Numerical Study of Resistance Performance of Super-Slender Catamaran in High Speed

Xinwang Liu, Aiqin Miao, Decheng Wan*
State Key Laboratory of Ocean Engineering, School of Naval Architecture, Ocean & Civil Engineering, Shanghai Jiao Tong University, Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, Shanghai 200240, China

Abstract : For the super-slender catamaran at a high speed, the ratio of the wave resistance to the total resistance is larger than that of the conventional hull forms. This paper, focusing on three proposed hull form design case, mainly calculates the wave resistance effectively through the Newmann-Michell theory , and estimates the frictional resistance by ITTC formula in order to obtain the total resistance.Then, the paper compares and analyzes the resistance and the wave patterns made by the hulls, and preliminarily selects the hull form design case which has the best resistance performance. Finally, more precise resistance performance prediction as well as information of the flow field is given by Computational Fluid Dynamics method, leading to the decision of the final preference of the hull form design.

Key words : super-slender catamaran; Neumann-Michell theory; resistance performance; preliminary design

1 Introduction

High-speed catamaran is one of the catamaran types which have rapid development nowadays. Typical high-speed catamaran hull form generally consists of two slender bodies connected with the deck structure. Super-slender high-speed catamaran belongs to a special high-speed catamaran because of its two extremely slender bodies. The rapidity of high-speed catamaran is good so it can achieve very high speeds in order to meet the demand of practical engineering. However, the wave made by the catamaran at high speeds can not only bring serious erosion damage to the shipping facilities and the coast, but also affect the resistance performance of itself[1]. Therefore, numerical calculation and forecast of resistance performance of the catamaran is of great significance for the hull form design.

There are generally two kinds of methods for high-speed catamaran resistance performance prediction. One is the methods based on the potential flow theory and the other is the methods based on computational fluid dynamics. Although CFD has developed rapidly in recent years, the methods based on potential flow theory still have their future.There are two mainly reasons : on the one hand, the ratio of the wave resistance to the total resistance is larger than that of the conventional hull forms and accurate prediction of wave resistance is which designers are concerned; on the other hand, in the ship preliminary design phase, designers need to quickly and accurately evaluate the resistance performance of the hull form design in order to do hull form design. One of the potential flow methods is Neumann-Michell theory(NM theory), proposed by Francis Noblesse *et al* based on the Neumann-Kelvin theory(NK theory)[2]. NM theory eliminate the ship waterline integral item in the NK theory, and the whole calculation can be converted to the integral on the wet surface of the ship. The theory adopts the coordination linear flow model and there's no need to solve the distribution on the boundary of the source but calculate the wave resistance through the iteration of velocity potential[3]. Besides, there are a lots of research about comparisons of experimental measurements of wave drag with numerical predictions obtained using the NM theory for the Wigley hull, the Series 60 and DTMB 5415 model. Zhang *et al* of our research group, self-developed the NMShip -SJTU solver based on NM theory and calculated the resistance of catamaran, including the resistance of Delft catamaran and Series 60 catamaran in different demihull spacings [4].The results showed that the calculation results are in good agreement with experimental measurements. Wu *et al* succeed to optimize hull form of Wigley with the best wave resistance performance evaluated by NM theory [5]. Yang and Huang presented that the sum of the ITTC friction resistance and the NM theory wave resistance could be expected to yield realistic practical estimates, which could be useful for routine applications to design and ship hull form optimization of a broad range of displacement ships [6]. The computation of the steady flow around a moving ship based on NM theory is efficient and robust due to the succinctness of this theory, and Kim *et al* pointed that the wave resistance predicted by NM theory is in fairly good agreement with experimental measurements[7]. Using NM theory can quickly complete the resistance performance forecast on personal computers. Calcuating the resistance of the ship based on CFD, by contrast, takes more time. For further investigation of the initial set of solutions, the CFD method has a big advantage that it can offer more precise flow field information and reduce the test costs.

This paper calculates the resistance of super-slender catamaran and compares the resistance of performance of three ship hull form design (named by Model 1, Model 2, Model 3) . Wave resistance is calculated by NM theory (at the speed of 30kn, 33kn, 36kn) and the friction resistance by ITTC formula. Then the paper further compares and analyzes wave patterns of free surface. Model 3 is chosen as its best resistance performance. The interference between demihulls has effect on the resistance obtained by CFD solver, naoe-FOAM-SJTU. At last, more accurate resistance evaluation of Model 3 by CFD method is realized and analyzed from several aspects.

