Investigation of the 2.5D method in added resistance prediction of high speed trimaran

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Abstract. The numerical simulation of hydrodynamic performance of trimarans has attracted a significant attention recently. A series of added resistance model tests for a trimaran model at different speeds and regular waves are carried out. The variation trend of trimaran added resistance with wavelength to ship length ratio is analyzed for Fn=0.353 and Fn=0.471 under different outrigger layout. On these bases, the 2.5D method is applied to calculate the added resistance of the trimaran model in the experiment under various conditions and compare with the experimental results. By comparing with the experimental results, the scope of application of the 2.5D method in added resistance prediction is verified.

1. Introduction

As high-performance ships, trimarans have been widely applied in marine engineering nowadays. Since a trimaran usually consists of a main hull and two identical outriggers, it often has better rolling stability and lower wave resistance in some Froude numbers ranges. Also, the passenger accelerations of trimarans are usually smaller than that of catamarans in head-sea waves [1,2]. In recent years, the research on trimaran added resistance has been paid more and more attention under the background of the promotion of the concept of green ship. Trimaran added resistance refers to the difference between the resistance of a trimaran sailing in waves and that of a trimaran sailing at the same speed in calm water. At present, the research on the added resistance of trimaran is not mature enough compared to conventional mono-hull ships. This is because the configuration of the trimaran is quite unique (i.e. a main hull and two identical outriggers). Therefore, additional consideration should be given to hydrodynamic interference between the main hull and outriggers during the calculation of added resistance.

The earliest research on the ship added resistance can be traced back to 1942. Havelock et al [3] first proposed the method of obtaining heave force and pitching moment by integrating the wet surface pressure along the longitudinal direction to solve the added resistance of ships. The advantage of their work is that the calculation is relatively clear and simple, but the effect of diffraction force and viscosity is neglected which leads to inaccuracy of the results. Subsequently, Maruo [4] made up for the shortcomings of Havelock's work, considered the influence of incident, radiation and diffraction, and obtained the added resistance by using the distributed source method. Later, in 1972, Gerritsma and Beukelman [5] proposed the method of solving wave resistance enhancement by using radiation energy. The principle of this method is that the unsteady wave energy carried by the radiation waves generated by ship motions is considered to be obtained by the work done by added resistance. In this way, the average value of added resistance can be obtained by the radiation energy generated by ship...
moving in waves.

In the research work of ship added resistance in recent years, the solution methods of added resistance are more and more novel and varied. Representative examples include the Enhanced unified theory proposed by kashiwagi et al [6] in 2010 to solve the added resistance of ships. The significance of their work is to calculate the wave amplitude function required in the formula of added resistance proposed by Maruo, and discuss in detail the variation law of added resistance with traveling speed. Duan et al [7] also numerically predicted the hydrodynamic force and motion response of high-speed ships moving in regular waves by using the 2.5D theory. On this basis, a method for calculating added resistance of high-speed ships is recommended. In addition, Wan et al [8] also calculate and analyze the motion and added resistance of a Wigley III type model in head sea waves by the self-developed CFD solver (naoe-FOAM-SJTU). The numerical results show good agreement with the experimental results. In terms of the calculation of trimaran added resistance, Wu et al [9] analysis the influence of outrigger layout on trimaran’s added resistance by CFD method. Although the numerical results agree well with the experimental result, the approach efficiency is not high enough. Therefore, this method is difficult to be used in trimaran outrigger layout analysis which requires large-scale computation. Besides, some major developments in the numerical modelling of wave propagation using the finite element method are also beneficial to the study of trimaran added resistance calculation [10,11].

In this paper, the model tests for a trimaran model at different speeds and regular waves are introduced. By measuring the resistance of the trimaran model in calm water and in waves at different speed, the variation law of trimaran added resistance with speed is analyzed. Based on the proposed model, the 2.5D method is applied to calculate the added resistance of the trimaran model according to the experimental conditions. By comparing the numerical results with the experimental results, the scope of application of the 2.5D method in added resistance prediction is verified.

2. Methodology

2.1. Trimaran added resistance model tests

In order to validate the application of the 2.5D method in trimaran added resistance prediction, the model tests of the trimaran under different speed and outrigger layout is performed in this paper. The model tests were conducted at Harbin Engineering University towing tank (108 m in length, 7 m in width and 3.5 m in depth). To measure the trimaran added resistance, a resistance sensor was set up on the trimaran model. The conditions of the trimaran model and the towing tank are shown in figure 1, the main parameters of this model are given in table 1.

