Hydrodynamic Characteristics of the Propeller-Rudder Interaction by RANS Solver

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Abstract This paper is presented the interaction between propeller and rudder at different operating conditions by using ANSYS-Fluent software. A moving reference frame (MRF) method is applied and the flow equations are solved using Reynolds-Averaged Navier-Stokes (RANS) method and the K-ω SST turbulent model. The propeller is selected VP1304 and rudder is spade type with NACA0015 section. Hydrodynamic characteristics of the propeller with and without rudder, effect of rudder on the propeller performance, rudder lift and drag, pressure and velocity contour are presented discussed. The results show that the rudder effect on the propeller is small while the propeller on the lift and drag of the rudder may be significant.

Keywords: propeller VP1304, spade rudder, hydrodynamic characteristics, lift and drag coefficients

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1. Introduction

Propeller and rudder are located behind the ship where the flow into the propeller is non-uniform and unsteady. Propeller generates thrust to run the ship. Rudder is for making maneuvering the ship. Both of them are lifting bodies like wing and hydrofoil. Working of the numerical methods for the propeller, rudder behind the ship is very complicated because of they are operating in the wake field. Many numerical methods have been done for the propeller-based on RANS method since 1990. The probability of solving the Navier–Stokes equations based on RANS method was presented [1]. The propeller geometry with flow properties and the propeller solution using RANS method determined [2,3].

Rudder is a control surface and is employed for the ship to maneuver the ship. A comprehensive book for the marine rudder and control surface is published by Moland & Turnock [4]. The flow in periphery of the rudder using numerical analysis was studied [5]. The hydrodynamic response of a 3D model on a hydrofoil using boundary element method with cavitation consideration investigated [6]. An idea to improve rudder performance by testing a scaled model proposed [7]. Interactions between the rudder and propeller in low velocities using two high precision meshes presented [8]. A four-blade propeller together with a rudder with NACA0020 cross-section was studied [9]. The hull-propeller-rudder interactions of twin-screw carried out by CFD [10]. The unsteady propeller and rudder interaction numerically investigated [11]. Ghassemi et al carried out comprehensively on different marine propulsors using computational fluid dynamics and boundary element method (CFD and BEM). They investigated on the hydrodynamic characteristics of the propeller-rudder system (PRS) and AZIPOD [12,13,14]. They also prepared a comprehensive HPSOP code for hydrodynamic multidisciplinary optimization of a ship and its propeller [15,16,17,18].

In this article, the numerical results of the propeller and rudder interactions are presented. The rudder angles are shown on the propeller performance. The following sections are organized as follows: Results of the hydrodynamic characteristics of the propeller is validated in Sec. 2. The propeller and rudder interaction are presented and discussed in Sec. 3. Finally, the conclusions are given in Sec. 5.

2. Hydrodynamic Characteristics of the Propeller

In that experiment the propeller was tested in conditions corresponding to the tow test, with shaft immersion equal to 1.5 of propeller diameter D. In the resent research, to obtain open water propeller characteristics the simulation calculations were performed for the following values of the advance coefficient J= 0.6, 0.8, 1.0, 1.2 and 1.4. The range of analysis usually includes the design operation point, i.e. the parameter for which the propeller has been designed. The results of experimental and numerical
examination of the propeller are shown in the form of dimensionless thrust and torque coefficients as functions of rotational speed \( n \) and diameter \( D \) of the propeller, and water density \( \rho \).

The propeller thrust coefficient:

\[
K_T = \frac{T}{\rho n^2 D^4}.
\]

The propeller torque coefficient:

\[
K_Q = \frac{Q}{\rho n^2 D^5}.
\]

Speed (advance) coefficient:

\[
J = \frac{V_a}{n D}.
\]

Propeller efficiency:

\[
\eta = \frac{J}{\pi} K_T K_Q.
\]

where \( T \) is thrust [N], \( Q \) is torque [Nm] and \( V_a \) is advance speed [ms\(^{-1}\)].

The propeller is tested in the fluid at 15.6°C that density and kinematic viscosity are 999 kg/m\(^3\) and 1.124e-6 m\(^2\)/s, respectively.

This paper is presented the hydrodynamic performance of the propeller-rudder behind the ship by using ANSYS-Fluent software. The propeller is VP1304 (or PPTC). The main dimensions are given in Table 1.

