Numerical Investigation of Propeller-Rudder Interaction Based on Body Force Approach

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ABSTRACT

Ship maneuvering is a very complex hydrodynamic problem, involving the hydrodynamic performance of hull, propeller and rudder. In the present study, the KP505 propeller and the rudder with NACA0018 section are adopted to study the propeller-rudder interaction in the ship maneuvering. The solver, pimpleDyMFoam in open source platform OpenFOAM, is used to predict the hydrodynamic characteristics of the model propeller and rudder. The mesh independency and time step convergence are performed to ensure the reliability of the numerical calculations. To perform the simulations on the propeller-rudder interaction quickly, a solver based on pimpleDyMFoam is independently developed by introducing three body force models including uniform thrust distribution, H-O distribution and blade element theory. In the numerical simulations, the advance ratio of propeller is design advance ratio, J=0.7 and the angles of rudder are 0°. The predicted results by using body force models are compared with the results for the model propeller. It is found that the propeller-rudder interaction can be better captured by using blade element theory.

KEY WORDS: Propeller, Rudder, Propeller-rudder interaction, OpenFOAM, Numerical simulation, Blade element theory, uniform thrust distribution, asymmetry distribution.

INTRODUCTION

Propeller and rudder are the two devices that are essential for ship self-propulsion. In the self-propulsion of ship, the fluid around the propeller is accelerated in the axial and tangential directions by the rotation of propeller. And since the rudder is typically placed downstream of the propeller, the rudder experiences the flow accelerated by the propeller and affects the hydrodynamic performance of the propeller in turn. In order to analyze the hydrodynamic performance of the propeller quickly, researchers have proposed various body force models of propeller, such as the uniform thrust distribution, Hough and Ordway distribution, blade element momentum theory. Originally, these body force models were only used to predict the open water performance of propellers (Benini, 2004; Allsop, 2017), but later they were gradually used to study the interaction of hull-propeller-rudder (Phillips, 2009; Win, 2013; Broglia, 2013).

Schetz and Favin (1977) simulated the flow field around a 2D section by implemented the uniform thrust distribution with the torque being negligible. Zhang (2010) used the body force approach and sliding mesh approach to study the propeller/hull interaction. And the Hough and Ordway distribution is selected in his study. Gao and Jin, et al. (2012) used three methods, such as the propeller open water test and momentum theory of the propeller, to calculate the propeller induced velocity. Their results showed the results from the momentum theory were over-predicted significantly. Zheng and Chen, et al. (2015) studied the hull/propeller interaction by coupling RANS and Vortex Lattice Method (VLM). And the predicted results were in good agreement with the measured data. The RANS/VLM method predicted the performance of self-propulsion accurately. Based on the Hough and Ordway distribution, Fu and Than, et al. (2015) simulated the viscous flow field of KCS at ship point. Their study indicated that the predicted accuracy can be improved by considering torque and the more flow features also was able to be captured.

The body force models of propeller are mainly used to investigate the hull/propeller interaction. The propeller-rudder interaction is rarely studied. Phillips and Turnock, et al. (2010) studied the propeller-rudder interaction by using three body force models including uniform thrust distribution, Hough and Ordway distribution and blade element momentum theory. In their study, three rudder angle, 0° and ±10°, were selected. And the calculated results were compared with the experiment. At last, the blade element momentum theory was proved to be a suitable body force method to capture pressure distribution on the rudder. While the contours of pressure distribution on the rudder were not presented, and the influence of the rudder on propeller was not analyzed. Currently, the open source code platform OpenFOAM...
are used increasing widely in the numerical simulation of the hydrodynamic performance of hull-propeller-rudder. He and Wan (2017, 2018) investigated the hydrodynamic characteristics of contra-rotating propellers. Xu and Wan (2018) studied the scale effect for propeller boss cap fins.

In the present work, the propeller-rudder interaction is studied by using three body force models. The code of body force models is developed based on pimpleDyMFoam, the single-phase solver in open source code platform OpenFOAM. The main framework of this paper goes as following. The first part is the numerical methods, where governing equations and body force models are presented. The second part is the geometry model of the propeller and rudder. Then comes the mesh independency and time step of the model propeller case, which is the basis for the body force models cases. And next is the comparison of calculated results obtained by different models. Finally, the conclusion of this paper is drawn.

