

Comparative analysis on the methods of preliminarily estimating resistance of yachts

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Abstract. The analysis of yacht resistance performance using empirical methods has become an accepted approach over the last decade. Which are based on existing statistical material of yachts to obtain the empirical equations or map methods. There are not many simple methods to obtain the resistance of yachts, and the accuracy of the results is not always uncertain for different types of yachts. The study is focused on determining the appropriate empirical equation to estimate resistance for different kinds of yachts. And based on computational fluid dynamics (CFD), XFlow software to calculate resistance of yachts under turbulent state is selected. This paper provides a review of these methods and two real yachts are chose as examples according to the classification of yachts .It discusses the resultant implications for practical applications. Simulations on an identical yacht using empirical methods and softwares are compared. Good agreements are achieved for both Daisumi Mihiro's empirical methods and numerical simulation methods, which shows that Daisumi Mihiro's empirical equation to estimate resistance of the planning yacht is relatively feasible and Daisumi Mihiro's map method is reliable for the transition and drainage boats.

1. Introduction

Most studies of performance of a ship are based primarily on the calm water resistance of the ship hull, and the same is true of yachts. The current methods for estimating resistance of yachts, using empirical equation estimation methods, or using Maxsurf software with empirical equation as calculation theory, is more efficient than predicting resistance of yacht by ship model test. But the drawback is that the results of different empirical equations have some differences, and the accuracy is uncertain. Looking at the literature on resistance calculation, most scholars focus on optimizing the CFD method of calculating resistance [1-3], but the quantitative analysis on the accuracy of the empirical equations is not sufficient. The existing estimation methods for resistance of yachts are finished to calculate the real yachts. The calculation results are compared with the numerical results to analyze the accuracy of these empirical equations.

The sailing state of yacht has certain influence on its performance, especially on the resistance performance. The applicability of the empirical equation is closely related to the navigation state, and the complex flow pattern often leads to the decrease of the accuracy of the empirical equation. The study focuses on the comparative analysis of the fast methods to estimate resistance of yachts.

2. The classification of yachts



According to the volume Froude number Fr_v , the yachts are divided into three categories, as show in equation (1).

$$Fr_v = \frac{V_s}{\sqrt{g\nabla^{1/3}}} \quad (1)$$

where V_s is designed speed, knot; ∇ is displacement volume of yacht, m^3 .

When Fr_v is less than 1.0, the speed is slow. The hull floating in the water is basically relying on the hydrostatic buoyancy. If the volume Froude number of yacht is in the range, it is called a drainage yacht.

When Fr_v is more than 1.0 but less than 3.0, the head of the yacht will rise more obviously as the speed increases. However, at first there is a slight decline occurring in the tail and then the hull gradually tilts. When the yacht is hull-borne, the power of fluid increases but the drainage volume is decreasing. When the volume Froude number of yacht is in the range, it is called the transitional yacht.

When Fr_v is more than 3.0, the yacht is at a high speed. At that time, its head and tail will show great changes in the draft, eventually the whole hull is above surface of water. In the case, it can be called a planing boat. Yachts are basically supported by fluid power due to the small static buoyancy.

According to the three categories of yachts, the appropriate empirical equations are selected to estimate resistance of yachts.

3. The empirical equation method to estimate resistance of the planing boat

Among methods to estimate the resistance of planing crafts, the empirical equation put forward by Daisumi Mihiro is a very typical method. Therefore, that is used to estimate the resistance of planing boat. Daisumi have collected the data about brake horsepower from low power to high power ship and effective horsepower values of bare boats. There are more than 100 ships. Finally, the brake horsepower and the effective horsepower spectrum are built on the basis of different ship parameters. At the same time, according to the data, Daisumi Mihiro put forward his own unique semi-empirical equation. The equation is mainly used to calculate brake horsepower required by the main engine BHP:

$$BHP = 1.45 * \beta * \Delta^{1.14} * V_s^{1.611} / L_{wl}^{0.806} \quad (2)$$

In the equation, L_{wl} is the length of waterline when the yacht is static, m; Δ is Displacement, t; V_s is designed speed, knot; BHP is brake horsepower, ps; β is The correction factor of ship length, $\beta = 1.12 - 0.0048 * L_{wl} \leq 1$, if β is greater than one, β is one.

