Numerical Simulation of Mutual Influence in 470 Sailing Hull and Rudder at Different Hull Speeds

Shijie Lin, Yong Ma, Weitao Zheng and Zhengye Pan

April 24, 2020

proceedings

Proceedings

Numerical Simulation of Mutual Influence in 470 Sailing Hull and Rudder at Different Hull Speeds †

Lin Shijie[1,2], Ma Yong[2,*], Zheng Weitao[2,3], Pan Zhengye[2,3]

[1] Graduate school of Wuhan Sports University, Wuhan, 430079, P.R. China
[2] School of Sports Engineering and Information Technology, Key Laboratory of Sports Engineering of General Administration of Sport of China, Wuhan Sports University, Wuhan, 430079, P.R. China
[3] School of health sciences, Wuhan Sports University, Wuhan, 430079, P.R. China

Emails: Lin Shijie: shijielin0819@163.com; Ma Yong: small_ma@163.com; Zheng Weitao: zhengweitao@sina.com; Pan Zhengye: pan960806@163.com.

* Correspondence: small_ma@163.com; Tel.: +86 27 87192075

† Presented at the 13th conference of the International Sports Engineering Association, Tokyo, Japan, 22-25 June 2020.

Published: date (leave it empty)

Abstract: 470 Sailing race requires effective cooperation between athletes to optimize hull position and correct heading. In order to understand the effect of hull on the maneuverability of rudder and the influence of rudder on the stability and rapidity of the hull at different ship speeds. Numerical 3D simulation and research on the viscous flow field of 470 Sailing based on Reynolds-averaged Navier-Stokes Equations. The results show that the rudder can reduce the wave making characteristics of hull, reduce energy loss and thus improving the hull's rapidity when the speed is greater than 6m/s, the effective area of rudder decrease and increases the stall angle, which reduces the manipulatable performance of the rudder to some extent. This study could quantify the performance of hull and rudder at different speeds. Moreover, this study might provide strategies for the athletes to effectively control the rudder and hull at different speeds.

Keywords: 470 Sailing; hull; rudder; numerical simulation; hydrodynamics

1. Introduction

470 Sailing is an Olympic sailing event in which two teammates tacitly cooperate with the sailboat for racing in the complex sea condition of certain sea areas. Generally, speed of the yacht ranges from 2 to 10 meter per second within the regular races. Each race will go through the process of multiple rounds of headwind, downwind and crosswind, fully testing the cooperation between the two athletes in adjusting the sail wing system and optimize hull position and correct heading by controlling the rudder, to make the sailing boat obtain enough power. In the course of sailing competition, the athletes often fall behind in the ship's deceleration ranking caused by the failure of coordination in the process of sailing and circling the standard. Scientific and systematic research on the interaction between the rudder control and the ship's position can realize the perfect coordination between the athletes, which has practical benefits for the athletes to improve their competitive ability. Therefore, the basic research on the hydrodynamic performance of sailing equipment will become very important.

Through the research on the dynamic performance of sports equipment, the former scholars can make athletes familiar with the overall operation performance of sports equipment, to complete technical actions more efficiently. Parolini et al. (2005) [1] studied the America Cup yacht by solving the RANSE and towing tank testing, including the optimization of hull performance of fully equipped sailboats under different motion conditions, the effect of hull appendage on hull performance, the influence of crew position on hull position [2], and the improvement of accuracy of numerical simulation method[3], so as to achieve the America Cup championship.

In terms of Olympic sailing, Ma Yong et al. [4,5] used numerical simulation and towing tank methods to study the fluid performance of windsurfing and sail. On the basis of summing up the law of resistance changing with speed under the condition of longitudinal and transverse inclination of windsurfing board and analyzing the influence of wing camber, angle of attack, angle of buckle, mast etc. on the aerodynamic performance of board, he put forward the strategy of adjusting windsurfing for sailing, cross tail wind section and the vicinity of the standard, which provides reference for the control of board and sail wing, his team's research promotes China won the windsurfing championship in 2008 and the laser women's championship in 2012.

