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Investigation on Rudder Hydrodynamics for 470 Class Yacht †

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Abstract: The rudder is an important appendage and used to adjust the course and balance the lateral displacement in the sailing regatta. RANSE (Reynolds-averaged Navier-Stokes Equations) was used to simulate the viscous flow field of the hull for 470 Class yacht based on CFD (Computational Fluid Dynamics). It is found that the stall angle was 30 degrees when the displacement is 280 kg and the boat speed is 2 m/s to 8 m/s. If the speed increases, the wake flow of the hull will influence the valid area of the rudder and span-chord ratio and the stall angle will be 35 degrees at the speed of 10 m/s. The lift-drag ratio will increase when the rudder angle is from 10 degrees to 25 degrees. The results would provide a theoretical reference for athletes to manipulate the sailboat.

Keywords: 470 Class yacht; rudder; stall angle; numerical simulation; hydrodynamics

1. Introduction

Class 470 yacht is one of the most important events at the Olympic Games, and sailing competition's course in the complex sea condition of certain sea areas. Each game is subjected to multiple rounds of up wind, down wind and crosswind processes [1]. Excellent athletes have tactics when jibing and tacking. The rudder plays an important role in adjusting courses and balancing the hull in a competition. Research on rudder hydrodynamics with different controlling methods would reveal the performance of the rudder equipment, promote coaches' and athletes' understanding of the equipment performance, which can make the adjustment of sailing equipment in the competition more reasonable, make a better control of the hull, help athletes keep heading, choose a better route to complete the race, and reduce resistance during the sailing process. The scientific manipulation of sailing is a guarantee of winning.

With the improvement of computer performance and numerical method, researches on the yacht project based on the CFD had become popular. Parolini et al. (2005) [2] made a research on the America's cup sailing ship of different states by solving the Reynolds-averaged Navier-Stokes equations, and the result of this research made a contribution for the winner of Alinghi Team in the America's cup. Mylonas et al. (2012) [3] made a research on the hydrodynamic performance of the America's cup sailing ship, which showed that simulated result of the Large Eddy Simulation method and the Detached Eddy Simulation method is smaller than the test results, it can more accurately simulate the near wall flow by using the LES model. Viola et al. (2014) [4] conducted a test of the optimal location of athletes on Aura 1:4 model in the towing tank. Giulio et al. (2016) [5] used CFD

method to capture the hydrodynamic performance of a naval supply vessel with a single rudder and a pair of rudders. It was found that twin rudder can improve stability of the hull.

China in recent years has witnessed many researches in this domain, Ma Yong et al. (2007) [6,7] worked on windsurfing and sailing for the fluid performance. Zheng Qinzhen et al. (2015) [8] based on the total station measured the 470 Class yacht and Laser yacht shape. Lin Shijie et al. [9] used CFD to study the variation law of hull resistance under different pitch angle of Laser hull, and obtained the best aspect angle of hull. Zhang Zhiyong (2016) [10] used CFD to study hydrodynamic performance of the different centerboard angle of the 470 Class yacht, analysed the law of the centerboard action and combined the sailing competition. Summary foreign researchers mainly focus on the America's Cup keel-type galleon research, while Chinese researchers gradually carried out the application of individual sailing from 1980s of last century. There is still room for research in 470 Class yacht rudder.

In order to investigate the hydrodynamic performance of 470 Class yacht rudder. This research method based on CFD for viscous flow of 470 Class yacht rudder assembly simulation is carried out through the analysis of hydrodynamic parameters, a clear effect of hull and rudder hydrodynamic performance, provided the basis for rudder maneuvering and the strategy aim to explore around the standard in sailing the actual game in the process, to provide theoretical and scientific guidance for coaches and athletes. Forthemore, the result preferred rudder manipulation and hull performance.

2. Methods of Analysis

2.1. Numerical Model and Conditions

Class 470 yacht is a two-person racing boat with excellent dirigibilities. The weight of the hull is 118 kg, and the weight of the two athletes ranges from110 kg to 180 kg. The tunnage is assumed to be 280 kg in this study. The numerical model is the hull-rudder assembly, modeling in CAD and ANSYS 15.0. The related parameters are shown in Table 1.

Table 1. Parameters of Class 470 yacht.

Hull (*L*)	**Beam (*B*)**	**Span-Rudder (*h*)**	**Chord-Length (*b*)**	**Wetted Area-Rudder (A_R)**
4.7 m	1.89 m	0.675 m	0.25 m	0.168 m^2

This paper simulated hull-rudder assembly of Class 470 yacht in different rudder angles and with different speeds and the data according to the actual research of the national sailing team. The velocities of yacht are 2 m/s, 4 m/s,6 m/s,8 m/s,10 m/s and the rudder angle range is from 0 to 40 degrees, and each interval is 5 degrees.

