



# Article Seakeeping Analysis of Planing Craft under Large Wave Height

# Xiaosheng Bi, Jiayuan Zhuang \* and Yumin Su

Science and Technology on Underwater Vehicle Laboratory, Harbin Engineering University, Harbin 150001, China; bixiaosheng@hrbeu.edu.cn (X.B.); suyumin@hrbeu.edu.cn (Y.S.)

\* Correspondence: zhuangjiayuan@hrbeu.edu.cn

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**Abstract:** The purpose of this paper is to conduct a seakeeping analysis of planing craft under regular wave with large wave height. To obtain a reliable numerical method to simulate the sailing of planing craft in waves, Reynolds-averaged Navier–Stokes (RANS) solver and overset method are adopted. The motion response and resistance of the planing craft USV01 in regular wave were numerical predicted and compared with the corresponding seakeeping experimental tests. The results show that the numerical method has high accuracy. For further study, a new planing craft whose name is improved vessel is selected for simulation, the low steaming of the USV01 and improved vessel in regular wave with large wave height was simulated, and the seakeeping of the two vessels was studied. The analysis about the influence of wave length on the motion response and navigation configurations of the improved vessel was also analyzed. The improved vessel can provide better seakeeping, and a reduction in the speed of the vessel will benefit its seakeeping, irrespective of its navigation configuration.

Keywords: planing craft; numerical method; seakeeping analysis; large wave height

# 1. Introduction

Planing craft have been widely used in various fields. The characteristic of the planing craft is that the bottom of the vessel will come into contact with the free surface when sailing at high speed. Since the bottom is relatively flat, the water pressure at the bottom is increased because the bottom of the boat squeezes water forward [1].

For a better hydrodynamic performance, numerical prediction is becoming increasingly important in the design of planing craft. The methods for predicting the resistance of planing craft include model test data, regression formulas, and semiempirical theory [2]. With the development of the computational fluid dynamics (CFD) method, the accuracy of numerical prediction in predicting the hydrodynamic performance of planing craft under calm water and wave conditions has been improved. In 2017, Diez et al. [3] selected the DTMB 5415 model (US Navy Combatant) as the parent hull of the destroyer, and the hull of the destroyer was improved based on the CFD method. In 2018, Campana et al. [4] used the numerical method to optimize the hull of a high-speed catamaran, and a real ocean environment was also considered. Their results indicated that larger computational power leads to an increase in computational efficiency and that the numerical method is becoming a necessary key to optimizing hull design.

In 2001, Azcueta et al. [5] conducted deep research into the free motion simulation of planing craft, based on the Comet, and the flow field around the hull were studied based on the k- $\epsilon$  turbulence model. Their results indicated that the numerical method can be adopted as an important complement to the study of the free surface flows around planing craft. In 2001, Caponnetto [6] conducted a

hydrodynamic analysis of a planing hull with an unknown center of gravity with Reynolds-averaged Navier–Stokes (RANS) solver. They also compared their results with Savitsky's method. In 2015, Weymouth et al. [7] conducted an analysis on the sailing of a ship under head wave conditions based on the unsteady RANS solver, and their work present accurate numerical results is uncertainties less than 2%. Their results indicate that the RANS solver has a better accuracy in simulating the sailing of a vessel and that the solver is suitable for both high speed and head wave conditions.

In 2015, Sun et al. [8] researched the grid factor in the numerical calculation of planing craft resistance, based on the prismatic glider. The effect of different grid parameters on the accuracy of the numerical results was analyzed. With this grid scheme, the resistance of planing craft in various navigation states is calculated, and the numerical results present good accuracy. Their results are useful for the grid setup and boundary condition definition in this paper. In 2013, Su et al. [9] put forward a numerical method to simulate the freedom motion of planing craft under head wave conditions, based on the six degrees of freedom (6-DOF) motion equation and volume of fluid (VOF) solver. The calculation results present a good agreement with the attitude of vessels under wave conditions. Their results show that the 6-DOF solver is suitable for simulating the motion of planing hull under head wave conditions. In 2017, De Marco et al. [10] conducted a seakeeping analysis of a stepped planing craft. A hydrodynamic experiment of the single-step hull model, as a new systematic series, was carried out, and the corresponding tests were based on numerical simulation, with an overset and morphing grid. Their high-accuracy numerical results show that the overset mesh can improve the efficiency, while ensuring the accuracy of simulation, and the setting of the overset grid is of great referential significance to our work. In 2017, Dashtimanesh et al. [11] provided a numerical prediction of the performance of two-stepped planing craft. based on the mathematical model and the obtained results present the good accuracy compared with the test results. Their results indicate that the CFD method has become a fundamental support for the hydrodynamics study and design of planing craft, and it can be highly beneficial with respect to the cost and duration of hydrodynamic tests.

