A Numerical Study of Drag force for Optimist Dinghy on Flat Water

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Abstract. This study investigates numerically the drag force on the Optimal dinghy, which is one of the official classes of international sailing regatta. The drag force is affected by the forward and backward tilt angles and the heels angles. The results revealed that the minimum drag force on the dinghy occurred under the flat dinghy and zero tilt angle condition. The drag force decreases with increasing backward tilt angle. Meanwhile the minimum drag force occurred at the 10 degree of the heeling angle under low velocity condition, and it occurred at the 5 degree while the sailing velocity exceeded 2 m/s. The correlation of the drag force and the sailing velocity can be expressed as $F_D = 13.87V^2$ for flat dinghy sailing.

1 Introduction

The Optimal dinghy is one of the official classes of international sailing regatta. It is also the most popular sailing within all classes. The sailing power come from the transform of air pressure and flow velocity as described by the Bernoulli's equation but not the reaction force impacting on the sail sheet. Therefore, the relative speed of the sail boat and the pressure difference caused by the sailing sheet can drive the boat sails in slightly up-wind and cross-wind direction. The resulting wind force is divided into two perpendicular direction that is parallel to the longitude length of boat and the transverse width of the boat. The former force drive the boat forward, and the later force pull the sideward. Modern Optimal dinghy equipped with a central panel, which suppress the side force to avoid the boat capsizing. Curry [1] firstly discussed the flow dynamic of the sailing boat. Then, many literature studied on the aerodynamic performance of sailing operation [2-5]. Recently, the complex fluid dynamic characteristics are discussed as the progress of computational technique. Akimoto [6] considered the flow dynamics with the free surface between water and the air, and compared the complex shape of sailing boat. Parolini and Quarteroni [7] studied the flow characteristic of sailing boat for competition in America's Cup, and obtained useful information for racing. The Optimist dinghy has the dimensions of 231cm

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in length, 113cm in width, and its weigh is 35 kg, the area of sail sheet is 3.5m². The photo and sketch of the Optimal dinghy are shown as Figure 1. This study aims to analyze the variation of dragged force resulting from water resistance under the various operating condition of the sailing Optimal dinghy, owing to the viscosity of water is much greater than that of air.

2. Theory Analysis

2.1 Governing Equations

A three-dimensional numerical model is performed to examine the flow characteristic of the Optimal dinghy by utilizing the software ANSYS. Thus, the continuity and momentum equations are described as follows.

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0$$

(1)

$$\frac{\partial}{\partial x_j} \rho(\overline{u}_i \overline{u}_j) = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j} \left[ \mu_{eff} \left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) - \rho \overline{u}_i \overline{u}_j \right]$$

(2)

The $k$-$\varepsilon$ turbulent model is adopted to couple with the Navier-Stokes equation. The forward tilt angle and side tilt angle affects significantly the contact area and perimeter shape, and resulting in the change of water resistance. The tilt angle is defined as the angle of the gunwale and the water plane. Owing to the center of gravity is depended on the position of the sailor, the boat experience forward when the sailor moving forward and moving to the left or right sides as the sailor changer the position. The resistance of water drag is composed of the pressure drag and the friction drag. The pressure drag is occurred while the flow along a varied shape surface, In contrast the friction drag is due to the viscosity induced shear fore on the interface of fluid-solid. They are defined as $D_p = \int p \cdot \cos \theta \cdot dA$ and $D_f = \int \tau_w \cdot dA$, respectively.

![Figure 1. (a) The photo and (b) the sketch of the Optimal dinghy](image)

2.2 Boundary Conditions

This study focus on the dragged force resulting from water resistance under the various operating condition of the sailing Optimal dinghy. The computational domain of the water and the numerical grids of the boat is sketched in Figure 2. The boundary conditions are assumed as follows: The surfaces of the boat is considered as non-slip boundary...
condition. The front plane (positive z plane) is a velocity inlet boundary, along negative z direction, to simulate the velocity of the boat. In contrast, the rear plane (negative z plane) is considered a pressure outlet boundary. The other planes are considered as symmetric planes to simulate the water flow in this simulation, owing to the limited computational domain in the study.

![Figure 2. (a) The sketch of the Optimal dinghy and (b) the computational domain](image)

**3. Results and Discussions**

Figure 3 displays the total water resistance exerted on the Optimal dinghy surface under horizontal sailing condition, i.e. zero forward and side tilt angle. The surface of boat comprises the surface of forward, aft, bottom, port, starboard, rudder, and centerboard. The centerboard and the bottom have the equivalent effect on the drag force; they contribute about total 70% of the resistance, owing to the greater surface area than the others. The total drag force is 15.6 N, 56 N, and 121N, for the 1 m/s, 2 m/s, and 3 m/s of sailing velocity, respectively. The drag force increases rapidly with an increase of the sailing velocity, the correlation can be expressed as $F_D = 13.87V^2$. Besides, the drag on forward surface is zero, owing to it is not wetted for this sailing condition.