2 Methodology

Assume a model based on potential flow: a ship of length L_s that steadily advances at speed V_s along a straight path in calm water without viscosity of effectively infinite depth and lateral extent. We define the Froude number $Fr \equiv V_s / \sqrt{gL_s}$ where g is the acceleration of gravity. The flow about the ship hull is observed from a righthanded moving system of orthogonal coordinates $\mathbf{X} \equiv (X, Y, Z)$

attached to the ship(the X axis is chosen along the path of the ship and points toward the ship bow; the Y axis is parallel to the mean(undisturbed) free surface and points toward the right side of te ship; and the Z axis is vertical and points upward, with the mean free surface taken as the plane Z = 0 , as shown in Fig.1),and thus appears steady with flow velocity given by the sum of an apparent uniform current $(-V_s, 0, 0)$ opposing the ship speed V_s and the (disturbance) flow velocity $\mathbf{U} \equiv (U, V, W)$ due to the ship. The ship length L_s and speed V_s are used to define nondimensional coordinates $\mathbf{x} \equiv \mathbf{X} / L_s$, flow velocity $\mathbf{u} \equiv \mathbf{U} / V_s$, and flow potential $\phi \equiv \Phi / (V_s L_s)$.

We define points $\mathbf{x} \equiv (x, y, z)$ (which are 'boundary points' located on the ship hull surface Σ^H)and $\tilde{\mathbf{x}} \equiv (\tilde{x}, \tilde{y}, \tilde{z})$ (which are 'flow-field points' that may be located on the ship hull surface Σ^H or in the flow region outside Σ^H)associated with a Green function $G(\tilde{\mathbf{x}}; \mathbf{x})$ that satisfies the Poisson equation that is used to formulate a boundary-integral flow representation:

$$\nabla^2 G(\mathbf{x}; \mathbf{x}) = \delta(x - \tilde{x})\delta(y - \tilde{y})\delta(z - \tilde{z}) \tag{1}$$

where $\delta(x - \tilde{x})$ represents the Dirac function, which is a singular function and can be defined by integral form:

$$\int_a^b \delta(x - \tilde{x}) f(x) dx = \begin{Bmatrix} f(\tilde{x}) \\ 0 \end{Bmatrix} \; if \; \begin{Bmatrix} a < \tilde{x} < b \\ \tilde{x} < a \; or \; b < \tilde{x} \end{Bmatrix} \tag{2}$$

Here, $f(\tilde{x})$ represents the function that is continuous at $x = \tilde{x}$. Formula (2) can also be extended to higher dimensions:

$$\int_D \delta(x - \tilde{x})\delta(y - \tilde{y})\delta(z - \tilde{z}) f(\mathbf{x}) dv = \begin{Bmatrix} f(\tilde{\mathbf{x}}) \\ 0 \\ f(\tilde{\mathbf{x}})/2 \end{Bmatrix} \; if \; \begin{Bmatrix} \tilde{\mathbf{x}} \in D \\ \tilde{\mathbf{x}} \notin D \\ \tilde{\mathbf{x}} \in \Sigma \end{Bmatrix} \tag{3}$$

where $dv = dxdydz, \; f(\mathbf{x}) \equiv f(x, y, z), \; f(\tilde{\mathbf{x}}) \equiv f(\tilde{x}, \tilde{y}, \tilde{z})$, and Σ is the envelope plane of the region D.

The flow potential at a flow-field point $\tilde{\mathbf{x}}$ or at a boundary point $\mathbf{X}$ is identified as $\tilde{\phi} \equiv \phi(\tilde{\mathbf{x}})$ or $\phi \equiv \phi(\mathbf{x})$ respectively. The flow velocities can be obtained by $\tilde{\mathbf{u}} \equiv (\tilde{u}, \tilde{v}, \tilde{w}) \equiv \nabla \tilde{\phi}$ and $\mathbf{u} \equiv (u, v, w) \equiv \nabla \phi$. Furthermore, da denotes the differential element of area at a point $\mathbf{X}$ of the ship hull surface Σ^H , and $\mathbf{n} \equiv (n^x, n^y, n^z)$ is a unit vector that is normal to Σ^H at $\mathbf{X}$ and points outside Σ^H ,as shown in Fig.1.