After the BHP obtained by the equation (2), according to the relationship between horsepower and power, the propulsive power P is determined. Then the resistance F can be determined by the equation $P = F * V$ between power and resistance.

The 26 'yacht is chose as an example for the planing craft, which is a small power yacht.

The principal dimension parameters are as following: $\Delta = 2.561$ t; $B_M = 2.20$ m; $B_T = 1.96$ m.

The model of the planing boat was completed by Rhinoceros software. As shown in figure 1, the model surface is smooth, which can reduce the error of the simulation result.

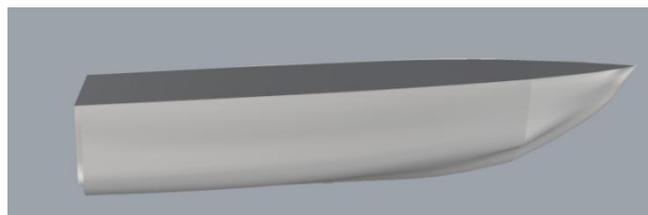


Figure 1. The 26-foot planing boat model.

Using the above method, resistance of the yacht under different volume Froude numbers is calculated .The results are shown in table 1:

Table 1. The result calculated by Daisumi Mihiro's empirical equation.

Fr_v	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4.0
$R(kN)$	9.00	9.18	9.35	9.52	9.69	9.86	10.03	10.19	10.36	10.52

4. The ways to estimate resistance of the transitional and displacement crafts

In the process of finishing the methods on calculating resistance of yachts, it is found that in most of ship model tests and theoretical methods analysis, the transition yachts and the drainage yachts are put into the same set of experiments, and the volume Froude number of the mother ship is mostly between 0.6~2.8. Therefore, in the classification of resistance calculation methods for yachts, it is envisaged that the resistance estimation methods of the transition and displacement yachts can be put into a group to analyze.

By reading and studying the relative references, it is found that Daisumi Mihiro's estimation method about brake horsepower at slow speed is used more frequently in estimating resistance of the transition and displacement yachts. As shown in figure 2, this is the brake horsepower estimation chart, the abscissa represents the ratio of the speed to the square root of the design waterline, that is V_s/L_{WL} ; the ordinate is $BHP/\beta * \Delta^{1.14}$; the curve in the figure represents $L_{WL}/\Delta^{1/3}$. Based on the above information, the resistance of transition and drainage yachts can be calculated by the medium-low-velocity brake horsepower chart.

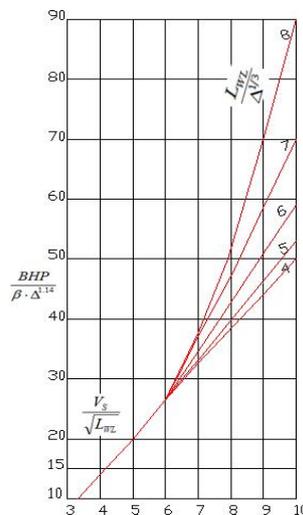


Figure 2. The estimation chart of Daisumi Mihiro's Brake horsepower.

Transitional and drainage yachts are usually medium-low speed yachts,so the 60'yacht is chose as an example. The principal dimension parameters are as follow:

$$L_{WL} = 19.45m, B=5.76m, D=2.56m, d=0.962m, \Delta = 39.96t, LCB=1.244m$$

This is a 60'yacht. The model built by Rhinoceros is shown in figure 3.



Figure 3. The 60' yacht model.