Vidmar et al (2013) [6] studied simple steering system and a hydrodynamic shaped single rudder, or multiple rudders, depending on upwind sail boat characteristics. Rickard et al. (2014) [7] investigated hydrodynamic resistance prediction using CFD and Towing Tank Testing for better position of Laser sailing. Huetz et al (2014) [8] optimized hull shape based on statistical methodology to treat the database. Through the total station, the shape measurement and drawing model of 470 sailing yacht and laser yacht are completed, and the numerical simulation of no wave laser trim hull position, wave navigation and interaction between the stable plate and hull of 470 sailing yacht is carried out [9,10]. The study of the interaction between the hull and the rudder will help to adjust the equipment reasonably, realize the control of the high speed and stability of the sailboat, and ensure the sailboat to complete the race according to the strategic route of the athletes.

2. Computational Method

2.1. Governing equations

The Navier-Stokes equations are based on the assumptions that fluid around the hull and the rudder is incompressible. This study adopted RANS equations and continuity equations as governing equations to simulate the yacht without trim and heeling, the general speeds in actual races are are 2m/s, 4m/s,6m/s,8m/s,10m/s and the rudder angle range measured is from 0 to 40 degrees. In Cartesian coordinates, the continuity equation and the momentum equation can be expressed as follows [11]:

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. Mesh generation and domain boundary

The hull-rudder parameters are shown in Table 1. The weight of the hull is 118kg, and the weight of the two athletes ranges from110kg to 180kg. The displacement is assumed to be 280kg in this study. The grids were meshed in ICEM CFD 15.0. As shown in figure 1, the simulations are carried out on a Cartesian grid for hull and a hybrid grid for hull-rudder assembly. The computational domain size is chosen as 7L×6L×2L (L is the length of hull) with approximately 5 million grids in total. The region around the rudder and hull model with high-resolution unstructured grids is employed to capture the boundary layer, satisfy the distance of the first neighbor grid and y^{+}=60~100. At the upstream boundary of the hull, it's a constant inflow velocity boundary condition. The downstream boundary is the pressure-outlet boundary, availing simulation iteration convergence. The bottom boundary is moving wall, the wall of hull and rudder are no slip wall. The symmetry boundary condition is provided at all other boundaries [11].

Table 1. Parameters of 470 Sailing yacht[11].

Hull (*L*)	Beam (*B*)	Span-rudder (*h*)	Chord-length (*b*)	Wetted area-rudder(A_R)
4.7m	1.89m	0.675m	0.25m	0.168m²

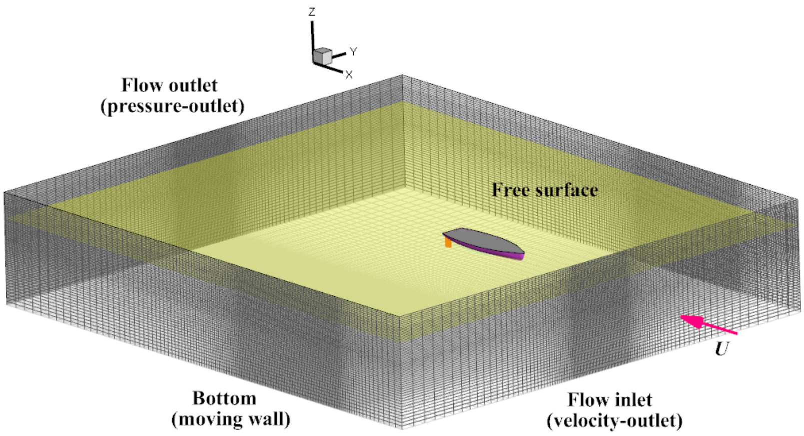


Figure 1. Schematic of the computational mesh and boundary conditions employed in the present simulations.

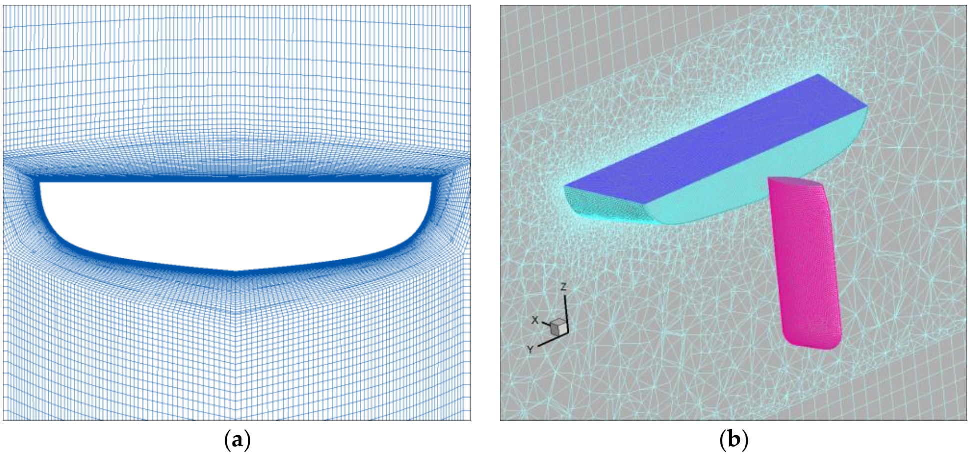


Figure 2. Schematic of the computational mesh of hull and rudder: (a) is hull and (b) is rudder [11].