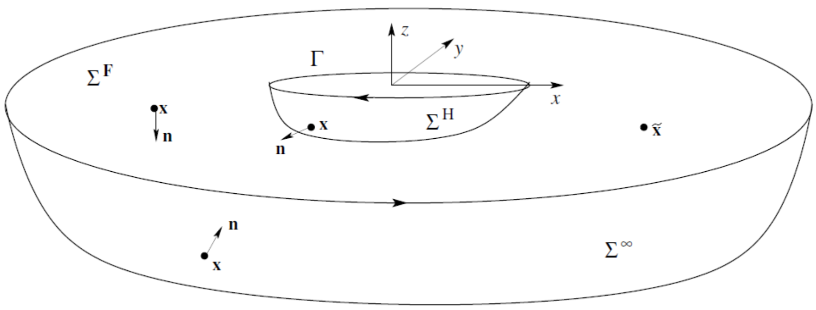


Fig.1 Coordinate system and boundary sketch

The Neumann-Michell potential representation is expressed as below, and more details of this theory can be found in the reference related [3].

$$\tilde{\phi} \approx \tilde{\phi}_H + \tilde{\psi}^W \equiv \tilde{\phi}_H^L + \tilde{\phi}_H^W + \tilde{\psi}^W \qquad (4)$$

The (modified) Hogner potential $\tilde{\phi}_H$ and the NM correction potential $\tilde{\psi}^W$ can be extended as follows:

$$\tilde{\phi}_H \equiv \int_{\Sigma^H} G\, n^x\, da - \int_{\Sigma^F} G\, \pi^{\phi}\, dxdy \qquad (5)$$

$$\tilde{\psi}^W \equiv \int_{\Sigma^H} (\phi_{t'} \mathbf{d}_* + \phi_{d'} \mathbf{t}_*) \cdot \mathbf{W} da \qquad (6)$$

where

$\sum^H$ is the average wet surface area;

G is the Green function;

n^x is the projection in x direction of $\mathbf{n} = (n^x, n^y\ n^z)$;

$\pi^{\phi} \equiv \phi_z + Fr^2 \phi_{xx}$, Fr is the Froude number;

$\mathbf{t}'$ and $\mathbf{d}'$ are two unit vectors tangent to the ship surface Σ^H. For instance, the unit vectors can be chosen as

$$\mathbf{d}' = (0, -\nu^z, \nu^y), \quad \mathbf{t}' = (\nu, -n^x \nu^y, -n^x \nu^z), \quad \nu \equiv \sqrt{(n^y)^2 + (n^z)^2}, \quad (\nu^y, \nu^z) \equiv (n^y, n^z)/\nu \qquad (7)$$

and $\phi_{t'}$ and $\phi_{d'}$ are the components of the velocity of the flow field on the wet surface of the ship at the directions of $\mathbf{t}'$ and $\mathbf{d}'$,

$$\phi_{t'} \equiv \partial\phi / \partial t' \equiv \mathbf{t}' \cdot \nabla\phi \equiv t'^x \phi_x + t'^y \phi_y + t'^z \phi_z$$
$$\phi_{d'} \equiv \partial\phi / \partial d' \equiv \mathbf{d}' \cdot \nabla\phi \equiv d'^x \phi_x + d'^y \phi_y + d'^z \phi_z \qquad (8)$$

Wave function satisfies $G = W + L$, $\nabla \times \mathbf{W} = \nabla W$ and we can get

$$\mathbf{d}_* \equiv \frac{\mathbf{n} \times \mathbf{t}' - \varepsilon \mathbf{n} \times \mathbf{d}'}{1 - \varepsilon^2}, \quad \mathbf{t}_* \equiv \frac{\mathbf{n} \times \mathbf{d}' - \varepsilon \mathbf{n} \times \mathbf{t}'}{1 - \varepsilon^2}, \quad \varepsilon \equiv \mathbf{t}' \cdot \mathbf{d}' \qquad (9)$$

NMShip-SJTU solver is based on the theory of Neumann-Michell theory, and it's developed using C++ language [8]. The input file contains the ship grid, free surface grid and grid type parameter, and we can get surface pressure distribution and resistance of the ship and wave pattern of the free surface, etc.