NUMERICAL METHOD

Governing Equations

In the simulations, the Unsteady Reynolds Averaged Navier-Stokes (URANS) equations are used for unsteady turbulent flows of propeller-rudder interaction. URANS equations (Wang, 2019) include the mass conservation equation and the momentum conservation equation. Both equations are written as

\[ \nabla \cdot U = 0 \]  
(1)

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho (U - U_g)) = -\nabla p_{pl} - g \cdot x \nabla \rho + \nabla \cdot (\mu_{eff} \nabla U) + (\nabla U) \cdot \nabla \mu_{eff} + f_b \]  
(2)

where \( U \) is fluid velocity field and \( U_g \) is the grid velocity; \( \rho \) is the mixture density; \( f_{pl} \) represents the dynamic pressure; \( p_{pl} \) is the mixture density; \( g \) is the gravity acceleration; \( \mu_{eff} \) is effective dynamic viscosity, in which \( v \) and \( v_t \) are kinetic and eddy viscosity, respectively, and \( v_t \) is obtained from turbulence model. \( f_b \) is body force term. And the body force obtained from different models is added to momentum equation. In the present work, the codes of the body force model of propeller are developed based on pimpleDyMFoam, the single phase solver in open source platform OpenFOAM.

The turbulence model, SST \( k-\omega \), is selected to solve the Reynolds stress, with the model combining the advantages of the standard \( k-\epsilon \) model and \( k-\omega \) model. Since the flow field of propeller-rudder interaction is an unsteady one, the rotation of propeller is simulated by the sliding mesh, which is more suitable than moving reference frame (MRF).

Uniform Thrust Distribution

The uniform thrust distribution is the simplest approach without torque being taken into consideration. The thrust is uniform in the radial direction. The axial force source \( f_{bx} \) and tangential momentum source \( f_{b\theta} \) can be obtained by the bellow equations:

\[ f_{bx} = \frac{T}{\Delta x \pi (R_p - R_h^2)} \]  
(3)

\[ f_{b\theta} = 0 \]  
(4)

where \( \Delta x \) is the thickness of the propeller subdomain, usually taken as the thickness of hub. \( R_p \) and \( R_h \) are the radius of hub and propeller, respectively. \( T \) is the thrust provided from experiments or numerical prediction.

Hough and Orday Distribution

Hough and Orday distribution is the asymmetry distribution of thrust and torque, which matched Goldstein’s optimum distribution. According to this distribution, there is zero loading at tip and root of the blade. The non-dimensional distribution of thrust and torque is given by (Phillips, 2010):

\[ f_{b_x} = A_x r^s \sqrt{1 - r^*} \]  
(5)

\[ f_{b_y} = A_y r^s \sqrt{1 - r^*} \]  
(6)

with

\[ A_x = \frac{C_T}{\Delta x 16(4 + 3Y_h)(1 - Y_h)} \]  
(7)

\[ A_y = \frac{K_Q}{\Delta x J^2} \]  
(8)

\[ C_T = \frac{K_q}{\pi [J^2]} \]  
(9)

where \( r^* \) is the non-dimensional radius, and it is defined as \( r^*=(Y-Y_h)/(1-Y_h) \) with \( Y=\pi R_p \) and \( Y=\pi R_h/R_0 \);

Blade Element Theory (BET)

According to the blade element theory, the thrust and torque distribution is determined by the pitch, rotation speed and advance ratio. The radial and circumferential variation of propeller can be captured by using blade element theory. The propeller disk is divided into 10 divisions in radial direction and 36 divisions in circumferential direction. The local thrust and torque are determined based on the segmented inflow of propeller. As shown in Fig. 1, \( V_A, 2\pi \alpha_n \) and \( \theta \) represent the axial, tangential and resulbtant velocity. \( V_A \) and \( 2\pi \alpha_n \) are obtained by interpolating the velocity from the grid unit of Finite Volume Method (FVM) to the actuator points. \( \alpha \) and \( \beta \) are the attack angle and pitch angle. The lift and drag are calculated according to the lift and drag coefficients at this attack angle and inflow velocity. The thrust and torque of blade element can be obtained by decomposing the lift and drag.
GEOMETRY MODEL

The propeller model, KP505, and rudder with NACA0018 section are adopted to investigate the propeller-rudder interaction in the present simulations. The geometry of propeller and rudder are presented in Fig. 2. They are matched to the ship model of KCS for the Case3.2 in SIMMAN2020. And the main parameters of KP505 and rudder are listed in Table 1.