For Froude numbers $Fr_v = 0.8, 1.3, 1.8, 2.3, 2.8$, the resistance of yacht is calculated. The results are shown in the table 2:

Table 2. Results calculated of the Daisumi Mihiro's Brake Horseforce Chart.

Fr_v	0.8	1.3	1.8	2.3	2.8
V_s (knot)	11.59	18.83	26.07	33.31	40.56
$L/\nabla^{1/3}$	2.63	4.27	5.91	7.55	9.20
$BHP/\Delta^{1.14}$	15.10	18.30	26.20	35.10	51.20
$R(kN)$	124.79	93.06	96.23	100.89	120.89

5. Numerical simulation based on XFlow software

5.1. Computational theory

XFlow is the simulation software which applied in the new generation of computational fluid dynamics (CFD). It is based on the particle and the whole Lagrangian function, which can simply deal with the traditional complex computational fluid dynamics (CFD) problems. XFlow software has adopted Lattice Boltzmann method and large eddy simulation (LBM-LES), without dividing the mesh, which is a numerical method based on mesoscopic frame work. The method uses the distribution function to count the real variables, and that also make sure the conservation of the mass, momentum and energy in the process of fluid calculation.

5.1.1. Lattice Boltzmann method (LBM).

Boltzmann transportation equation [4] is as equation (3):

$$f_i(r + c_i \Delta t, t + \Delta t) = f_i(r, t) + \Omega_i^B(f_1, \dots, f_b) \tag{3}$$

where f_i is the distribution function in the direction i , Ω_i^B is the collision operator, t is the discrete time, r is a position in the lattice and c_i is a velocity.

In the Boltzmann calculation method, the collision operator is simplified by BGK[4], which can solve the problem of low Mach number flow in fluid dynamics.

The operator is defined as equation (4):

$$\Omega_i^{BGK} = \frac{1}{\tau} (f_i^{eq} - f_i) \tag{4}$$

where f_i^{eq} represents the local equilibrium function, and τ is the relaxation characteristic time (which is related to the macroscopic viscosity).

Generally, the expression of equilibrium distribution function [5-6] is as equation (5):

$$f_i^{eq}(r, t) = t_i \rho \left[1 + \frac{c_{i\alpha} v_\alpha}{c_s^2} + \frac{v_\alpha v_\beta}{2c_s^2} \left(\frac{c_{i\alpha} c_{i\beta}}{c_s^2} - \delta_{\alpha\beta} \right) \right] \tag{5}$$

In the above equation, c_s is the sound velocity; v_α and v_β are macro viscosities; $\delta_{\alpha\beta}$ is the Kronecker function, t_i is the parameter to ensure the spatial isotropy and ρ is the macroscopic density.

5.1.2. Turbulence model

In XFlow software, the turbulence model is simulated by the large eddy simulation (LES)[7-9]. LES solves the problem that turbulence sizes are larger than or less than given filters .LES is based on local numerical methods to simulate microscopic scales. Its analysis focuses on small scale turbulence simulation, which is close to the real physical model, and that does not require any subjective parameters to describe turbulence phenomena.

That is the approach employed in XFlow. In predicting resistance of yachts, the Wall-Adapting Local Eddy-viscosity (WALE) model is selected to describe the minimum scale of turbulence. WALE model has good performance. For laminar and turbulent flow, it is close to and away from the wall. The model recovers the asymptotic behavior of the turbulent boundary layer when the layer can be directly solved and it does not add artificial turbulent viscosity in the shear regions out of the wake. The model directly simulates the boundary layer, which can reflect the gradual change of the turbulent boundary layer and also do not need to add artificial turbulent viscosity at the shear zone outside the tail vortex.

5.1.3. Surface info

After completing the resistance prediction of yachts, the surface information of the geometric models can be obtained by post-processing. The correlation coefficients are defined as follows:

C_p : Pressure coefficient, defined as equation (6):

$$C_p = \frac{2P_{static}}{\rho V_{ref}^2} \tag{6}$$

where P_{static} is local static pressure, ρ is the reference density and V_{ref} is the specified reference velocity.

