Full scale KCS self-propulsion simulation using different propulsion models

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Abstract. It is critical to be able to estimate the full-scale ship self-propulsion, since the more real sailing performance of the ship can be assessed. Results of scaling model are used to predict full-scale self-propulsion performance. However, the difference between the full-scale prediction and reality would be caused by scale effect. URANS simulations is conducted to predict self-propulsion of a full-scale KRISO Container Ship with the propeller KP505. Design speed is selected as simulation working condition according to Gothenburg 2010. In house CFD code HUST-Ship will be used to solve RANS equation coupled with two degrees of freedom (2DOF) solid body motion equations including heave and pitch. RANS equations are discretized by finite difference method and solved by PISO algorithm. The discretized propeller model and improved body-force model are used as the propulsion models. Grid and time step sensitivity analysis of full-scale propeller and hull is conducted separately. The self-propulsion indexes of full-scale simulation are compared with the extrapolation of model experimental data and full-scale simulation results from literatures. The prediction self-propulsion indexes based on different propulsion models are compared and discussed.

1. Introduction

It is critical to be able to estimate the ship self-propulsion performance, since the more real sailing performance of the ship can be assessed. The traditional method of prediction is self-propulsion experiment in the towing tank, and it will provide data for both exploration of flow physics and for CFD validation [1]. CFD simulation of ship self-propulsion not only reduces lots of time and cost, but could provide more information of ship flow, ship wave and other details related to the ship hydrodynamic performance. So it is considered an effective approach to predict and access the self-propulsion performance. For a real step forward in prediction accuracy, the full-scale ship simulation using accurate and reliable viscous flow solvers is necessary [2]. Castro et al. [3] performed full-scale KCS self-propulsion computations with direct discretization of the propeller. Differences between the scale model and full-scale ship in the self-propulsion performance are discussed. Hrvoje et al. [4] performed full-scale CFD self-propulsion simulations for a cargo carrier and a car carrier and. Three grids were used to assess the grid sensitivity. Compared with sea trials, the results proved the reliability of using high–fidelity numerical methods to directly simulation full-scale ship performance.

There are two methods to simulate hull-propeller interference: discretized propeller and body force method. While discretized propeller can capture the detailed flow features around propeller blades, body force method can quickly obtain the self-propulsion parameters. Body-force method is recommended to simulate hull-propeller interference when the detailed propeller flow is not essential.
Stefano et al. [6] used a coupled BEM/RANS approach to extensively simulate self-propulsion and investigate its strength and weakness. This approach can make self-propulsion simulations affordable in the ship design stage. Feng et al. [7] proposed an improved body force propulsion model and verified the reliability of the method. For the open water propeller and wake flow effect, the hydrodynamic simulation results of new body force model are almost same to that of the discretized propeller model and save a lot of computation time.

In this paper, two propulsion models are adopted to simulate the full-scale KCS self-propulsion using PI speed controller, including discretized propeller model and an improved body-force method [7]. The analyses are performed at design speeds, using in house CFD code HUST-Ship to solve RANS equation coupled with two degrees of freedom (2DOF) solid body motion equations including heave and pitch. The full-scale simulations are compared with the extrapolation of model experimental data and full-scale simulation results from literatures to prove that the full self-propulsion result of HUST-Ship is reliable. The self-propulsion results and computation time of different propulsion models are compared each other. URANS equations are discretized by finite difference method and solved by PISO algorithm. Computations have been made using structured grid with overset technology.

2. Numerical method

2.1. CFD model

RANS solver HUST-Ship was used for all simulations in this paper. For an incompressible and viscous flow, the governing equations for conservation of mass and momentum can be written as:

\[ \nabla \cdot \vec{v} = 0 \]  \hspace{1cm} (1)

\[ \rho \left( \frac{\partial \vec{v}}{\partial t} + \nabla \cdot (\vec{v} \vec{v}) \right) = -\nabla \cdot \vec{p} + \nabla \cdot \vec{\tau} \]  \hspace{1cm} (2)

where \( \vec{v} \) is the velocity vector, \( \rho \) is the density, \( \vec{p} \) is dynamic pressure and \( \vec{\tau} \) is turbulent stress tensor. The anisotropic two equations Shear Stress Transport (SST) \( k-\omega \) model is selected as turbulence model.