3. Numerical results and analysis

In order to understand the influence of the hull on the maneuverability of the rudder at different hull speeds and the influence of the rudder on the stability and rapidity of the hull at different ship speeds, this paper used Reynolds-averaged Navier-Stokes Equations to simulate the viscous flow field of 470 Sailing by ANSYS 15.0. Considering the impact of free liquid used VOF method, this paper made Turbulence modelled with SST turbulence model. And the numerical simulation of this model was analysed through first-order upwind difference scheme.

The rudder may have a substantial impact on the stability and rapidity of the hull, so this paper analyzes the resistance, lateral forces of the hull, and the lift, drag of the rudder. The dimensionless expressions were as follows:

Drag Coefficient of Hull:

$$C_{Rt} = \frac{R_t}{\frac{1}{2}\rho U^2 S} \quad (3)$$

Lateral Force Coefficient of Hull:

$$C_Y = \frac{Y}{\frac{1}{2}\rho U^2 S} \quad (4)$$

Drag Coefficient of Rudder:

$$C_d = \frac{D_t}{\frac{1}{2}\rho U^2 A_R} \quad (5)$$

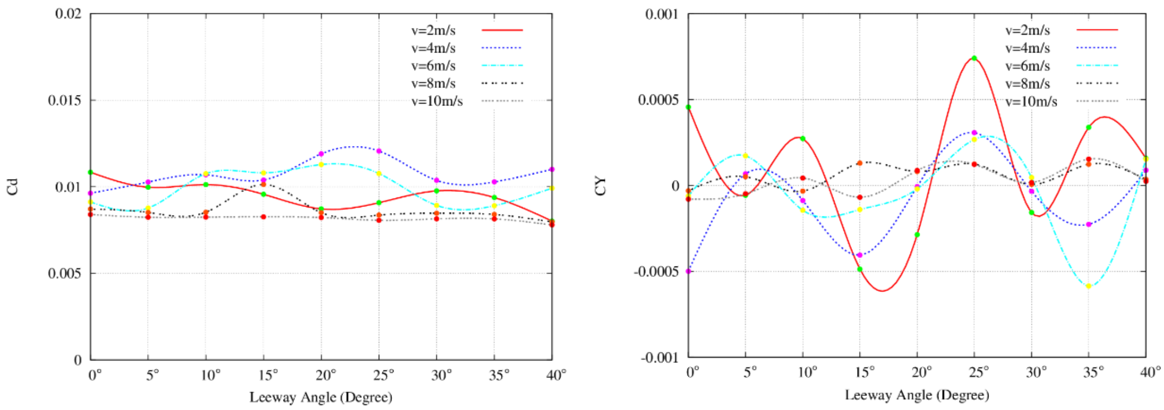
Lift Coefficient of Rudder:

$$C_l = \frac{L_t}{\frac{1}{2}\rho U^2 A_R} \quad (6)$$

Where *Rt* is drag force of hull and Y is lateral force of hull, S is wet area of hull when the displacement is 280 Kg. D_t is drag force of rudder, L_t is lift force of rudder, R_t is wet area of rudder, and U is inflow velocity.