**Table 1. Main dimensions of the VP1304 propeller**

| Parameter                   | Value   |
|-----------------------------|---------|
| Diameter (D) [m]            | 0.250   |
| Pitch ratio at r/R=0.7 (P/D) [-] | 1.635  |
| Expanded area ratio (EAR) [-] | 0.779  |
| Chord length at r/R=0.7 (c/D) [-] | 0.1047 |
| Skew angle [deg]            | 18.84   |
| Hub ratio (r/h/R) [-]       | 0.300   |
| Number of blade (Z) [-]     | 5       |
| Rotation direction          | CW      |
| Propeller type              | CPP     |

**2.1. Validation for Propeller Results in Open Water**

The propeller was designed in Solidworks software according to the reported information by SVA. In this study, the 2012 version of this software and Ansys collection software including ICEM and Design Modeler were applied for geometrical designs. It should be noted that, in numerical analysis, the CAD model should be simplified and the complications should be avoided. Moreover, sharp edges should be avoided designing the propeller. Figure 1 shows the CAD model of the propeller in Solidworks.

In this study, the MRF is employed for simulation. Solution field and the moving frame were designed in periphery of the propeller. Computational domain of the propeller is shown in Figure 2. For numerical modeling, the solution field should be divided in finite volumes. So, a proper mesh should be applied to the model. In this study, the meshing was done using ANSYS-ICEM software. Figure 3 presents the Meshes of the propeller and its moving frame.

![Figure 1. CAD model of the propeller in Solidworks](image1)

![Figure 2. Computational domain of the propeller](image2)

![Figure 3. Meshes of the propeller and its moving frame](image3)
After finding the mesh numbers and the results of thrust coefficient, the numerical method extended to calculate the hydrodynamic characteristics of the propeller in open-water condition. Figure 5 show the comparison of the numerical results and experimental data of the open-water propeller characteristics. The maximum relative error for the thrust coefficient is less than 10% and for the torque is less than 9% that are occurred at low advance.

3. Results of the Propeller-Rudder Interaction

A spade rudder is selected for the ship with section of the NACA0015. The selected rudder has 276 mm height (or span) and 194 mm chord (chord at root 270 mm and at tip is 118). Aspect ratio and taper ratio are 1.4 and 0.42, respectively. Figure 6 is presented the propeller and rudder.

The lift (lateral force) and drag of the rudder coefficient are defined as

\[ C_L = \frac{L}{0.5\rho A_R U^2} \]  

\[ C_D = \frac{D}{0.5\rho A_R U^2} \]

where \( L \) and \( D \) are lift [N] and drag [N], \( U \) is inflow velocity to the rudder [ms\(^{-1}\)]; and \( A_R \) is the rudder area.

When the rudder is located behind the propeller (distance from the propeller to rudder, 0.25D) the propeller characteristics with and without rudder is shown in Figure 7. Here the rudder angle is zero (\( \delta_R = 0 \)). As shown in this figure, the thrust is almost the same with and without rudder, except at \( J=0.2 \) that is increased with rudder.

\[ KT, 10Kq, \eta \]
Figure 8. Thrust coefficient of the propeller against rudder angle at three advance coefficients

Figure 9. Torque coefficient of the propeller against rudder angle at three advance coefficients

Figure 10. Lift coefficient of the rudder with and without propeller (J=0.4, J=1.1).
Figure 8 and Figure 9 show the thrust and torque of the propeller against rudder angles at three advance coefficients (J=0.16, 0.8 and 1.4). It is observed that both thrust and torque are very slightly increased.

Rudder lift and drag coefficients (C_L and C_D) against rudder angles are presented at Figure 10 and Figure 11 at two advance coefficients (J=0.4 and 1.1) with and without propeller. When the rudder is located behind the propeller the lift and drag are more than in case of without propeller. It is may be due to the propeller induced velocities.

Pressure and velocity contour are presented at J=1.1 and $\delta_R = 30$ in Figure 12. The high pressure is found at face side of propeller and in one side of the rudder.
4. Conclusion

In this study, hydrodynamic characteristics of propeller and rudder at various conditions are calculated. Based on the numerical results, the following conclusions may be drawn:

- The present numerical results of the propeller characteristics are well agreed with the experimental data at high and low advance coefficients. The maximum relative error for the thrust coefficient is less than 10% and for the torque is less than 9% at low advance coefficients. Average error is less than 5%.

- Effect of the rudder on the propeller characteristics is caused to increase slightly

- Rudder lift and drag are increased when it is located behind the propeller. So, it may be concluded that rudder effect on the propeller is very small while the propeller on the rudder lift and drag is significant.

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