Free surface would be simulated by single-phase level-set method. In this method, the water surface is regarded as the free interface, ignoring the influence of air. \( \varphi \) is defined as the distance from any point in flow field to free surface. The level-set function [7] is:

\[ \frac{\partial \varphi}{\partial t} + \vec{v} \cdot \nabla \varphi = 0 \] \hspace{1cm} (3)

\[ \varphi = \begin{cases} 
< 0, & \text{in water} \\
= 0, & \text{at free surface} \\
> 0, & \text{in air}
\end{cases} \] \hspace{1cm} (4)

In addition, initial thickness of grid is supposed to be smaller than viscous sublayer to capture the flow in the boundary layer. Usually, the non-dimensionalized distance from wall \( y^+ < 5 \) is required since the thickness of viscous sublayer is very small. The aspect ratio of the grid isn’t allowed to be too large. So full-scale simulation greatly increases the calculation cost because of its extremely thin boundary layer. To solve this problem, the multilayer wall function model [8] is used, which allows initial thickness of grid to be less than log layer where \( 30 < y^+ < 200 \).

In self-propulsion simulation, PI (proportional–integral) speed controller [5] in the form of equation (13) is used is applied to match propeller rotating speed at target speed:

\[ n = Pe + I \frac{\delta \theta}{dt} \] \hspace{1cm} (5)

where \( e = U_{\text{target}} - U_{\text{ship}} \) is the difference between instantaneous speed and target speed, \( P \) and \( I \) are the proportional and integral constants.

2.2. Propulsion models
There are two propulsion models used to simulate self-propulsion: discretized propeller model (left in figure 1) and body force model (right in figure 1). The rotation of discretized propeller is defined in ship local frame. The complex geometries and large-amplitude rotation of discretized propeller are processed using structured dynamic overset grid technique. For the body-force method, the improved method based on BEMT and considering the three-dimensional viscous effect of propellers is selected to simulate self-propulsion [5]. The propeller blade would be divided into 10 parts and the local velocity field is used to calculate the thrust and torque of each part.

\[
dL = 0.5C_L U_r^2 c(r) dr \tag{6}
\]

\[
 dD = 0.5C_D U_r^2 c(r) dr \tag{7}
\]

\[
 dT = dL \cos \beta - dD \sin \beta \tag{8}
\]

\[
 dQ = (dL \sin \beta + dD \cos \beta) r \tag{9}
\]

\[
 C_L = k_\alpha \sin \alpha + C_{\alpha} \tag{10}
\]

\[
 C_D = k_1 C_L^2 + k_2 \tag{11}
\]

\[
 \begin{bmatrix}
 k_a \\
 C_a \\
 k_1 \\
 k_2 \\
 \end{bmatrix} =
 \begin{bmatrix}
 -1.152 & 5.723 & -9.267 & 5.944 \\
 -0.047 & 0.216 & -0.278 & 0.170 \\
 0.199 & -0.972 & 1.589 & -0.323 \\
 -0.009 & 0.032 & -0.037 & 0.177 \\
 \end{bmatrix}
\]

\[
 \begin{bmatrix}
 c_r \mu \\
 c_r \eta \\
 c_r \gamma \\
 c_r \pi \\
 \end{bmatrix} =
 \begin{bmatrix}
 3 \\
 2 \\
 1 \\
 0 \\
 \end{bmatrix}
\]

\[
 \begin{bmatrix}
 1.9 \\
 0.2 \\
 1.5 \\
 -0.2 \\
 \end{bmatrix}
\]

In which, four coefficients \(k_a, C_a, k_1, k_2\) decide the performance of propeller (the lift coefficient \(C_L\) and the drag coefficient \(C_D\)) and are related to the propeller parameters, \(U_r\) is the local resultant speed, \(c(r)\) is the chord length at radius \(r\), the overall thrust \(T\) and torque \(Q\) are obtained by integrating the individual contribution of each element \(dT\) and \(dQ\) [5].

2.3. Computational domain and boundary conditions

The full-scale KCS (KRISO Container Ship) and propeller KP505 are selected as the self-propulsion computational models. Data for self-propulsion tests is available from Tokyo 2015 [9] and the complete database of ship KCS can be found via a web site link: https://t2015.nmri.go.jp/kcs.html.
structured dynamic overset grid is helpful to implement the motion (the 2DOF motion of ship and the rotation of propeller) and deal with the surface (the hull, tail of KCS and the blades, hub of KP505). The computational domain and the boundary conditions as well as the overset grids for hull and propeller are shown in figure 2 and figure 3.

![Figure 2. Computational domain and the boundary conditions.](image)