3.1. Hydrodynamic analysis of the influence of rudder on hull

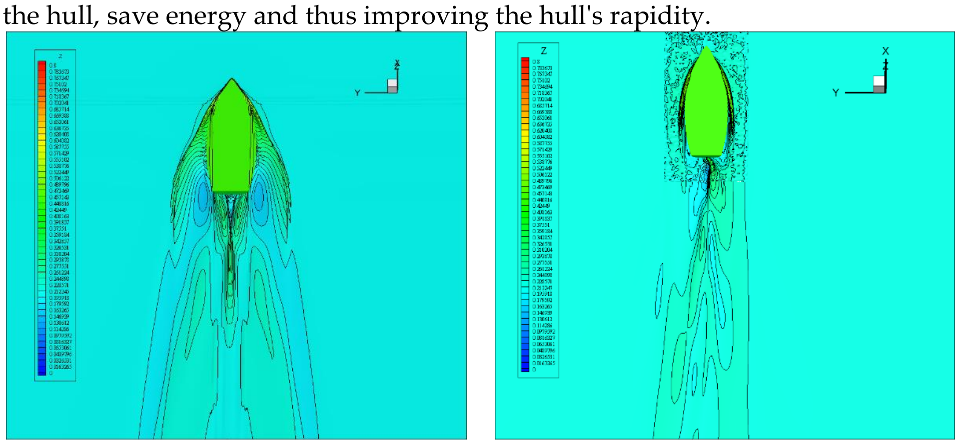
In this section, this paper aim to understand the effect of the rudder interaction on the hydrodynamic performance of hull when rudder turn from 0 degree to 40 degrees at the velocities are 2m/s, 4m/s,6m/s,8m/s,10m/s. Extracted the resistance and lateral force of the hull for analysis, as shown in figure 3, the drag coefficient is distributed at 0.01 and lateral force coefficient is around 0. It is hard to found rudder increase the resistance and lateral force of the hull.



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

Figure 3. The result of relation between hull force coefficient and leeway angle: (a) is hull drag and (b) is lateral forces.

Evident in figure 4 is that the rudder has impact on wake profile behind the hull. Figure 4a show the wake profile of the naked hull is complex and fully flowing, and figure 4b show the rudder reduce waveform of the hull wake effectively, and make wake profile asymmetry, weaken the waveform and save energy. In summary, the rudder plays the role of rectifying plate, reducing the wave-making ability of the hull, save energy and thus improving the hull's rapidity.



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

Figure 4. The wake profile of 470 Sailing: (a) is naked hull and (b) hull-rudder assembly.

As shown in figure 5, when inflow velocity is less than 6m/s, the resistance of hull is almost unaffected by the rudder, while the velocity exceeds 6m/s, the presence of the rudder causes the drag to decrease compared to the naked hull. Therefore, the rudder can reduce the wet area and drag of hull when the peed is greater than 6m/s.

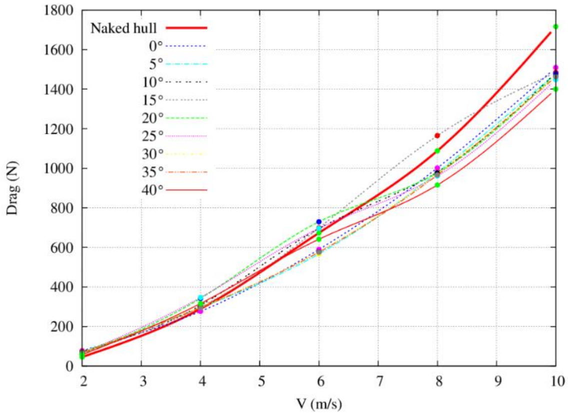
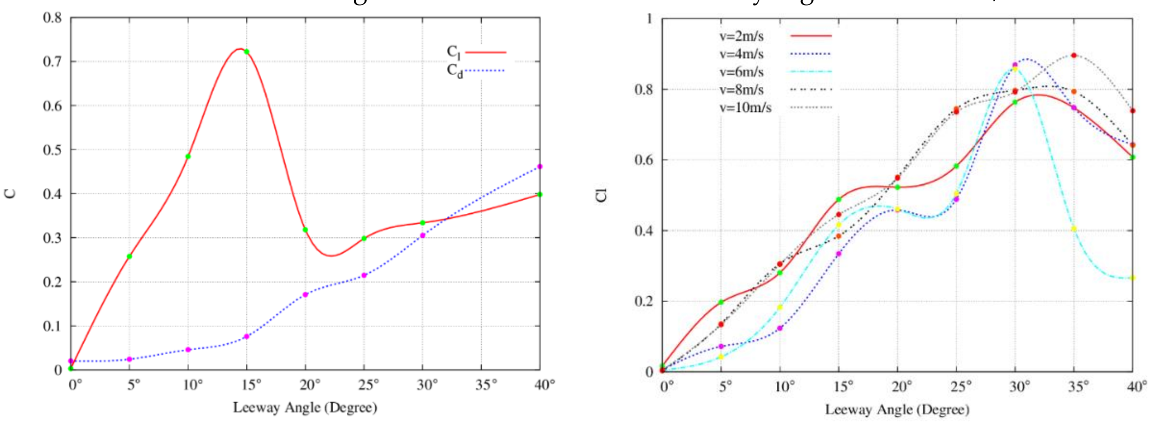


Figure 5. The result of relation between hull resistance and speed.