With the increasing demand for planing craft, the ability to sail in rough sea condition is necessary, and this requires an adequate seakeeping performance. However, traditional design of planing craft makes it difficult to navigate safely. Due to the maturity of the numerical method, the complex motion problems associated with viscous flow, the nonlinear problem, and the transient response problem can all be directly solved by the numerical method. In 2000, Ikeda et al. [12] simulated the motion of planing craft under waves, and the porpoising oscillations and motion responses were numerically forecasted. This means that the unsteady motion of vessels can also be numerically simulated. This has great significance for the study of the extremely high-speed navigation of planing craft. In 2003, Azcueta et al. [13] conducted an analysis on the speed performance of a power boat, based on the free-surface RANS, and their method is suitable for predicting the severe responses of the vessel in waves, making it possible to predict the nonlinear motion of planing craft in rough sea conditions. In 2014, Begovic et al. [14,15] conducted research on the responses of hull forms of a vessel in waves, and the response amplitudes in both regular and irregular waves were obtained and compared with the corresponding test data. The Weibull distribution was adopted to analyze the motion response of the model in irregular waves, especially in relation to the acceleration of the center of gravity (CG). Irregular waves are closer to actual sea conditions, and the study of sailing in irregular waves is more reflective of actual sailing conditions. In 2016, Jiang et al. [16,17] conducted a study on the resistance performance of a planing trimaran with numerical and experimental methods. The CFD simulations were based on 2-DOF motion equations, and high speed sailing of the vessel was simulated. The results were validated with a good accuracy by comparing them with the test data. Their experimental design and setting is referential for our work, and their results indicate that numerical method can also be used to analyze the aerodynamic and hydrodynamic performance of trimaran.

In this paper, the STAR-CCM+ software (Germany) was adopted to simulate the sailing of a small-scale planing craft under regular wave. In regular wave with large wave height, due to the large wave height and wave disturbance, planing craft need to maintain low-speed navigation. This

paper will focus on the research of the motion response and navigation configuration of planing craft in regular wave with large wave height at a low speed. The RANS solver and overset grid were adopted in the numerical simulation of the navigation of the vessel under head waves to obtain better accuracy, and validation was carried out by comparing the numerical results with the corresponding test results. Additionally, a new planing craft with better seakeeping is selected for further analysis, the low steaming of both vessels in regular wave with large wave height was numerically simulated and compared; and the influence of wave length and speed on the motion response and navigation configuration of the vessels is also analyzed.

Previous studies are mainly about the prediction of the motion response of planing craft, this paper focus on the seakeeping and changes of navigation configuration of planing under the regular wave with large wave height. In 2019, we have carried out a research on the seakeeping analysis of planing craft [18], mainly focus on the optimization effect of hydrofoil. This paper aims to illustrate a study on the navigation configuration of small planing craft under large wave height. And the numerical methods used in the two papers are similar.

