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Numerical prediction of effective wake field for a submarine based on a hybrid approach and an RBF interpolation *

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Abstract: A hybrid approach coupled with a surface panel method for the propeller and a Reynolds averaged Navier-Stokes (RANS) model for the hull with the propeller body forces are presented for predicting the self-propulsion performance and the effective wake field of underwater vehicles. To achieve a high accuracy and simplicity, a radial basis function (RBF) based approach is proposed for mapping the force field from the blade surface panels to the RANS model. The effective wake field is evaluated in two ways, i.e., by extrapolation from the flat planes upstream of the propeller disk, and by direct computation in a curved surface upstream of and parallel to the blade leading edges. The hull-propeller system of a real propeller geometry is further simulated with the sliding mesh model to numerically verify the hybrid approach. Numerical simulations are conducted for the fully appended SUBOFF submarine model. The high accuracy of the RBF-based interpolation scheme is confirmed, and the effective wake fraction predicted by the hybrid approach is found consistent with that obtained by the sliding mesh model. The effective wake fractions predicted by the two methods are, respectively, 4.6% and 3% larger than the nominal one.

Key words: Submarine, effective wake, panel method, Reynolds averaged Navier-Stokes (RANS), radial basis function (RBF)

Introduction

The effective wake distribution is an important factor in designing the wake-adapted propellers. But nominal wakes and waves on free surface are still hot spots in ship and offshore structure engineering[1-4] since it is impossible to obtain effective wake distribution experimentally. Usually one has to predict it empirically with the nominal wake distribution and the effective wake fraction, which are both obtained from model tests along with scale effect corrections. In this context, and owing to the rapid progress in the computational fluid dynamics (CFD), the numerical prediction of the effective wake distribution becomes possible and has attracted the attention of the ITTC[5].

To our knowledge, all numerical predictions of the effective wake are based on the viscous flow CFD simulation of self-propulsion, combined with body-force models built on different potential flow propeller models or just empirical formulas. The action of the propeller behind the ship hull is represented by a body force distribution acting on a cell zone, which is either the propeller disk, a circular cylinder, or a cylinder swept out by the rotating blades. Wu et al.[6] and Fu et al.[7] analyzed the self-propulsion performance of the container ship KCS with the body force models, in which the forces of the propeller were expressed approximately by an empirical analytic function. Tahara et al.[8] evaluated the self-propulsion characteristics of the KCS using overset grids. The force field of the propeller was predicted with an infinite-blade propeller model. Sanchez-Caja et al.[9] analyzed a counter rotating propeller (CRP) unit by coupling the Reynolds averaged Navier-Stokes (RANS) and lifting-line models. A correction method was proposed in the study of the CRP unit to improve the prediction accuracy of the propeller induced velocities. Sakamoto

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et al.[10] carried out numerical and experimental studies of a twin-skeg container ship using a simplified propeller theory to predict the propeller forces. The simulated resistance and the self-propulsion performance were close to the experimental results. In the studies of the KCS ship by Zheng et al.[11] and Yang et al.[12], the body forces were determined by a vortex lattice method and a panel method, respectively. In the preceding studies, the body forces were acted upon the fluid in a circular cylindrical zone, which can be quite different from the actual geometry of the propeller blades. Tian et al.[13] combined the vortex lattice method and the RANS simulation to predict the effective wakes of ducted propellers. A conservative interpolation scheme (CIS) with high accuracy was adopted for the force field interpolation from the potential flow to the RANS simulation. Villa et al.[14] studied the self-propulsion performance of the KCS ship by using an actuator disk model and a coupled viscous/inviscid flow method. Starke et al.[15] and Rijpkema et al.[16] presented a hybrid RANS and boundary element method (BEM) to determine the effective wake of the KCS ship. An interpolation scheme was proposed to map the body force field from BEM to RANS grids. In Refs.[13-16], the body force zone takes the shape of a cylinder swept out by the blade outlines, which allows the body forces to act on their actual locations. These studies all focused on surface ships. For underwater vehicles, the effective wake field is more important for designing low-noise propellers, however, there is a lack of related studies.

In this paper, the effective wake of a fully appended SUBOFF is predicted based on a hybrid approach coupled with a surface panel method and the RANS simulation. To achieve a high accuracy and simplicity, a radial basis function (RBF) based approach is proposed for mapping the force field from the blade surface panels to the RANS grids. The effective wake field is determined in two ways, i.e., by extrapolation from the planar transverse sections upstream to the propeller disk, and by direct computation in a curved surface which is upstream of and parallel to the surface swept out by blade leading edge. The hull-propeller system of a real propeller geometry is further simulated with the sliding mesh model to verify the hybrid approach. The high accuracy of the RBF-based interpolation scheme for the body force field is confirmed, and the predicted effective wake fractions based on the hybrid approach and the sliding mesh model are found consistent.

1. Numerical method

1.1 *Hull resistance and nominal wake simulation*

To validate the present approach for the viscous flow simulation, the resistance and the nominal wake of the fully appended SUBOFF are predicted based on a steady RANS model. The standard k-ε model and the standard wall function are employed for the turbulence closure. The SIMPLE algorithm and the second-order upwind schemes are adopted for the pressure-velocity coupling and the spatial discretization, respectively. Numerical computations are carried out by using the ANSYS FLUENT software. A grid dependency study is conducted first with three sets of block-structured grids and a refinement ratio of $\sqrt{2}$, in circular cylindrical domains of identical size. The distances from the inlet to the bow, from the outlet to the stern, and from the central axis of the hull to the lateral boundary are, respectively, L, $2L$ and $10D_m$, where L and D_m denote the overall length and the maximum diameter of the hull, respectively. Figure 1 shows the grids on the hull surface.

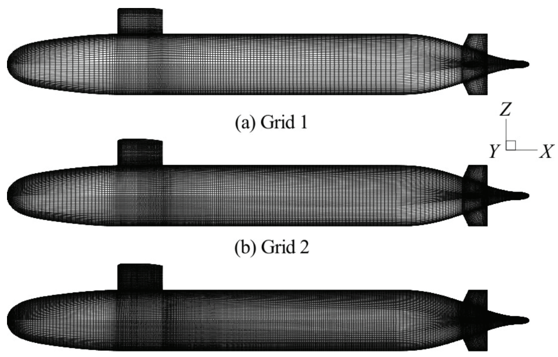

Fig.1 Grids on hull surface of SUBOFF

Table 1 shows the errors, as compared with the experimental data, of the calculated resistance at the model speed $V_m = 3.051$ m/s and the Reynolds number $Re = 1.2\times10^6$. The averaged y^+ of the wall-adjacent cells over the hull surface is about 50. It is seen that the maximum error is 3%, and the prediction error decreases with the increase of the number of cells.

Table 1 Comparison of resistance prediction results using different grids

	No. of cells	R / N	Error /%
Grid 1	2.47×10^6	105.33	3.0
Grid 2	4.98×10^6	104.21	1.9
Grid 3	11.18×10^6	103.25	0.9

The comparisons of the simulated and measured nominal wake fields in the propeller plane (longitudinal location $x/L = 0.978$ with $x = 0$ at the

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