3.2. Manipulative analysis of the influence of hull on rudder

Figure 6 present the lift coefficient of rudder with leeway angle in some speeds, as shown in figure 6-a, the stall angle is about 15 degrees, the lift coefficient of the rudder assembly is changed with leeway angle shown in figure 6-b. At 2-6 m/s, the stall angle is about 30 degrees, while stall angle increases to 35 degrees when speed reaches 8m/s to 10 m/s. Compared with the free liquid surface wave cloud diagram of the rudder assembly in Figure 4b, and the hull wake is caused by the increase of the ship speed. The effective area of the rudder body continues to decrease, and the aspect ratio is reduced to increase the stall angle of the rudder body. The data results of the comprehensive numerical test and the results of the free surface cloud analysis show that as the speed increases, the hull wake increases the stall angle of the rudder when the velocity is greater than 6 m/s.



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

Figure 6. The relationship between the coefficient of force and leeway angle: (a) is naked rudder and (b) [11] is rudder on the hull.

4. Conclusions

This paper investigates the hydrodynamics of 470 Sailing at different hull speeds using the commercial software ANSYS 15.0. The results showed that the rudder can reduce the wave-making characteristics of the hull, reduce energy loss and thus improving the hull's rapidity when the speed is greater than 6m/s. The wake wave of hull reduces the effective area of the rudder and the stall angle increases, which reduces the manipulatable performance of the rudder to some extent. Our findings could enhance the understanding of coaches and athletes on the performance of hull and rudder at different speeds. Moreover, our study might provide strategies for the athletes to effectively control the rudder and hull at different speeds.

Acknowledgments: This study was partially supported by National Natural Science Foundation of China (Grant No. 51679183, 51279154), the East Lake Scholars Sponsorship Program of Wuhan Sports University, Hubei Natural Science Funds for Distinguished Young Scholar (Grant No. 2013CFA038) and Hubei Dominant Characteristic Discipline Group.

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

References

1. Parolini, N., Quarteroni, A. Mathematical Models and Numerical Simulations for the America's Cup. *Computer Methods in Applied Mechanics and Engineering*. **2005**,194, 1001-1026.
2. Mylonas, D., Sayer P. The hydrodynamic flow around a yacht keel based on LES and DES. *Ocean Engineering*. **2012**, 46,18-32.
3. Viola, I.M., Enlander, J., Adamson, H. Trim effect on the resistance of sailing planning hulls. *Ocean Engineering*. **2014**,88,187-193.
4. Ma Y., Tang Y.H., West N., Zhang Z.Y., Lin S.J., Zheng Q.Z. Numerical Investigation on Trimming of a Single Sail in a Regatta. *Sports Engineering*. **2016**, 19, 81-90.
5. Lei X.S., Ma Y., and Lin S.J. Comparative Study of an Aerodynamic Performance of the Neil Pryde RS：X Class at Different Wind Speeds Based on One-way and Two-way Fluid-Structure Interaction Methods. *China Sport Science and Technology*.**2019**,55,51-56.
6. Vidmarn P., Perkovič M. Optimization of upwind sailing applying a canting rudder device. *Ocean Engineering*.**2013**,73,55-67.
7. Levin R. L., Finnsgård C., Peter J. Hydrodynamic Resistance Prediction of an Olympic Class Sailing Dinghy Using CFD and Towing Tank Testing. *International Congress on Sports Science Research and Technology Support*. Springer, Cham, **2014**: 85-106.
8. Huetz, L., Guillerm, P.E. Database building and statistical methods to predict sailing yacht hydrodynamics. *Ocean Engineering*. **2014**,90,21-33.
9. Lin S.J., Ma Y., Zheng Z., et al. Investigation on hull Hydrodynamics with different trim angles for Laser Radial Class Yacht. *Journal of Wuhan Institute of Physical Education*.**2016**,50,98-93.
10. Zhang. S. Hydrodynamic Performance of Laser Radial Class in Regular Head Waves. Master, Wuhan Sports University, Hubei, 2019.
11. Lin S.J., Ma Y., Zheng Z., et al. Investigation on rudder application for 470 Class Yacht based on mechanical analysis. *China Sport Science*.**2017**,37,25-32.