C_f :Skin friction coefficient, defined as equation (7):

$$C_f = \frac{2T_w}{\rho V_{ref}^2}, T_w = \mu \left(\frac{\partial v}{\partial y} \right)_{y=0} \tag{7}$$

where T_w is the wall shear stress.

5.2. Numerical calculation of yachts

XFlow software is used to calculate the resistance of yachts.

5.2.1. Numerical calculation of the planing yacht

In the case of different Froude number, the corresponding resistance is shown in the table 3:

Table 3. The results for the planing yacht are calculated by XFlow.

Fr_v	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4.0
$R(kN)$	9.31	9.55	9.82	10.11	10.57	11.09	12.15	12.57	12.81	12.91

When the Froude number is 3.1, the free liquid surface of yacht changes as shown below: Changes in velocity field are shown in figure 4 and figure 5.



Figure 4. When $t=1s$, the free surface velocity field.

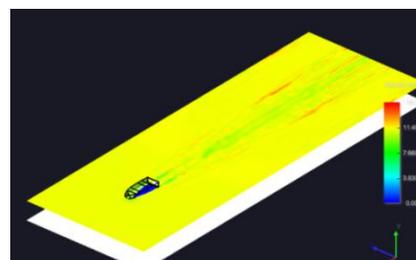


Figure 5. When $t=30s$, the free surface velocity field.

It can be seen that the velocity of the free liquid surface is small when $t=1s$, and the change of the free liquid velocity distribution becomes more and more obviously over time. When $t=30s$, the yacht tail produces a large number of velocity field, free liquid surface velocity distribution gradually

spreads. After 30 seconds, the liquid level changes little and tends to be steady. The velocity distribution at each time is substantially symmetrical. The variation of the velocity field over time is close to the distribution of the flow field in the actual working condition.

Changes in free surface swirl current field are shown in figure 6 and figure 7.

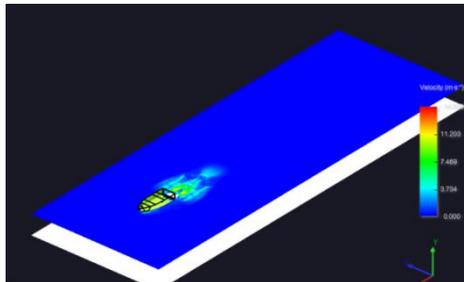


Figure 6. The free surface eddy current field at $t=1s$.

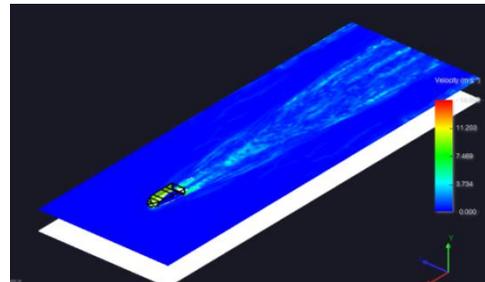


Figure 7. The free surface eddy current field at $t=30s$.

From the above two free surface vorticity graphs, it can be seen that when $t=1s$, smaller vortices are generated at both sides of the yacht and at the head, the vorticity is larger at the end of the yacht. When $t=30s$, the vortices at the rear of the yacht are noticeably large and the vorticity generating area becomes larger. As time increases, the vorticity distribution in the computational domain becomes larger and larger until the entire region is covered, and the vorticity distribution tends to be in a relatively stable state.

5.2.2. Numerical calculation of the transitional and displacement yacht

The resistance of yacht is calculated under different Froude numbers. The calculation data is shown in the table 4:

Table 4. Resistance of the 60' yacht is calculated by XFlow software.