![Figure 1. Trimaran model and wave tank.](image)

| Main feature     | unit | value |
|------------------|------|-------|
| Length overall   | m    | 3.343 |
| Breadth          | m    | 0.641 |
In the experiment we set 6 kinds of outrigger layout (see table 2), 2 transverse distance \((p/L=0.096, 0.15)\) and 3 longitudinal distance \((a/L=0.0, 0.26, 0.78)\), where \(a\) represents the longitudinal distance between main hull stern to outrigger stern and \(p\) represents the transverse distance between main hull center to outrigger center.

### Table 2. Parameters of outrigger layout.

| Serial number | \(a/L\) | \(p/L\) |
|---------------|--------|--------|
| L1T1          | 0.0    | 0.096  |
| L1T2          | 0.0    | 0.15   |
| L2T1          | 0.26   | 0.096  |
| L2T2          | 0.26   | 0.15   |
| L3T1          | 0.78   | 0.096  |
| L3T2          | 0.78   | 0.15   |

The traveling speed we set in the experiment are \(Fn = \frac{V}{\sqrt{gL}} = 0.353\) and 0.471 respectively. For the convenience of reference, the added resistance is dimensionless as \(\frac{LR_a}{\rho g \xi^2 B^2}\) where \(R_a\) is the added resistance of the trimaran, \(\rho\) represent the density of water, \(g\) is gravity taking \(g = 9.81m/s^2\), \(\xi\) is the wave height, \(B\) is the breadth of the main hull. The added resistance of each condition is shown in the figures 2 and 3 (\(R_a\) is derived by the difference between resistance in waves and in calm water).

![Figure 2](image1.png)

**Figure 2.** Added resistance of trimaran in different outrigger layout at \(Fn=0.353\).

![Figure 3](image2.png)

**Figure 3.** Added resistance of trimaran in different outrigger layout at \(Fn=0.471\).

It can be obviously seen from figures 2 and 3 that L3T2 layout \((a/L=0.26, p/L=0.15)\) has the highest value of added resistance in any traveling speed. For \(Fn=0.353\), the wavelength to ship length ratio corresponding to the peak point of added resistance is around 1.1. While in the case of \(Fn=0.471\), the wavelength to ship length ratio corresponding to the peak point of added resistance is around 1.3. In addition, for most cases, the added resistance will increase first then decrease with the increase of wave length to ship length ratio. To sum up, for both \(Fn=0.353\) and \(Fn=0.471\) and for most cases, it will lead to a smaller value of added resistance when the outriggers are placed near the stern of the main hull.
2.2. Theoretical calculation method of trimaran added resistance

High speed slender body potential flow theory is also named two dimensional and a half potential flow theory (2D+t theory or 2.5D theory). This method considers the free surface condition with forward speed and retains the assumption of two-dimensional flow field according to the geometry characteristics of slender body. It was first used by Faltinsen and Zhao [12] for the theoretical prediction of ships seakeeping performance and been widely applied since then. Based on the following assumptions, this method simplifies the calculation of ship motions. (1) Slender body assumption (the ship hull is assumed to be a slender body). (2) The steady wave-making potential is neglected. (3) There are no waves in front of the ship bow.

To predict added resistance of a trimaran, motions (including heave and pitch) of the trimaran must be accurately calculated. 2.5D method is adopted to calculate the vertical motion of the trimaran, the information of this method can be referred to reference [13] and will not be described here. According to the linear potential flow theory, the velocity potential of the flow field around the trimaran can be expressed as:

\[ \Phi = \Phi_I + \Phi_B \]  

In the frequency domain analysis, we have:

\[ \Phi_I = Re(\phi_I e^{i\omega t}) \]  

\[ \Phi_B = Re[\phi_B e^{i\omega t}] \]  

\[ \phi_I = \frac{iga}{\omega_0} e^{k_0 x} e^{-ik_0(x\cos \beta + y \sin \beta)} \]  

where \( \phi_I \) is the velocity potential of regular waves, \( \phi_B \) is the diffraction potential. \( \phi_I \) \((i = 1,2,\ldots6)\) is the unit radiation potential. The steady drift force on a ship in waves can be expressed as a first order potential:

\[ \vec{F}_m = -\frac{\rho}{2} [\int \int_{SB} (\Phi \frac{\partial \Phi}{\partial n} + \nabla \Phi - \nabla \frac{\partial \Phi}{\partial n})d\sigma]_m \]  

