of correction to model-scale thrust and torque coefficients depend on the model- and full-scale section drag coefficients at 0.75*R*, the chord and pitch ratios at the same radius, and the number of blades, where *R* denotes propeller tip radius. Apparently, the corrections would be the same for two propellers which differ in the skew and rake only. Special tip geometries, such as the tip endplates and tip-rake, are not accounted for in the ITTC method as well. For more accurate prediction of the full scale performance, it is necessary to know how and to what extent the geometric parameters not considered in the ITTC method would influence the results of scale effect corrections. To elucidate the problem and update the present ITTC method for correcting propeller scale effects when possible, the Propulsion Committees of the 27th and 28th ITTC initiated a computational campaign in each term of service using the PPTC, a conventional highly skewed propeller, and the PPTC-II, an unconventional propeller with the tip-rake, respectively. The two test cases were provided by SVA Potsdam, and the data are available to the public at the company's website.

In fact, viscous flow CFD simulation has been almost the only approach for the research of propeller scale effects since the last century [2]. The extensive laminar flow region at the Reynolds number of $2–3 \times 10^5$ is an issue which necessitates the use of very fine prism grid layers to resolve the viscous sub-layer and the low *Re* turbulence model at model

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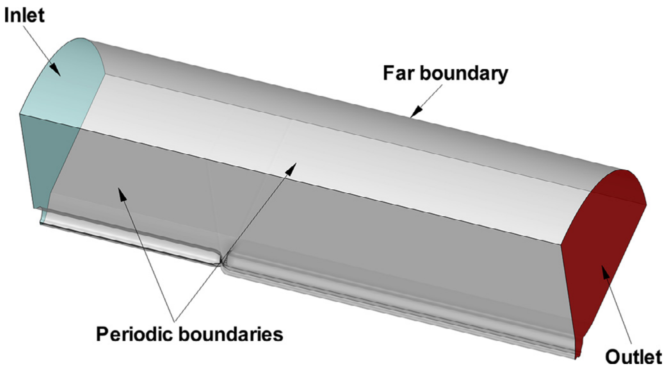

Fig. 1. The computational domain.

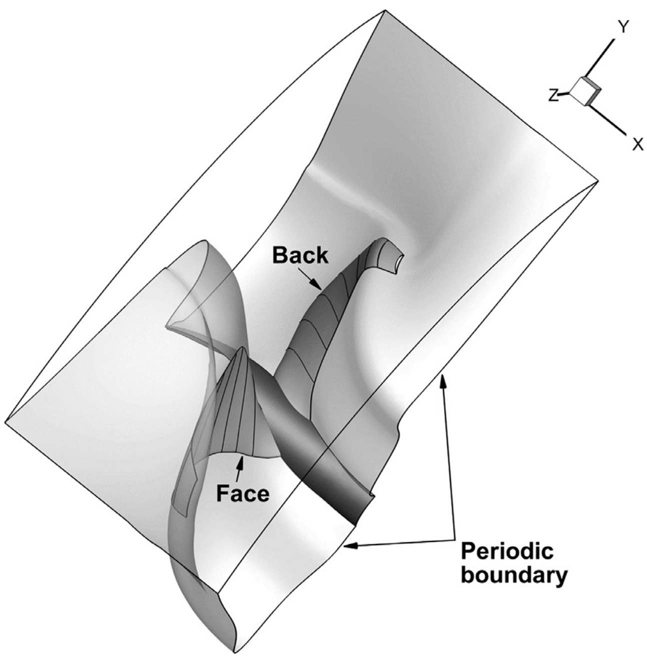

Fig. 2. Geometry of the sub-domain enclosing the back and face of adjacent blades.

scale [3,4]. It was found that the scale effects on propeller thrust and efficiency are underestimated by the ITTC method when compared with the RANS results, especially for highly skewed propellers [4]. Alternative extrapolation formulae for propeller open water performance were proposed via analysis of RANS simulation results [5], where the thrust loading, skew, and the changes in magnitude and direction of section force were taken into account in addition to the geometric parameters considered in the ITTC formulae. The comparison for one test case shows that the CFD-based formulae predicts the increments in thrust and efficiency from model- to full-scale are larger than those predicted by the ITTC method.

Propellers with special tips may present new challenges to the ITTC method for predicting propeller scale effects. It was found through CFD simulations that the scale effects on the Kappel and CLT propellers are larger than those on conventional propellers [6]. More recently, the RANS approach was employed in selecting optimal endplates of the CLT propeller [7]. Besides, the RANS tool was also utilized in the scale effect researches for ducted propellers [8] and the rudder bulb [9].

This paper presents our numerical study of the scale effects on a tip-rake propeller, the PPTC-II, based on the RANS simulations using software FLUENT 6.3. The low *Re* option in SST k–ω model is adopted in model scale, together with fine prism grids to resolve the viscous sub-layer. At full scale, standard wall function is adopted. The scale-effect corrections yielded by our RANS simulations are compared with those obtained from the ITTC method. To explain the CFD results, an analysis of sectional forces is performed. To investigate how the tip rake influences propeller scale effects, the geometry of PPTC-II is modified by removing the tip rake only, and the RANS-predicted scale effects for the modified propeller, PPTC-II-m, are compared with those for the PPTC-II.

2. Numerical modeling approach

2.1. Governing equations

The flow around the propeller working in open water is simulated by solving the RANS equations together with the SST k–ω model for turbulence closure. The continuity and momentum transport equations for an incompressible fluid are

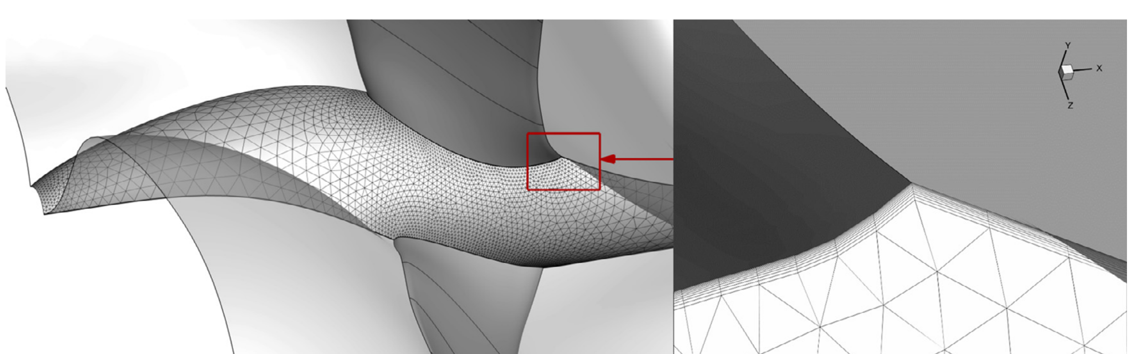

Fig. 3. Zoom-up view of blade-surface prism layer grids.

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