#### 2. The Numerical Method

#### 2.1. RANS Equation

To simulate the viscous flow field around a sailing ship is to solve the Navier–Stokes equation. In response to this problem, the RANS Equation is commonly used in engineering. In the actual solving process, the time average value is used to replace the statistical average value, the momentum equations is as follows:

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}(\mu \frac{\partial u_i}{\partial x_j} - \rho \overline{u'_i u'_j}) + S_i$$
(1)

Here  $u_i$  and  $u_j$  are the time mean of the velocity component, (i, j = 1, 2, 3), p is piezometric pressure coefficient,  $\rho$  is fluid density,  $\mu$  is coefficient of dynamic viscosity,  $\rho u'_i u'_j$  is the Reynolds stress term,  $S_i$  represents the generalized source term

Equation (1) and the continuity equation of incompressible fluid motion constitute the control equations for solving the viscous flow field around the hull. The continuity equation is as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0 \tag{2}$$

In the RANS equation, the Reynolds stress term is introduced in addition to the progressive equalization. In order to close the control equations, an appropriate turbulence model is introduced to calculate the Reynolds stress term.

#### 2.2. Turbulence Model

In this paper, the Shear Stress Transport turbulence (SST) model is used to seal the control equations. The SST k– $\omega$  model [19] has been widely adopted in the solving of turbulence problems, especially the high Reynolds number flow problems, which is particularly suitable for the simulation of the high-speed navigation of planing craft. Similar to the k– $\omega$  model, the transport equation of k (turbulent kinetic energy) and  $\omega$  (dissipation rating) are presented as follows:

$$\nu_{\rm t} = \frac{a_1 k}{\max(a_1 \omega; \Omega F_2)} \tag{3}$$

$$\frac{D\rho k}{Dt} = \frac{\partial}{\partial x_j} [(\mu + \sigma_k \mu_t \frac{\partial k}{\partial x_j})] + \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta^* \rho \omega k \tag{4}$$

$$\left(\tau_{ij} = -\rho \overline{u_i' u_j'}\right) \tag{5}$$

$$\frac{D\rho\omega}{Dt} = \frac{\partial}{\partial x_j} [(\mu + \sigma_\omega \mu_t \frac{\partial \omega}{\partial x_j})] + \frac{\gamma}{v_t} \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta \rho \omega^2 + 2(1 - F_1) \rho \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}$$
(6)

where  $\Omega$  is the absolute value of the vorticity,  $\rho$  is fluid density.

$$F_2 = \tanh\left(\arg_2^2\right) \tag{7}$$

$$\arg_2 = \max\left(2\frac{\sqrt{k}}{0.09\omega y}; \frac{500\nu}{y^2\omega}\right) \tag{8}$$

where *y* is the distance to the wall.

The constants  $\Phi$  are obtained from  $\Phi_1$  and  $\ \Phi_2$  .

$$\Phi = F_1 \Phi_1 + (1 - F_1) \Phi_2 \tag{9}$$

$$F_1 = \tanh\left(\arg_4^1\right) \tag{10}$$

$$\arg^{1} = \min(\max(\frac{\sqrt{k}}{0.09\omega y}; \frac{500v}{y^{2}\omega}); \frac{4\rho\sigma_{\omega 2}k}{CD_{k\omega}y^{2}})$$
(11)

$$CD_{k\omega} = \max(2\rho\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j};10^{-20})$$
(12)

The constants of Set  $\Phi_1$  are Wilcox:

$$a_1 = 0.31, \sigma_{k1} = 0.85, \sigma_{\omega 1} = 0.5, \beta_1 = 0.075, \beta^* = 0.09, \kappa = 0.41, \gamma_1 = \beta_1 / \beta^* - \sigma_{\omega 1} \kappa^2 / \sqrt{\beta^*}$$
(13)

The constants of Set  $\Phi_2$  are Jones–Launder:

$$a_1 = 0.31, \sigma_{k2} = 1, \sigma_{\omega 2} = 0.856, \beta_2 = 0.0828, \beta^* = 0.09, \kappa = 0.41, \gamma_1 = \beta_2 / \beta^* - \sigma_{\omega 2} \kappa^2 / \sqrt{\beta^*}$$
(14)

# 2.3. Boundary Conditions

The setting of the boundary conditions has a significant influence on solving physical problems of flow field. When the governing equation is given to solve different physical problems, the different boundary value conditions are adopted. The boundary conditions are presented as follows:

Velocity inlet:

The incoming boundary of the flow field, the boundary is usually set far from the ship. The incoming velocity is given, the pressure is obtained by using reconstructed gradient interpolation.

$$v = (U, 0, 0)$$
 (15)

$$\frac{dp}{dn} = 0 \tag{16}$$

The estimation formula of *k* and  $\omega$  are:

$$k = \frac{3}{2} (I_k U)^2$$
 (17)

$$\omega = \rho \frac{k}{\mu} \left(\frac{\mu_t}{\mu}\right)^{-1} \tag{18}$$

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$$\alpha = \begin{cases} 1 & z \le 0\\ 0 & z > 0 \end{cases}$$
(19)

 $I_k$  is turbulence intensity,  $\mu_t/\mu$  is turbulent viscosity ratio,  $\alpha$  is volume fraction.

Pressure outlet:

The outlet of the flow field in the computation domain, it is set far behind the stern. The variables of outlet boundary are generally unknown, but the boundary is usually far away from the hull, the physical variables change little. Except for the pressure, the normal gradient of other physical variables is zero:

$$\frac{\partial \mathbf{u}}{\partial n} = 0, \frac{\partial k}{\partial n} = 0, \frac{\partial \omega}{\partial n} = 0, \frac{\partial \alpha}{\partial n} = 0$$
(20)

Symmetry plane:

To reduce the total number of grids, only half computation domain is typically built, the symmetry plane has no physical meaning. The normal velocity of the boundary is zero, the gradient of the physical quantity of the flow is zero.

$$u_n = n \cdot v = 0 \tag{21}$$

$$\frac{\partial \mathbf{u}}{\partial n} = 0, \frac{\partial k}{\partial n} = 0, \frac{\partial \omega}{\partial n} = 0, \frac{\partial \alpha}{\partial n} = 0$$
(22)

Wall condition:

In the computation domain, only the hull needs wall conditions. The wall surface of the hull is non-slippable:

$$v = (0, 0, 0)$$
 (23)

$$\frac{dp}{dn} = 0 \tag{24}$$

2.4. Wall  $y^+$ 

In the numerical simulation of turbulence, especially with respect to the high Reynolds number problems, the hull is regarded as a non-slip wall, and because of the viscous damping of the wall, the velocity gradient near the hull is very large. In the numerical method, the wall function is used for the near wall treatment as a hybrid approach. In 2005, Wang [20] conducted research on the turbulence problem, indicating that the  $y^+$  value near the hull should be controlled between 30 and 300. The wall  $y^+$  value is dimensionless quantity, and the formula for calculating the  $y^+$  value is as follows:

$$y^{+} = \frac{y}{v} \sqrt{\frac{1}{2} U^{2} \frac{0.074}{\operatorname{Re}_{L}^{\frac{1}{5}}}}$$
(25)

Here y is the distance from the wall to the boundary layer grid; U is the speed; v is the fluid viscosity coefficient; Re is the Reynolds number.

In the numerical simulation, the prism layer grid is generated to replace boundary layer. However, due to the intense motion of the planing craft, the waterline length will be sharply reduced as well. A low  $y^+$  value will greatly affect the accuracy, the value of  $y^+$  should be larger.

# 2.5. Volume of Fluid Method

In the numerical simulations of the sailing of vessel, the flow field is complex, tracking the free surface with a high accuracy method will ensure the accuracy of numerical simulation. To solve this problem, in 1981, Nichols and Hirt [21] proposed the volume of fluid method (VOF). The VOF method is to obtain and track the function *F*, which is defined as the volume ratio of different fluid occupancy

in the grid. If the value of this function on each grid is obtained, the motion interface of the two phases of the flow will be tracked. The function *F* is defined as follows [22]:

$$\frac{\partial F}{\partial t} + u \frac{\partial F}{\partial x} + v \frac{\partial F}{\partial y} + w \frac{\partial F}{\partial z} = 0$$
(26)

Here u, v, w are the velocity components.