3 Computational model

In this paper, the calculation models are three super-slender catamarans in different shapes with a waterline length of 53.74m (as shown in Fig. 2 ~ 4), and self-developed NM theory solver NMShip-SJTU is used to calculate the resistance. According to the requirement of design, the calculation speeds are 30 kn, 33 kn, and 36 kn. Specific values are shown in Table 1.

Fig.2 Model 1

Fig.3 Model 2

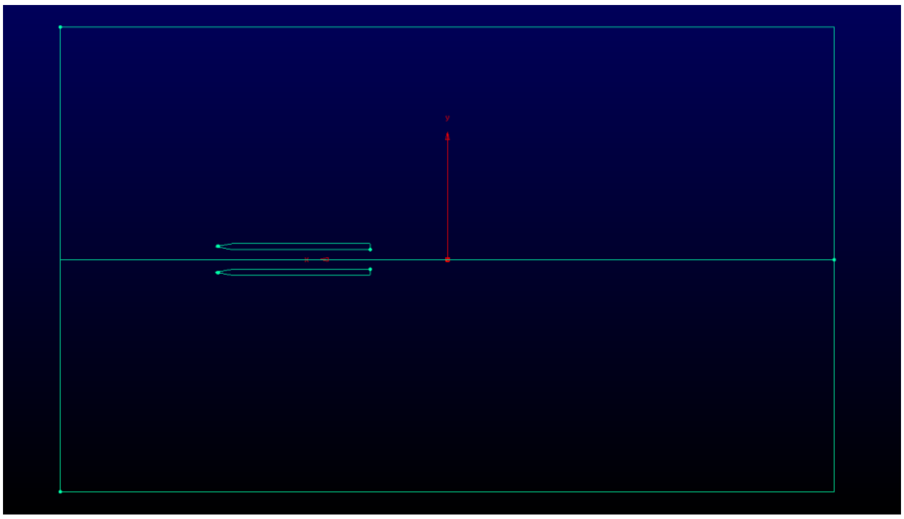
Fig.4 Model 3

Table 1 Different ship parameters and number of hull panels in numerical calculation

Ship model	B/L	D/L	s/L	Number of panels
Model 1	0.03653	0.00913	0.16438	26594
Model 2	0.03684	0.01289	0.16579	22818
Model 3	0.03730	0.00791	0.16744	23326

It can be seen from Table 1 and Fig. 2 ~ 4 that the three catamaran's ship bows are obviously different; for the hull form parameters, Model 3 has the largest relatively breadth, Model 2 has the largest relatively draft, while the relatively demihull spacings of the three models are basically the same.

Free surface area and its grid are shown in Fig. 5, where the size of free surface area is $-L<x<4L$ and $-2L<y<2L$, and the total number of grid cells is about 500 thousand.