![Fig. 1 Definition of flow and force directions on a blade element](image1)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Model scale</th>
<th>Full scale</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scale</strong></td>
<td>37.89</td>
<td>1</td>
</tr>
<tr>
<td><strong>Propeller</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D$ (m)</td>
<td>0.2085</td>
<td>7.900</td>
</tr>
<tr>
<td>$P/D$ (mean)</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>$A_0/A_0$</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Rake$^\circ$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Skew$^\circ$</strong></td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td><strong>Rudder</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Section</td>
<td>NACA0018</td>
<td>NACA0018</td>
</tr>
<tr>
<td>$S$ rudder (m$^2$)</td>
<td>0.0801</td>
<td>115.0</td>
</tr>
</tbody>
</table>

MESH INDEPENDENCY AND TIME STEP

In the numerical simulations, grid independence and time step are very critical to ensure the predicted accuracy. The computational domain is presented in Fig. 3. Since the propeller and rudder are always operating near the free surface, the distance between the top boundary and the origin is only 0.85D. In the present simulations, the top boundary is set as the symmetry plane to ignore the influence of free surface to propeller-rudder interaction. The outerCylinder is the patch with velocity being zero gradient.

**Mesh Independence**

Three mesh resolution are adopted to analyze the mesh independency. The all hex-unstructured grids are generated with the refinement ratio being $\sqrt{2}$ (Yu, 2019). Since the sliding mesh approach is used, the computational domain is divided into two static and rotational domains. The interface between both domains is set as the arbitrary mesh interface (AMI). The grid size on the interface should be as same as possible to avoid the possible divergence.

Table 2 shows the grids schemes with different mesh resolutions. The total mesh with medium mesh resolution is about 1.71 million. Fig. 4 depicts the grid distribution with medium mesh resolution. Fig. 4 (a) shows the global grid distribution. Red and blue represent the rotational and static domain, respectively. Fig. 4 (b) and (c) are the grid distribution of propeller and rudder.
In the present calculations, the design advance ratio of propeller is selected with zero rudder angle. The setup is presented in Table 3. At the advance ratio, the propeller is the most efficient. The thrust and torque coefficients of propeller shown in Table 3 are the results in open water. The rotation speed of propeller is 11.88rps. The comparison will be carried out between the open water and propeller-rudder interaction.

Table 3 Calculation conditions

<table>
<thead>
<tr>
<th>Propeller (open water, experiment)</th>
<th>Rudder</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J$</td>
<td>$K_r$</td>
</tr>
<tr>
<td>0.7</td>
<td>0.177</td>
</tr>
<tr>
<td>0°</td>
<td></td>
</tr>
</tbody>
</table>

Unlike propeller in open water, the hydrodynamic performance of propeller is affected by the rudder downstream. As shown in Fig. 5, there are large fluctuations appeared on the time history curve of the torque; and five peaks appear in one period with the propeller having 5 blades. As we can see, the torque obtained from the coarse mesh resolution is slightly larger than the other results. The almost same results are achieved by the medium and fine mesh resolutions. The mean values in a period are listed in Table 4. As listed in the table, the results obtained from three cases are almost the same. The error is relative to the value for the minimum time step. However, the predicted thrust and torque obtained from the largest time step is larger than the other two cases slightly. And the predicted results using medium time steps are satisfactory. This indicts that the medium time step can achieve the accuracy requirement in the numerical simulations.

Table 4 Comparison of predicted results with different mesh resolution level

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Thrust/N</th>
<th>Error</th>
<th>Torque/NM</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse</td>
<td>51.3158</td>
<td>0.665 %</td>
<td>1.9532</td>
<td>1.349 %</td>
</tr>
<tr>
<td>Medium</td>
<td>51.0129</td>
<td>0.071 %</td>
<td>1.9327</td>
<td>0.285 %</td>
</tr>
<tr>
<td>Fine</td>
<td>50.9767</td>
<td>-</td>
<td>1.9272</td>
<td>-</td>
</tr>
</tbody>
</table>

Time Step

Since the flow field of propeller-rudder interaction is an unsteady one, it is necessary to carry out the time step convergence analysis. In this segment, three time steps are adopted. $\Delta t_1, \Delta t_2, \Delta t_4$ indicates that the propeller rotates by 1°, 2°, 4° in a time step, respectively. The predicted thrusts by using different time step are shown in Fig. 6. As we can see, the result obtained by the case $\Delta t_4$ is larger than the other two cases. And the mean values of the thrust and torque in one period are listed in Table 5. As listed in the table, the results obtained from three cases are almost the same. The error is relative to the value for the minimum time step. However, the predicted thrust and torque obtained from the largest time step is larger than the other two cases slightly. And the predicted results using medium time steps are satisfactory. This indicts that the medium time step can achieve the accuracy requirement in the numerical simulations.