### 2.6. Overset Method

Overset grid is the method of region segmentation and grid combination, which consists of background and overset region. The overset method consists of two parts: (1) Divided grid cells in the whole flow field area into effective cells and invalid cells by hole cutting. Effective cell refers to the grid cell which participates in solving discrete governing equations, the grid cells that do not participate in computation are invalid cells. (2) Find the contributor cell, which configures the corresponding contributor cell for the recipient cell. The receiver cell layer is formed along the boundary of the overset region, and it is this layer of receiver cell layer that divides the background grid into effective cell region and invalid cell region. The overset region and the background region are closely coupled, and the governing equation is solved simultaneously in the effective cells of the two regions. The overset grid around the hull is presented in Figure 1.



Figure 1. Background grid and overset grid.

### 3. Towing Tank Experiments

To validate the accuracy of the numerical method, a planing craft model (USV01) is selected as the study object. The seakeeping tests of USV01 were carried out in 2011 by Hailong Shen and colleagues [18]. The hull model and the specific parameters of the model are presented in Figure 2 and Table 1.



Figure 2. Three-dimensional (3D) model of the USV01 model.

Main feature	Symbol	Value
Model scale	k	1:4
Length overall	L	2.75 m
Beam overall	В	0.78 m
Mouded depth	h	0.325 m
Displacement	Δ	125.4 kg
Draft	d	0.1325 m
Longitudinal position of the centre of gravity	$L_{CG}$	1.048 m
Rotational inertia	J	58.6 (kg·m <sup>2</sup> )
Deadrise angle	β	18 deg

Table 1. Parameters of the model of USV01.

The setup of test is presented in Figure 3. All the experimental installations were installed under the carriage platform, and the guide rods are inserted into the guide plates, which were set at the bow and stern to ensure stability in the drag. In this way, the yaw and roll motions are prevented, and the heave and pitch motions of the model are free. The resistance is measured by a dynamometer in the front of the model, the pitch angle is measured by a gyroscope, which is set at the center of gravity, the heave is measured by the cable-extension displacement sensor, which is set on the above model, and the acceleration of the CG and bow of the model are measured by two acceleration sensors, which are set at the center of gravity and 0.275 m from bow. A snapshot of the model is presented in Figure 4.



Figure 3. Experimental setup.



Figure 4. Snapshot of the model.

In the regular wave test, the towed velocity (U) was 6 m/s (Fn = 1.16), the wave height is 0.21 m, and the wave length ranged from 1.5 L to 5 L. The regular wave test matrix is presented in Table 2, where the wave length is  $\lambda$ , the wave height is H, and the encounter frequency is  $\omega$ . The motion parameters of the model were read when it crossed ten wave lengths in waves.

No.	U (m/s)	Fn	H (m)	$\lambda/L$	λ(m)	ω (rad/s)	Η/λ
1	6	1.16	0.21	1.5	4.125	13.031	0.051
2	6	1.16	0.21	2.25	6.1875	9.261	0.034
3	6	1.16	0.21	3	8.25	7.301	0.025
4	6	1.16	0.21	3.5	9.625	6.446	0.022
5	6	1.16	0.21	4	11	5.787	0.019
6	6	1.16	0.21	5	13.75	4.816	0.015

Table 2. Regular wave test matrix of the seakeeping test.

Under the same speed and wave height, based on the curves of the model's motion, the peak–peak values of the motion response and the average resistance of the model in different conditions were obtained.

# 4. Numerical Simulation Validation

### 4.1. Computational Domains

For a better accuracy, the boundaries of the calculation domain were set far enough away to reduce the reflection of waves, and the entire computational domain should be no less than five times the wave length in the navigation direction. To improve the computing efficiency, only half of the model was built for the simulation. The definition of the boundary conditions and the size of domains are illustrated in Figure 5 and Table 3, respectively.

The point at the bottom of the stern is set as the origin. The distance between each boundary and the origin are presented in Table 3, and all the distances are dimensionalized in terms of the overall length of the model.





Figure 5. The size of the calculation domains.