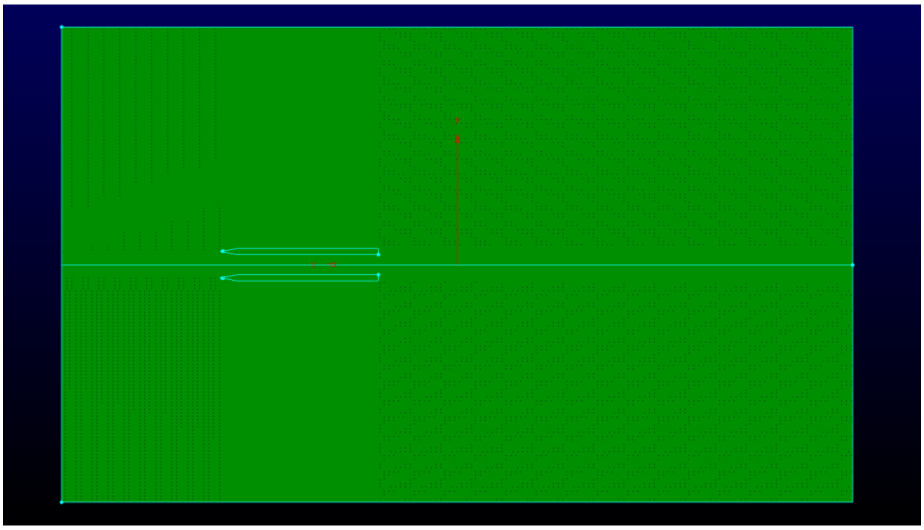


Fig.5 Free surface area and meshes

4 Results and analysis

Table 2 Calculation results of the resistances

Ship model	Speed(kn)	Friction resistance (ITTC) (N)	Wave resistance(N)	Total resistance(N)
Model 1	30	47345.24	3850.57	51195.82
	33	56605.51	4123.97	60729.48
	36	66636.61	4413.81	71050.41
Model 2	30	50268.13	9308.04	59576.17
	33	60099.70	10144.41	70244.11
	36	70749.59	10981.08	81730.67
Model 3	30	43829.09	3610.17	47439.27
	33	52400.91	3932.31	56333.22
	36	61686.13	4291.69	65977.82

It can be seen from Table 2 that the Model 2 has the largest frictional resistance and wave resistance, so the total resistance is the largest. Since Model 2's draft is the largest, and the wet surface area is also the largest, so the friction resistance is the largest. Frictional resistance value is dominant in the total resistance. The total resistances and the components of the total resistances of Model 1 and Model 3 are similar, while Model 3 has less than 10 % smaller ones.

For the wave resistance component, we can get the free surface wave patterns under different speeds based on the NM theory for further analysis.