2.2. Research Methods

2.2.1. Governing Equations

Assuming that the flow field around the sailboat is incompressible, this study adopted RANS equations and continuity equations as governing equations. In Cartesian coordinates, the continuity equation and the momentum equation can be expressed asfollows:

Continuity equation:

$$\frac{\partial u_i}{\partial x_i} = 0, \tag{1}$$

Momentum conservation equation:

$$\frac{\partial (u_i u_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[v_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] - \frac{\partial \left(\overline{u_i' u_j'} \right)}{\partial x_j} + B_i, \tag{2}$$

Where u_i is average velocity and $u_i^{'}$ is fluctuation velocity (i = 1, 2, 3), ρ is the fluid density, t is time, v_t is the kinetic viscosity of the fluid, B_i is body force and $\overline{u_i^{'}u_j^{'}}$ is turbulent influence.

2.2.2. Boundary Conditions

The computational domain and boundary conditions as shown in Figure 1, the boundary conditions were velocity-inlet, the direction was the negative X direction; pressure-outlet, which is easy for iteration converges; left and right boundaries were symmetry planes; the bottom boundary was slip wall named moving wall; rudder wall was no slip wall.

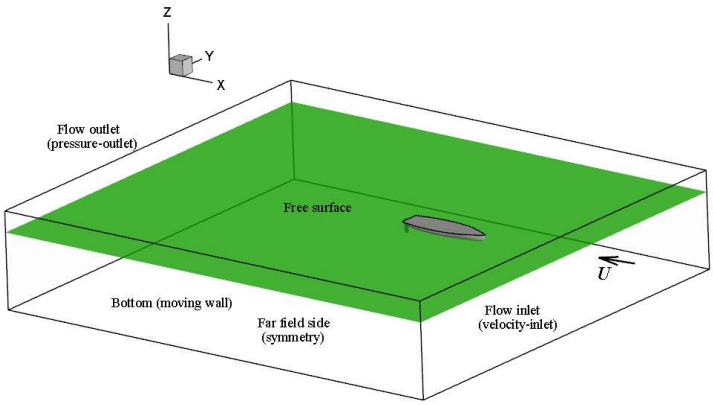


Figure 1. Computational Domain and Boundary Conditions of Numerical model (The green plane is the free surface).

2.2.3. Mesh Generation

The rudder grids were meshed in ICEM CFD 15.0, and the computational domain of the hull-rudder assembly was a hybrid grid. The hull-rudder assembly area was unstructured grid. As a result, it improves the computational efficiency of the numerical simulation. Among them, the first mesh size and the gradient parameter were set up to capture the boundary layer in unstructured grids, so that the boundary layer satisfied the distance of the first neighbor grid, the first mesh distance y^+ = 60~100, and the total grid amount was about 5 million.

2.2.4. Coordinate System and Dimensionless Expression of Hydrodynamic Force

The hull-rudder assembly XY section coordinate system can be indicated by Figure 2. The bow was along the X positive direction, and the Z direction was the water depth direction. The flow direction was negative X. The distance between the center of the rudder and the center of gravity of the hull was 2.52 m.

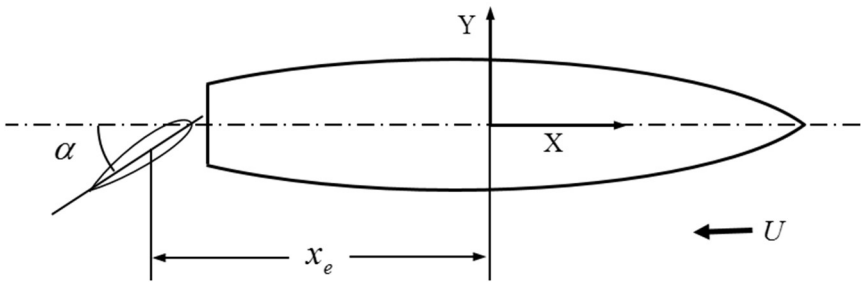


Figure 2. Coordinate System of Ship-Rudder Assembly on XY Cross Section.

In this paper, the hydrodynamic performance of rudder was mainly studied. The dimensionless expressions of lift cofficient, drag coefficient and moment coefficient were as follows:

Lift Coefficient of Rudder:

$$C_l = \frac{L}{\frac{1}{2}\rho U^2 A_R}, \tag{3}$$

Drag Coefficient of Rudder:

$$C_d = \frac{D}{\frac{1}{2}\rho U^2 A_R}, \tag{4}$$

Moment Coefficient of Rudder:

$$C_m = \frac{M}{\frac{1}{2}\rho U^2 A_R x_e}, \tag{5}$$

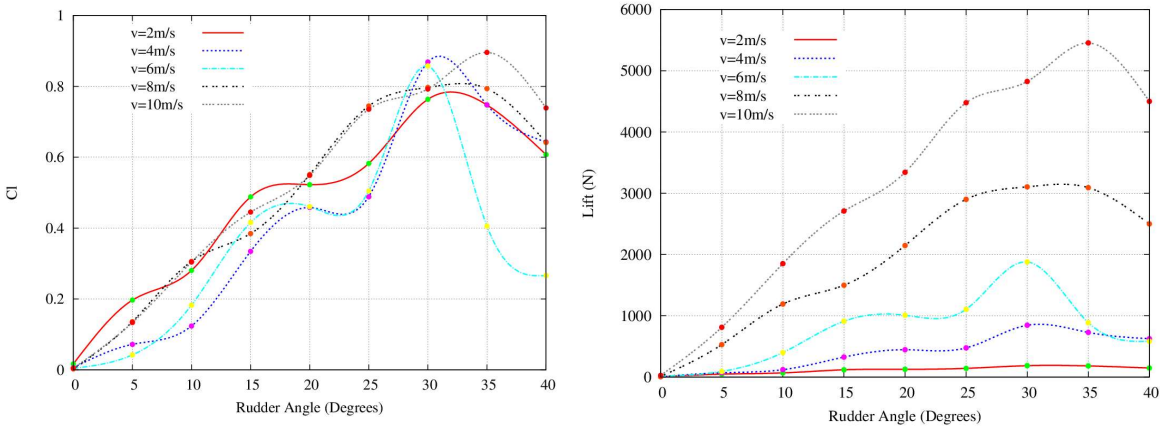
where L is lift force of rudder, D is the drag force of rudder, M is moment of turning hull.

3. Numerical Results and Analysis

This paper used Reynolds-averaged Navier-Stokes Equations to simulate the viscous flow field of 470 Class yacht by ANSYS 15.0. Considering the impact of free liquid used VOF method, this paper made Turbulence modelled with SST k-ω turbulence model. And the numerical simulation of this model was analysed through first-order upwind difference scheme and QUICK scheme.

3.1. Results and Analysis of Rudder Lift Force

Transform the rudder lift force into dimensionless coefficient, as shown in Figure 3a, the relationship between lift coefficient and rudder angle. The results shown that when the speed was at the range from 2 m/s to 8 m/s, when rudder angle ranged from 0 degree to 30 degrees, the lift coefficient increased, and 35 degrees to 40 degrees, the lift coefficient decreased. It is found that the stall angle was 30 degrees. With the increase of speed, the stall angle was 35 degrees at the speed of 10 m/s. Figure 3b shown the relationship between lift force and rudder angle. Numerical simulation results shown that the faster the sailboats, the greater disparity the change-over plug of lift force will have, which has practical application in the actual competition for rudder control.



(**a**) (**b**)

Figure 3. The relationship between the lift force and rudder angle. (**a**) Lift coefficient; (**b**) Lift value.

Figure 4 shown the appearance of free surface when sailboat was at a speed of 10 m/s, different rudder angles at 25 degrees, 30 degrees, 35 degrees and 40 degrees, lower water level was found near the rudder, so a high speed of 10 m/s, the stern wake impact would cause effective areas of the rudder reduce, and the corresponding aspect ratio decreased, the stall angle of rudder increased. As a result, the lift force of rudder came to maximum at the rudder angle of 35 degrees. It can be found that the presence of the hull affected the stall angle of the rudder and it was related to the speed.