![Figure 3. The variation of drag force with the sailing velocity](image)

Note that the drag force shown in Figure 3 considers the full immerged length of 700 mm of centerboard, which is a movable device used in the Optimal dinghy to control the sailing direction against the wind. Therefore the immerged length of centerboard is varied from 7 mm through 700 mm. Figure 4 shows the variation of drag force with the immerged length of centerboard for 1 m/s of sailing velocity. The drag force increased linear with the immerged length, owing to the centerboard is shaped in rectangular. A turning point
occurred at the length of 175 mm, however, the influence of the immersed length increases on the weighting of total drag force, it varied from 0% to 35%.

Figure 4. The variation of drag force with the sailing velocity

The variation of the drag force along the sailing direction (z-direction) with the forward tilt angle is displayed in Figure 5(a)-(c). The minimum total drag force occurred at the 0 degree of tilt angle whatever the sailing velocity is, it increase linear with the both forward and backward tilt angle as shown in Figure 5(a). The total drag forces are 125N, 305N, and 345N, for the tilt angle are 0, forward 10 degree, and backward 10 degree, respectively. This yields a 140% and 175% incensement of total drag force, respectively. The total drag force is composed of the pressure drag and friction drag as mentioned, which are displayed in Figure 5(b) and (c). It depicts that the increased total drag force is resulted from the pressure drag, moreover, the friction drag decreases while increase the forward or backward tilt angle. As shown in Figure 1, the bottom surface of the Optimal dinghy is a smooth streamline surface while sailing in horizon. The premiered surface is varied with the tilt angle; therefore, the pressure drag increases. The influence of the backward tilt angle is greater than that of forward tilt angle. That mean while the sailor move backward causing the smooth streamline surface changed and resulting in more drag force exerted on the boat. Besides, the decrease in friction drag is owing to the decrease of the immersed surface as shown Figure 5(d)

(a)                                                   (b)
The velocity contour and the streamline for 1 m/s of sailing velocity with the 10 degree of backward tilt angle are displayed in Figure 6. The low velocity region appeared behind the centerboard and the rudder is obvious, as the flow circulation appeared behind the rudders, which affect the pressure drag significantly.

The total drag force for various side tilt angle under 0 degree of forward tilt angle is shown in Figure 7. The drag force decreases with an increasing of side tilt angle, the minimum drag force occurred around at 5-10 degree of side tilt angle. Reversely, the drag force increase as the tilt angle greater than 10 degree. Besides, the angle of the minimum drag force is slightly shifted from about 5 degree to 10 degree, while the sailing velocity increases from 1 m/s to 3 m/s. It is similar to the suggestion of Slater [8] for the Optimal racing.

4. Conclusions
The drag force of water resistance for the Optimal dinghy has been performed. Based on the above results: The drag force increases rapidly with an increase of the sailing velocity, the correlation can be expressed as $F_D = 13.87V^2$. Besides, the drag on forward surface is zero, owing to it is not wetted for this sailing condition, the influence of the immersed length increases on the weighting of total drag force, it varied from 0% to 35%. The tilt angle of forward 10 degree, and backward 10 degree, yields a 140 % and 175% incensement of total drag force, respectively. The Figure revealed that the minimum drag force occurred about 10 degree of side tilt angle for 1 m/s of velocity. It shifted to about 5 degree of tilt angle while the velocity increased to 2 m/s and 3 m/s.

References

1. Curry, M., Yacht Racing, The Aerodynamics of Sails and Racing Tactics, New York, Holt, 1925.
2. Davidson, K., Some Experimental Studies of the Sailing Yacht, SNAME Transactions, 1936.
3. Hammit, A.G., Sailboat Rudders, Ancient Interface 3, AIAA Symposium on the Aero/Hydrodynamics of Sailing, AIAA, 1971.
4. Gerritsma, J., Course Keeping Qualities and Motions in Waves of a Sailing Yacht“, Ancient Interface 3, AIAA Symposium on the Aero/hydrodynamics of sailing, AIAA, 1971.
5. TiTlowt, J.D., A Dynamic Model for Downwind Sailing”, Ancient Interface 8, AIAA Symposium on the Aero/Hydrodynamics of Sailing, AIAA, 1977.
6. Akimoto, H., Finite Volume Simulation of the Flow around a Sailing Boat with Unsteady Motion, Journal of the Society of Naval Architects of Japan. 1997, Vol. 181, pp. 35-44.
7. Parolini, N., Quarteroni, A., Mathematical models and numerical simulations for the America’s Cup, Computer Methods in Applied Mechanics and Engineering. 2005, Vol.194 pp. 1001-1026.
8. Slater, P., Optimist Racing, fernhurstbooks, UK, 2001