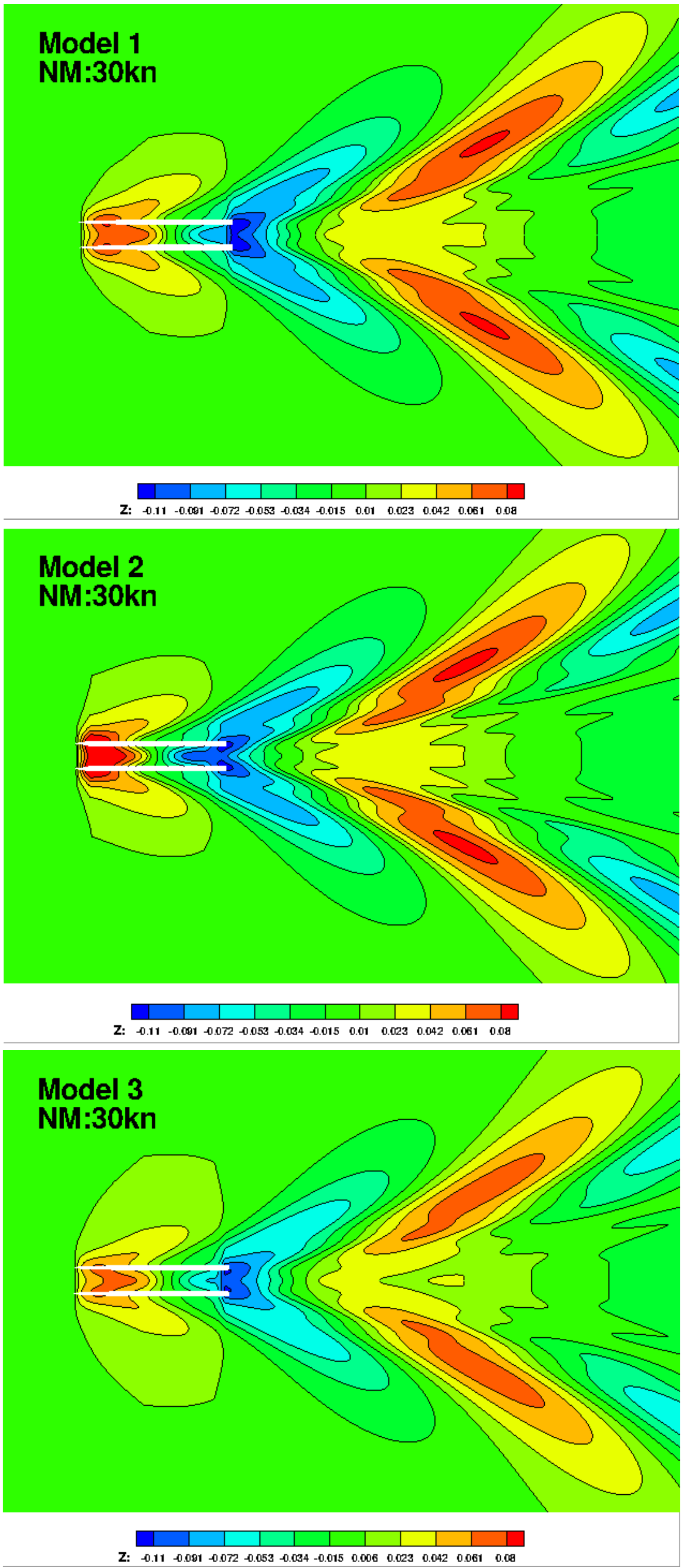


Fig.6 Free surface wave patterns at 30kn

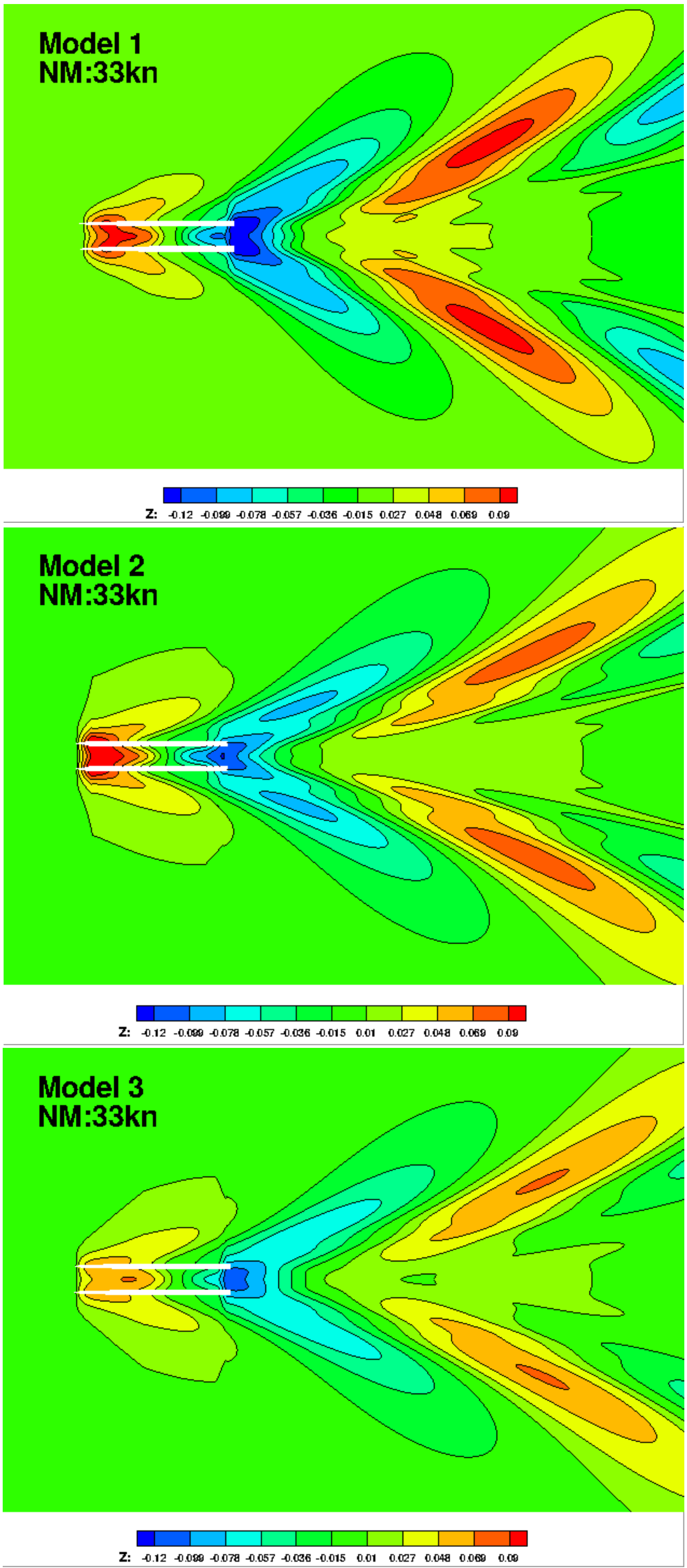


Fig.7 Free surface wave patterns at 33kn

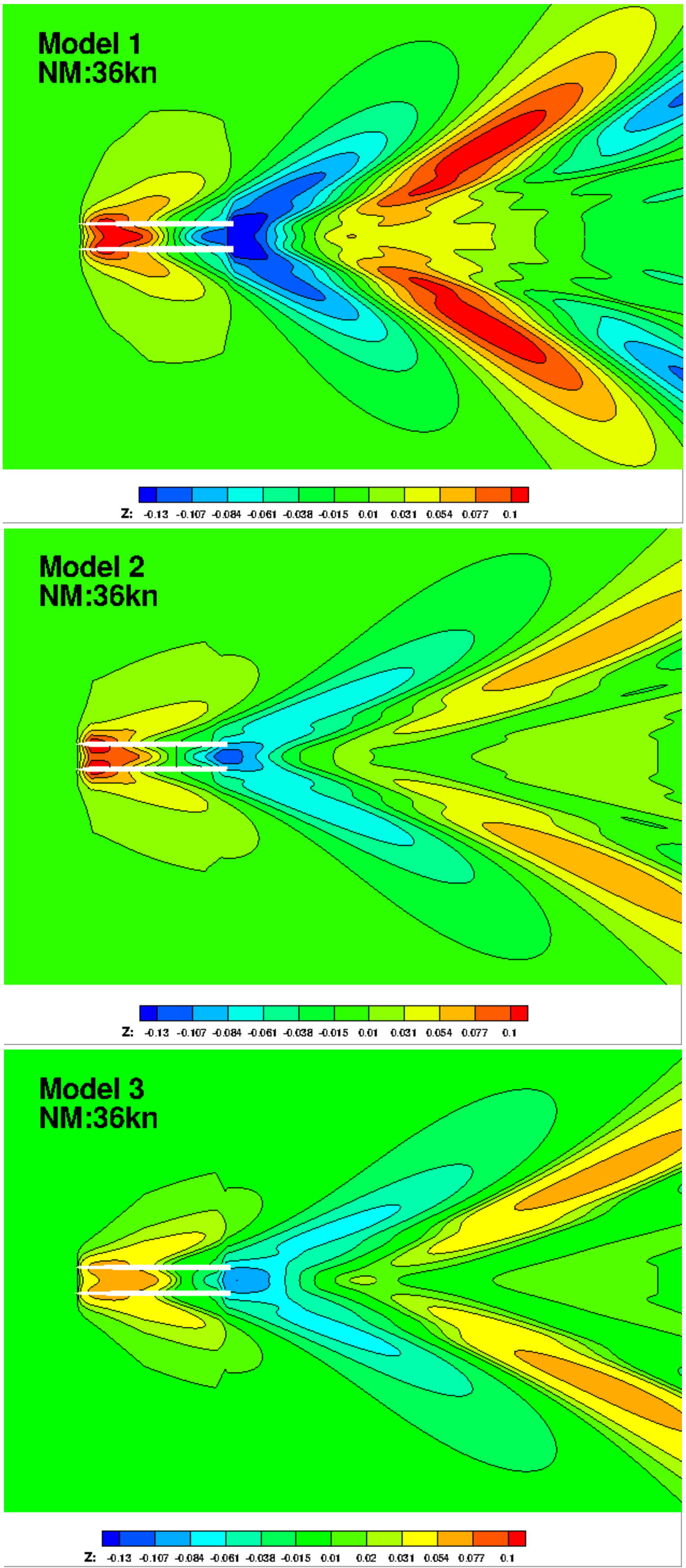


Fig.8 Free surface wave patterns at 36kn

We can see from Fig. 6 ~ 8 that under the same speed, Model 3 has the lowest free surface wave height, thus, the wave resistance is relatively smaller, while Model 1 has the highest free surface wave height and Model 2 takes the second place. The wave of Model 1 and Model 2 is more obvious, and the stem wave crest and stern wave trough are significantly greater than Model 3. However, Model 2 has the largest wet surface area, the wave resistance value is higher than Model 1. At the same time, for the same model, the higher speed it has, the greater wave pattern it will generate while the smaller interference of two demihulls there will be.