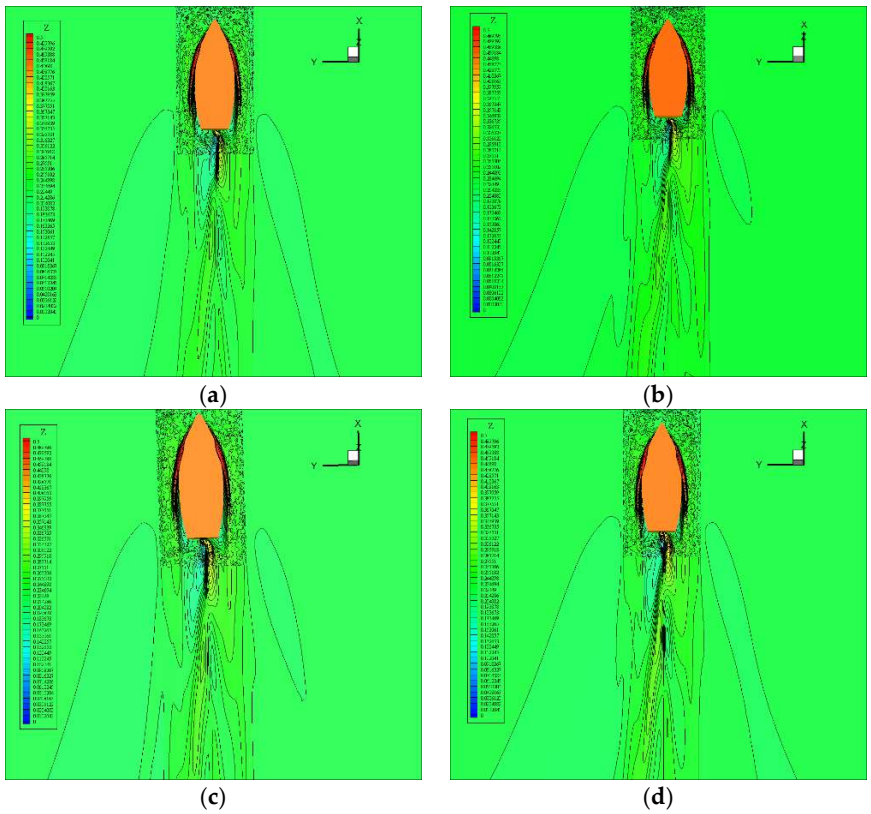


Figure 4. The free surface appearance of ship-rudder assembly. (**a**–**d**) indicate rudder angles of 25 degrees, 30 degrees, 35 degrees and 40 degrees with speed of 10 m/s.

3.2. Results and Analysis of Moment of Turning Hull

The steering of the hull is mainly based on rudder angle, resulting in the asymmetry of the water on both sides of the rudder. The core was the rudder's moment of turning hull. Figure 5a shown the relationship between moment of turning hull coefficient and rudder angle with different speeds. It could be seen that the turning moment is consistent to the trend of lift force. With a speed of 10 m/s and a deflection angle of 35 degrees, the turning moment reached maximum.

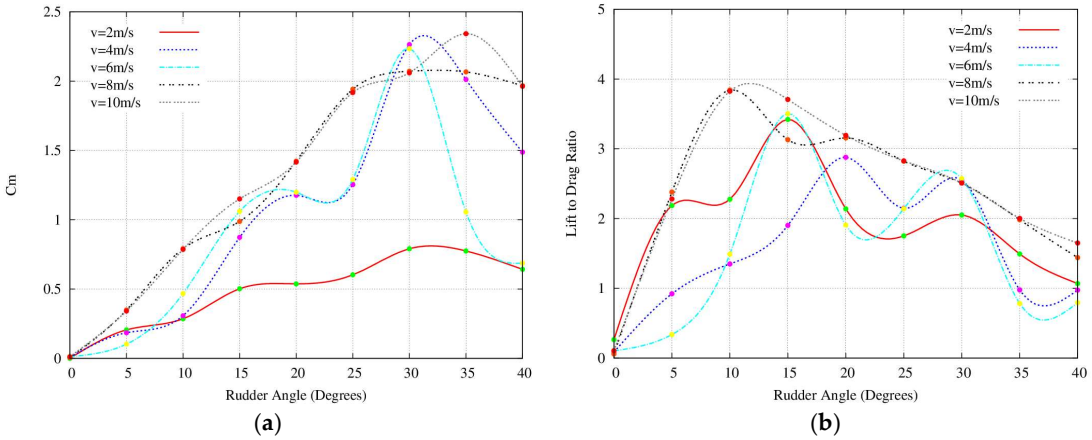


Figure 5. (**a**) is the relationship between moment of turning hull and rudder angle; (**b**) is the relationship between rudder's lift-drag ratio and angle.

3.3. Results and Analysis of Rudder's Lift-Drag Ratio

Figure 5b shown the lift-drag ratio of the rudder with the change of the rudder angle. The lift-drag ratio is an index parameter that reflects the hull rapidity. It was found that the lift-drag ratio was somewhat different at different speeds. When the speed was 2 m/s and 6 m/s, the maximum of

the lift-drag ratio shown at the rudder angle of 15 degrees; When the speed was 4 m/s, the maximum of the lift-drag ratio shown at the rudder angle of 20 degrees. It is found that the lift-drag ratio of the rudder increased with the increase of speed, and the rudder angle decreased conversely. In a word, the rudder angle of the high lift-drag ratio came at 10 degrees to 25 degrees.

4. Conclusions

This paper used the CFD to simulated hull-rudder assembly of Class 470 yacht with different rudder angles and different speeds. The hydrodynamic performance through kinetic parameters and flow phenomenon was analysed and the stall angle of hull-rudder was at 30 to 35 degrees. In the series under the condition of high lift-drag ratio of rudder angle ranged from 10 to 25 degrees. After the free surface was analysed, a conclusion could be drawn that the hull had some effects on the rudder's stall angle, and with the increased of speed, the effective area of rudder the stern wake shock leaded to lower, and when the corresponding aspect ratio decreases, the rudder stall angle increased. These kinds of studies would provide theoretical guidance to coaches, and help athletes get a breakthrough in training and matches.

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Conflicts of Interest: The authors declare no conflict of interest.

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