The velocity potential can be divided into the incident potential \( \Phi_I \) and the disturbance potential \( \Phi_B \). It can be concluded that the added resistance of the ship sailing in waves can be expressed as five parts as follow:

\[ R_a = F_3^1 + F_3^2 + F_3^2 + F_3^2 + F_3^3 \]  

\[ F_3^1 = Re \left[ \frac{1}{2} \rho k_0 \eta_3 \int_L dx \int_{S_1} \omega_0 N_3 \phi_i^* d\sigma \right] - Re \left[ \frac{i}{2} \rho k_0 \eta_3 U \int_{S_1} N_3 \phi_i^* d\sigma \right] \]  

\[ F_3^2 = Re \left[ \frac{1}{2} \rho k_0 \eta_5 \int_L dx \int_{S_1} \omega_0 (-x N_3) \phi_i^* d\sigma \right] - Re \left[ \frac{i}{2} \rho k_0 \eta_5 U \int_{S_1} (-x N_3) \phi_i^* d\sigma \right] \]  

\[ F_3^3 = Re \left[ \frac{i}{2} \rho k_0 \eta_3 \int_L dx \int_{S_1} \phi_3 N_3 \phi_i^* d\sigma \right] \]  

\[ F_3^4 = Re \left[ \frac{1}{2} \rho k_0 \eta_5 \int_L dx \int_{S_1} \phi_5 N_3 \phi_i^* d\sigma \right] \]  

\[ F_3^5 = Re \left[ \frac{i}{2} \rho k_0 \eta_3 \int_L dx \int_{S_1} \phi_5 N_3 \phi_i^* d\sigma \right] \]  

\[ F_3^3 = Re \left[ \frac{i}{2} \rho k_0 \eta_3 \int_L dx \int_{S_1} \phi_5 N_3 \phi_i^* d\sigma \right] \]
where $S_i$ is the $i^{th}$ cross section (from the stern to the bow), $N_3$ is the vertical component of the normal vector in the transverse section. $\phi_3, \phi_5$ is the unit radiation potential of heave and pitch respectively. $\phi_D$ is the diffraction potential.

3. Results and discussion

For the convenience of reference, note that $R'_a = \frac{L R_a}{\rho g C^2 B^2}$ is the non-dimensional added resistance. The results obtained by experimental data (black symbols) are compared with the prediction results (red lines) and are shown in figures 4 and 5.

Figure 4. Added resistance of the trimaran at $Fn=0.353$. (a) $a/L=0.0, p/L=0.096$, (b) $a/L=0.0, p/L=0.15$, (c) $a/L=0.26, p/L=0.096$, (d) $a/L=0.26, p/L=0.15$, (e) $a/L=0.78, p/L=0.096$ and (f) $a/L=0.78, p/L=0.15$. 

(a) (b) (c) (d) (e) (f)
It can be observed that the results obtained by the proposed model are basically in good agreement with the test results, the average error of each group of results is distributed around 5% to 20%. Although the numerical prediction results in some individual conditions are far from the test results, the overall results show that the numerical prediction results can accurately reflect the variation tendency of added resistance curve.

For most conditions, the added resistance will increase first then decrease with the increase of wave length to ship length ratio. The wavelength to ship length ratio corresponding to the peak value of added resistance are mostly distributed between 1.0 ~ 1.2 for $Fn=0.353$ and 1.2 ~ 1.4 for $Fn=0.471$. With the increase of traveling speed, the wavelength to ship length ratio corresponding to the peak point of added resistance tends to increase. It should be noted that for both $Fn=0.353$ and $Fn=0.471$, the L3T2 layout ($a/L=0.78$, $p/L=0.15$) has the greatest value of added resistance. For L3T2 layout at $Fn=0.471$, the prediction results are quite different from the experimental results (figure 5(f)). This may due to the reason of slamming (the slamming phenomenon has been observed in the experiment).
4. Conclusion
This paper first introduced the added resistance model tests of a trimaran. Then a theoretical approach of trimaran added resistance prediction based on 2.5D method is described. Finally, the trimaran added resistance prediction method adopted in this paper is verified for $Fn=0.353$ and 0.471 by comparing the experimental results with the prediction results. The following conclusions can be obtained:
- In general, the prediction results are in good agreement with the experimental results. The predicted results can better reflect the trend of added resistance.
- In the case of the wavelength to ship length ratio more than 0.8, the added resistance will increase first and then decrease with the wavelength to ship length ratio for all outrigger layouts.
- The wavelength to ship length ratio corresponding to the peak value of added resistance are mostly distributed between 1.0~1.2 for $Fn=0.353$ and 1.2~1.4 for $Fn=0.471$.

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