From the perspective of the ship hull form, Model 1 has a more apparent bow forward than Model 3, and the stem profile of Model 2 is less streamlined than that of Model 3. In conclusion, Model 3 has the best resistance performance, which can be chosen as the preliminary model of the three hull form designs.

In order to determine the resistance performance of Model 3 more accurately, we use the naoe-FOAM-SJTU solver for ship and ocean engineering hydrodynamics that was developed by Shen *et al* based on an open source CFD platform OpenFOAM [9].

Table 3 NM and CFD resistance calculation results of Model 3

Speed (kn)	NM result（N）			CFD result（N）			Error	
	Friction resistance	Wave resistance	Total resistance	Friction resistance	Pressure resistance	Total resistance	Absolute (N)	Relative
30	43829.09	3610.17	47439.27	43586.2	7220.54	50806.74	-3367.47	-6.63%
33	52400.91	3932.31	56333.22	53238.7	9030.9	62269.6	-5936.38	-9.53%
36	61686.13	4291.69	65977.82	63992.78	9563.14	73555.92	-7578.1	-10.30%

According to the results of Table 3, the friction resistance prediction based on CFD has a small difference with the results calculated by ITTC formula, although the deviation becomes larger with the increase of speed. In fact, the friction resistance prediction should also take the wave interference of the demihulls into consideration but not calculate the friction resistance and the wave resistance independently. However, due to the limitation of potential flow theory and the demand of the rapid prediction of the resistance performance and the optimization of hull form, it is a feasible way to use NM theory and ITTC formula. For the total resistance, with the increase of speed, the error of the two methods increases. However, within the allowable range of engineering errors, the NM theory can be used to predict the resistance quickly and reliably.

5 Conclusions

This paper focuses on the resistance prediction of a special ship type, which is the super-slender catamaran. The NM theory is used to analyze the resistance performance of the three different cases at three high speeds, and a more reasonable ship design case is preliminarily chosen. Reasonable stem profile design can reduce the wave interference of the demihulls. According to the calculation results, the smaller stem forward and the more streamlined stem profile can reduce the wave resistance, leading to a better resistance performance. Aiming at the preliminary selection of hull form design, the resistance calculation results of the CFD method and NM method are finally given, which further verifies the reliability of the NM theory in the fast resistance performance prediction of catamaran.

References

[1]. 赵连恩, 谢永和. (2009)高性能船舶原理与设计(精). 国防工业出版社.p:64-69.

[2]. Noblesse, F., et al. (2012) The Neumann–Michell theory of ship waves. *Journal of Engineering Mathematics* **79**(1): 51-71.

[3]. Noblesse F, Huang FX, Yang C. (2013) The Neumann-Michell Theory of Ship Waves. *Journal of Engineering Mathematics* **79**(1): 51-71.

[4]. Chengliang Zhang, Jiayi He, Chao Ma, et al. (2015) Validation of the Neumann-Michell Theory for Two Catamarans. *Proceedings of the Twenty-fifth (2015) International Ocean and Polar Engineering Conference*.

[5]. 吴建威, 刘晓义, 万德成. (2015)基于 NM 理论的船型优化技术应用[C], 中国海洋.

[6]. Chi Y, Huang F, Noblesse F. Practical evaluation of the drag of a ship for design and optimization[J]. (2013)水动力学研究与进展 B 辑, **25**(5):645-654.

[7]. H. Kim, C. Yang, H. Kim, H.H. Chun. (2009) Hydrodynamic optimization of a modern container ship using variable fidelity models. *19th International Offshore and Polar Engineering Conference*, Osaka, Japan.

[8]. ZHANG C L, WAN D C. (2015) The manual of NMShip-SJTU solver[R]. Technique Report No. 2015SR011407, Shanghai Jiao Tong University.

[9]. Shen ZR, Jiang L, Miao S, Wan DC, Yang C. (2015) RANS simulations of benchmark ships based on open source code. *7th International Workshop on Ship Hydrodynamics (IWSH 2011)*, Shanghai, China.