Boundary	Distance	<b>Boundary Conditions</b>
Inlet	2.5 L	Velocity inlet
Outlet	4 L	Pressure outlet
Тор	2 L	Velocity inlet
Bottom	1 L	Velocity inlet
Side	1.5 L	Symmetry plane
Inlet of overset region	1.25 L	
Outlet of overset region	0.25 L	
Top of overset region	0.25 L	Overset grid
Bottom of overset region	0.25 L	
Side of overset region	0.3 L	

Table 3. Sizes of the computational domains.

The definitions of boundary conditions in the domain are presented as follow: in the background region, the inlet, top and bottom are defined as the velocity inlet; the outlet is defined as the pressure outlet; and the sym and side are defined as the symmetry plane. In the overset region, all the boundaries of the region are defined as the overset grid, and the surface of the hull is defined as the nonslip wall. The definition of the boundary conditions and the setting of the calculation domains are illustrated in Figure 6.



Figure 6. Boundary conditions of the calculation domains.

# 4.2. The Verification of Overset Method

The heave and pitch motion of the model in waves is intense, the accuracy of the numerical method, based simply on the Dynamic Fluid Body Interaction, is reduced due to grid quality deterioration. Therefore, the overset grid is more appropriate in this case. The overset mesh method in this paper refers to the solution adopted in [8,18,23].

# 4.2.1. Grid Parameter

In the computational domains, the grids of two regions are refined: the region around the overset region and the free surface. The grids in the overset region are small, the size of the background region grid around the overset region needs to be consistent with that of the boundary of the overset region. And the grids around the free surface are also refined in order to track the free surface accurately, and the whole free surface is guaranteed to be included in the refinement region. The refinement regions are presented in Figure 7.



Figure 7. Refinement of grids.

To verify the grid parameters, the sailing of USV01 in calm water was numerical simulated, the numerical results of resistance was compared with the test results, the model and the setting of the test is consistent with Section 3, the test condition is changed to calm water, towing speed is 8 m/s.

The grid parameter is presented in Table 4, four grids were adopted in the verification. Only in grid 1, the free surface is not refined, the refinement of the other three grids are different in the size. The grids on the hull and the free surface are presented in Figure 8.

Grid parameter	rs	Grid 1	Grid 2	Grid 3	Grid 4
Total		150 k	280 k	650 k	1400 k
Grid on hull	Relative Size (% L)	1	1	1	0.5
Refinement grid on the boundary of overset region	Relative Size (% L)	4	2.	1.5	1
Refinement Grid around overset region	Relative Size (% L)	4	2.5	1.5	1
Ű	Polativo fizo of grid in V		4	2.5	1.5
Refinement Grid around free surface	V Z direction (% I)	Ν	4	2.5	1.5
	1 Z uncedon (70 L)		2	0.8	0.5

Table 4. Size of the grid.





The numerical results of the four grids are presented in Table 5, the resistance curves are presented in Figure 9.

C 11	Resista	ance/N	Deviation (0/)
Gria	CFD	EFD	Deviation (76)
1	N	235.8	N
2	206.52	235.8	12.41
3	229.41	235.8	2.71
4	230.24	235.8	2.35

**Table 5.** Numerical results of four grids. CFD, computational fluid dynamics; EFD, experimentalfluid dynamics.



Figure 9. The resistance curve of different grids.

Table 5 and Figure 9 indicate that, due to the lack of refinement grid around free surface, the resistance curve of grid 1 cannot converge, and the resistance curves of the other three grids show good convergence. Comparing the numerical results of grid 2 and 3, both the grids were refined, but the numerical results of the grid 2 show a large deviation, the size of the refinements of grid 2 is too large to ensure the accuracy of numerical results. It proves that the refinement grid around free surface is necessary in tracking the free surface. Moreover, the size of grid refinement should be small enough to ensure the accuracy of numerical simulation.

Comparing the numerical results of grid 3 and 4, the deviations and difference of the grids are both small. The two schemes of grids refinement can both guarantee the requirement of numerical simulation, but the size of grid 4 is too small, and the total number of the grids is too large, the computing efficiency will drop significantly.

Summing up the above, parameters of grid can satisfy the accuracy of numerical simulation and improve the computational efficiency at the same time. Subsequent grid settings are all referenced to that of grid 3.