Fr_v	0.8	1.3	1.8	2.3	2.8
$R(kN)$	109.86	97.65	112.41	135.31	156.32

6. Prediction on the resistance of yachts based on Maxsurf

6.1. The theoretical method for calculating resistance by Maxsurf

In sailing, the resistance of a ship consists mainly of the following three parts: frictional resistance R_f , viscous pressure resistance R_{pv} and wave resistance R_w . Hughes held that anything related to viscosity including viscous resistance and frictional resistance should be combined together [10]. The total resistance of ship above static water can be integrated into the viscous resistance R_v which related to Reynolds number, and the wave resistance R_w related to Froude number as equation (8):

$$R_t = R_{pv} + R_f + R_w = R_v + R_w \tag{8}$$

The ratio of viscous pressure resistance coefficient C_{pv} and friction resistance coefficient C_f is the constant k . The total resistance can be expressed as equation (9):

$$R_t = (1 + \kappa) R_v + R_w \tag{9}$$

Viscous resistance includes frictional resistance and viscous pressure resistance. The Hull speed module of Maxsurf uses the ITTC-57 friction resistance equation recommended by ITTC to calculate the viscous resistance R_v . The viscous resistance equation can be seen as equation (10):

$$R_v = \frac{1}{2} c_f (1 + \kappa) \rho V^2 S \tag{10}$$

where V is the speed, kn; S is wet area, m².

6.2. The results about resistance of the planing craft

The example resistance of the planing craft under different volume Froude number has been calculated. The results are shown in the table 5:

Table 5. The results of the planing craft are calculated by Maxsurf.

Fr_v	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4.0
$R(\text{kN})$	10.0	10.3	10.5	10.8	11.0	11.4	11.7	12.1	12.4	12.7

When the volume Froude number is 3.1, the waveform of the free surface is shown in figure 8 below:

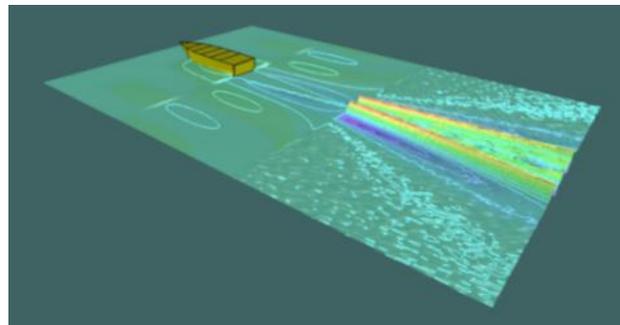


Figure 8. The waveform of the planing craft in free surface.

As can be seen from the above figure, when $Fr_v = 3.1$, the waveform of free liquid is symmetrical on the side of the yacht and is concentrated at the end of yacht. The peaks and valleys have changed dramatically, that concentrated in the rear of the yacht. The waveform of the yacht in the free liquid surface also corresponds to the variation of the waveform under the actual conditions.

6.3. The calculation results about resistance of the transition and drainage yacht

Resistance of the transition and drainage yacht under different volume Froude number s has been calculated by Maxsurf.

The results are shown in the table 6:

Table 6. Resistance results of the transition and drainage yacht calculated by Maxsurf.

Fr_v	0.8	1.3	1.8	2.3	2.8
$R(\text{kN})$	33	57	107	137	180

7. The Comparative analysis on the resistance results of yachts calculated by different methods

The results of various methods for calculating the resistance of yachts are summarized, and the estimation methods for resistance of planning boats and drainage yachts are compared and analyzed respectively.

7.1. Comparative analysis on resistance of the planing boat by different methods

Based on numerical simulation, the Maxsurf software and the empirical equation, the resistance versus the volume Froude number is investigated by using these methods to calculate the resistance of planning boat. As shown in the following figure 9:

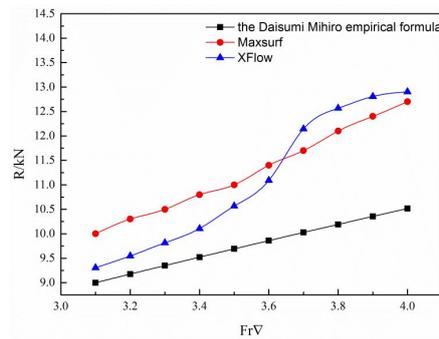


Figure 9. Resistance comparison analysis chart for the planing boat.