3. Results and discussion

3.1. The grid and time step sensitivity analysis

| Table 1. Full-scale ship resistances in different grid cases ($F_r = 0.26$). |
|---------------------------------------------------------------|
| Total Cell (M) | $C_T$ | Error (Medium %) |
|---|---|---|
| Coarse | 3.56 | 0.002631 | 4.12 |
| Medium | 4.94 | 0.002527 | — |
| Fine | 6.99 | 0.002513 | 0.55 |

| Table 2. Full-scale propeller results in different grid cases ($J=0.8$). |
|---|---|---|---|
| $K_T$ | Error (Medium %) | $K_Q$ | Error (Medium %) |
|---|---|---|---|
| Coarse | 0.121 | -3.20 | 0.0222 | -3.90 |
| Medium | 0.125 | — | 0.0231 | — |
| Fine | 0.126 | 0.80 | 0.0232 | 0.43 |

| Table 3. Full-scale propeller results in different time steps ($J=0.8$). |
|---|---|---|---|
| $K_T$ | Error (Medium %) | $K_Q$ | Error (Medium %) |
|---|---|---|---|
| Coarse | 0.118 | -5.60 | 0.0221 | -4.33 |
| Medium | 0.125 | — | 0.0231 | — |
| Fine | 0.127 | 1.60 | 0.0233 | 0.87 |
Before the full-scale simulation, grid and time step sensitivity analysis of full-scale propeller and hull is conducted separately. The grid sensitivity analysis of the full-scale ship resistance had been conducted before and results are listed in table 1. In addition, three grid cases and time step cases were used to conduct the grid and time step sensitivity analysis of full-scale KP505 using discretized propeller model as shown in table 2 and table 3. Medium grid spacing and time step were selected with less accuracy loss and higher efficiency.

3.2. Results of self-propulsion

Before full-scale self-propulsion simulation, open water simulations of the model- and full-scale propellers have been carried out. As shown in figure 4, the simulated open water characteristics have a great agreement with the experiment. In addition, the results of model- and full-scale propeller are almost same. The differences are less than 1% and 2.4% for thrust coefficient and torque coefficient. Thus, the model-scale body-force coefficients $k_a, C_a, k_1, k_2$ are used here to substitute the full-scale propeller for self-propulsion simulation.

For full-scale self-propulsion thrust deduction factor:

$$t_s = \frac{T_s - R_{ts}}{T_s}$$  \hspace{1cm} (13)

Self-propulsion wake factor:

$$w_t = 1 - \frac{JnD}{U}$$  \hspace{1cm} (14)

where $T_s$ is the thrust of propeller for self-propeller and $R_{ts}$ is resistance of ship for towed test, the advanced velocity coefficient $J$ can be obtained using the thrust identity method [10], $n$ is rotating speed of propeller, $D$ is diameter of propeller and $U$ is the ship velocity.

| EFD | CFDSHIP-Iowa 4.5[11] | HUST-Ship |
|-----|---------------------|-----------|
|     | Result  | Diff.   | Discretized | Result | Diff.  | Result  | Diff.   |
| $K_T$  | 0.170  | 0.166  | -2.35% | 0.169  | -0.59% | 0.168  | -1.18% |
| $n$   | 31.43  | 32.35  | 2.93%  | 33.04  | 4.87%  | 32.73  | 4.14%  |
| $J_t$  | 0.853  | 0.842  | -1.29% | 0.827  | -3.05% | 0.832  | -2.46% |
| $J_w$  | 0.792  | 0.794  | 0.19%  | 0.814  | 2.78%  | 0.808  | 2.02%  |
| $J$    | 0.728  | 0.714  | 1.92%  | 0.726  | -0.27% | 0.718  | -1.37% |

PI control method is used to match the propeller rotating speed at $F_r = 0.26$ where the target velocities for full-scale are 24kn. The self-propulsion simulation and experiment results are non-
dimensionalized for comparison as shown in table 4. $n' = n/U \times L$ is non-dimensionalized rotation velocity. Differences between EFD prediction and full-scale results of different propulsion models are less than 5%. Compared with CFDShip-Iowa 4.5 [11], the simulation results using HUST-Ship almost have no difference. Therefore, it is credible to simulate full-scale ship self-propulsion by HUST-Ship. Moreover, it is reasonable to extrapolate the model-scale self-propulsion results to full-scale. Comparing body-force results with discretized propeller as shown in table 4, it is found that all the self-propulsion factors of body-force simulation are smaller except that $1 - t_s$ is larger. The smaller $1 - w_t$ of body-force indicates the wake velocities are smaller leading to the smaller resistance and the smaller rotation speed. But all the differences of self-propulsion results between body-force and discretized propeller model are less than 1.5% which can prove the reliability of body-force for full-scale self-propulsion prediction. In addition, body-force model has saved about 50 times computation time.

4. Conclusions
In the present study, URANS simulations are carried out to obtain full-scale self-propulsion performance using HUST-Ship. By analyzing and comparing simulated self-propulsion indexes with EFD prediction, the conclusions are following as:

1. Comparing the CFD results with the EFD data and CFDShip-Iowa 4.5, it is found to be credible to simulate full-scale ship self-propulsion by HUST-Ship.

2. Results of open water characteristics show that the propeller scale effect can be ignored. The model-scale body-force coefficients are allowed to substitute the full-scale propeller for self-propulsion simulation.

3. Using improved body-force to predict full-scale self-propulsion performance is reliable. Moreover, it can greatly reduce the computation time.

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