According to the predicted results and analysis, the medium mesh resolution (1.71million) and medium time step ($\Delta t_2$) are used in the subsequent numerical simulations.
RESULTS AND ANALYSIS

Hydrodynamic Characteristics of Propeller

In the present numerical simulations, three body force models are adopted to predict the propeller-rudder interaction. The predicted results are listed in Table 6. As we can see, the results obtained by the Hough and Ordway distribution and Uniform Thrust distribution are the same as the experiment in open water. This is because that thrust and torque obtained from the experiment are applied to the flow field in both body force models. But the influence of the rudder on the propeller is not captured. While the propeller-rudder interaction is capture well though the blade element theory, and the thrust and torque increase slightly by comparing with the experiments in open water. And compared with the results obtained from the model propeller case, the errors of thrust and torque are 1.16% and -3.11%, respectively.

Pressure Distribution on Rudder

Fig. 7 shows the pressure distribution of rudder, which is the mean value in a period. Firstly, As we can see, the results achieved by blade element theory is almost the same as that in the case of model propeller qualitatively. While, there is a larger difference between the pressure distribution obtained by H-O and UT distributions. Although the rotation effect of the propeller has been considered according to H-O distribution, the influence of the rudder on the propeller cannot be reflected. So the pressure distribution of rudder cannot be accurately captured. And the rotation effect is not taken into consideration in the uniform thrust distribution, so the pressure distribution is more worse.

Table 6 Predicted thrust and torque of the propeller from different body force models

<table>
<thead>
<tr>
<th>Setup</th>
<th>Thrust/N</th>
<th>Error</th>
<th>Torque/NM</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propeller (Open water, EFD)</td>
<td>47.1624</td>
<td>-</td>
<td>1.6667</td>
<td>-</td>
</tr>
<tr>
<td>Propeller-Rudder Interaction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model propeller (CFD)</td>
<td>51.0129</td>
<td>8.16%</td>
<td>1.9327</td>
<td>15.96%</td>
</tr>
<tr>
<td>Blade Element Theory</td>
<td>51.6027</td>
<td>9.41%</td>
<td>1.8726</td>
<td>12.35%</td>
</tr>
<tr>
<td>Hough Ordway</td>
<td>47.1624</td>
<td>-</td>
<td>1.6667</td>
<td>-</td>
</tr>
<tr>
<td>Uniform Thrust</td>
<td>47.1624</td>
<td>-</td>
<td>1.6667</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5 Comparison of thrust and torque with different time step

<table>
<thead>
<tr>
<th>Time step</th>
<th>Thrust/N</th>
<th>Error</th>
<th>Torque/NM</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>51.1536</td>
<td>0.507%</td>
<td>1.9391</td>
<td>0.524%</td>
</tr>
<tr>
<td>Δt1</td>
<td>51.0129</td>
<td>0.230%</td>
<td>1.9327</td>
<td>0.192%</td>
</tr>
<tr>
<td>Δt2</td>
<td>50.8957</td>
<td>-</td>
<td>1.9290</td>
<td>-</td>
</tr>
</tbody>
</table>
From the previous section, the blade element theory method better simulates the pressure distribution on the rudder. The next is the analysis of wake field on three planes obtained by the model propeller and blade element theory cases, as shown in Fig. 10, Fig. 11 and Fig. 12. Overall, the wake field obtained by the blade element theory is almost the same as the results from the model propeller case. However, the velocity normal to the blade section is not taken into consideration according to this theory. So that the three dimensional effects are not well reflected. As shown in Fig. 10 (e) and (f), the highest velocity on the portside is not captured by the blade element theory. And the axial and lateral velocity are almost the same in both cases. In Fig. 11, the gradient of axial velocity calculated by BET model is larger than that in the model propeller case. And the axial velocity near the rudder is lower than the results presented in Fig. 11 (a). The large differences in vertical velocity are also presented in Fig. 12 (e) and (f). The area of high velocity is larger than the results obtained by the blade element theory obviously. This indicates that the propeller-rudder interaction can be predicted by the blade element theory at the design advance ratio.
CONCLUSION

In the present study, the code implementing body force models of propeller is developed based on the solver, pimpleDyMFoam, in the open source code platform OpenFOAM. The propeller and rudder of KCS are adopted in the present simulations. In order to ensure the accuracy and reliability of the numerical prediction, the mesh independency and time step converge are performed. The propeller-rudder interaction is investigated by the numerical simulations with the model propeller and three body force models. Due to the influence of the rudder, the thrust and torque of the propeller increases by 8% and 16% approximately by compared with that in open water. The blade element theory is more suitable for the propeller-rudder interaction. Though the blade element theory, not only the increase of thrust and torque of propeller are accurately predicted, but also the pressure distribution on the rudder is accurately captured. And the both aspects are not predicted accurately by using the other two body force models obviously.

In the future work, the propeller-rudder interaction with non-zero rudder angle will be carried out by the numerical simulations. In addition, the flow incident angles are also taken into account. The
mechanism of propeller-rudder interaction is going to be studied further.

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