As can be seen from the diagram, the results of the three methods to calculate resistance of planing boat are different. The results of XFlow software and Maxsurf software are relatively close, and that are larger than the resistance obtained by the Daisumi Mihiro empirical equation. The tendency of the resistance curve increases with the increase of the volume Froude number, which agrees with the change tendency in actual conditions.

7.2. Comparative analysis on resistance of the transition and drainage yacht by different methods

By comparing the results of XFlow with the resistance of Maxsurf and empirical equation, the analysis curve can be drawn, as shown in figure10.

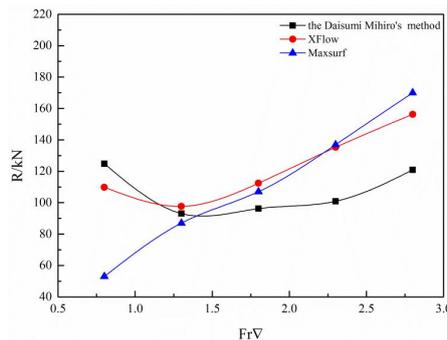


Figure 10. The comparative analysis chart of resistance for the transition and drainage boat.

From the diagram above, the results of the Daisumi Mihiro’s map method and XFlow software are relatively close under the same condition. The trends of their resistance curves are the same. Which go down first and then rise. The change is consistent with the trend of resistance for the transition and drainage yacht under actual operating conditions. The results of Maxsurf are quite different from the XFlow when the volume Froude number is small, but with the increase of volume Froude number, the resistance calculated by the two methods is closer.

8. Conclusions

For single yachts, starting from resistance forecast, it has analyzed the predicting methods of the resistance for displacement yachts, transitional yachts and planning boats. The results are compared and analyzed. The following conclusions are drawn:

8.1. The comparison and analysis on resistance estimation methods for the planning boat

The results show that resistance curves obtained by the three methods have the same trend and are consistent with the actual situation. Quantitative analysis shows that the results calculated by Maxsurf and XFlow are relatively close and are larger than the Daisumi Mihiro empirical equation. With the increase of the volume Froude number, the difference between the resistance results obtained from the software and the empirical equation is greater.

Therefore, in the preliminary analysis of resistance, Daisumi Mihiro empirical equation to estimate resistance of the planning craft is relatively credible. These computational experiences provide an effective reference for resistance prediction of planning boats in the future.

8.2. The comparison and analysis on the ways to estimate resistance for the transition and drainage boats

The results of three methods for calculating resistance of the transition and drainage boats are presented. From qualitative analysis, the resistance of Maxsurf software varies with volume Froude number is not in conformity with the actual yacht. But in quantitative analysis, when the volume Froude number is greater than 1.3, the calculation result is closer to the result of XFlow software and the Daisumi Mihiro's map method. Because XFlow is more comprehensive in theory compared with Daisumi Mihiro's map, so the final results in the later high speed part is are higher than the results of Daisumi Mihiro's map method. But the overall trend is consistent with the actual resistance trend of the transition and displacement type yacht with the volume Froude number. To sum up, for estimating resistance of the displacement and transitional crafts, Daisumi Mihiro's map method is more helpful and credible. When the volume Froude number is greater than 1.3, it is feasible to estimate the resistance of transition and drainage yacht by Maxsurf. That has some guidance and reference for the resistance prediction of transitional and drainage yachts in the future.

Above all, the XFlow software efficiently calculates the resistance of yachts. Which is easy to handle free surface, but the stability of free surface needs to be improved. In terms of time and cost, there is no model test to determine the resistance of yachts. Therefore, further research is needed on the forecast for the resistance of yachts.

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