### 4.2.2. Value of y<sup>+</sup>

As mentioned in Section 2.4, the value of  $y^+$  has influence on the accuracy of calculation, under normal conditions the value of  $y^+$  ranges from 30 to 300.

For verification, the influence of  $y^+$ , the values of 50, 100, 200, 250, and 300 were adopted, the boundary layer grid generated according to different values of  $y^+$  are presented in Figure 10.



(e)

**Figure 10.** Boundary layer grid: (a)  $y^+ = 50$ , (b)  $y^+ = 100$ , (c)  $y^+ = 200$ , (d)  $y^+ = 250$ , (e)  $y^+ = 300$ .

The Figure 10 indicates that the trim motion of the planing craft leads to a great change of the waterline of the vessel. The decrease of the waterline length makes the  $y^+$  value of hull less than the theoretical value during the sailing.

The numerical results and the resistance curves of different  $y^+$  are presented in Table 6 and Figure 11, respectively.

+	Resista	$\mathbf{D}_{\mathbf{x}} = \left( \mathbf{x} \right)^{1} \left( \mathbf{x} \right)^{1} \left( \mathbf{x} \right)^{1}$	
y	CFD	EFD	Deviation (%)
50	223.06	235.8	5.4
100	220.82	235.8	6.35
200	221.78	235.8	5.95
250	229.41	235.8	2.71
300	228.56	235.8	3.14
Resistance/N	340 320 300 280 260 240 200 180 160 0.0 0.2 0.4 0.6	0.8 1.0 1.2 1.4 T/s	y+=50 y+=100 y+=200 y+=250 y+=300

Table 6. Numerical results of different y+.

Figure 11. The resistance curve of different y+ s.

The Table 6 and Figure 11 indicate that resistance curves corresponding different y+ have similar convergence. The deviations of different values of  $y^+$  are all less than 10%, but the deviation which  $y^+ = 250$  is the smallest. Due to the intense motion of the planing craft, the waterline length sharply reduces. A low  $y^+$  value greatly affect the accuracy. In subsequent numerical simulations, the  $y^+$  value was set at 250.

# 4.2.3. Time Step of Iteration

The  $\Delta t$  (time step) of iteration should be set at the value which allows the physical field to move no less than the distance of the minimum free surface mesh in each iteration, thus improving the calculation efficiency, with the aim of ensuring accuracy.

To verify the value of  $\Delta t$ , four values: 0.001 s, 0.002 s, 0.006 s, 0.01 s, 0.02 s were adopted and the numerical results corresponding to different values were compared in Table 7 and the resistance curves of different y<sup>+</sup> are presented Figure 12.

Δt (s)	Resista CFD	nnce/N EFD	Deviation (%)
0.001	228.84	235.8	3.11
0.002	229.41	235.8	2.71
0.006	209.72	235.8	11.06
0.01	200.82	235.8	14.83
0.02	180.66	235.8	23.38

**Table 7.** Numerical results of different  $\Delta t$  (time steps).



**Figure 12.** The resistance curve of different  $\Delta t$ .

The comparison between results of different values of  $\Delta t$  indicate that the convergence trends of the five resistance curves are consistent, but different values will affect the accuracy of numerical results. The deviations of the results become larger with the increasing of  $\Delta t$ , this indicates a short time interval between two iterations will benefit the accuracy of the numerical results. But a too small value of  $\Delta t$  can lead to a waste of computational efficiency. The results of  $\Delta t = 0.001$  s and 0.002 s are almost the same and the accuracy is high,  $\Delta t = 0.002$  s is adopted for its better accuracy and computational efficiency.

Summing up the above, the influence of the grid parameter, value of  $y^+$ , and the time step of iteration on the accuracy and computational efficiency are verified. The results show that the numerical method has good convergence and high accuracy in simulating of the sailing of USV01 in calm water. Based on the overset method which has been verified, the numerical simulation validation for the seakeeping test of USV01 will be carried out.

#### 4.3. Validation of Numerical Method

On the basis of the verification of overset method, the grid parameters refer to grid 3, the value of  $y^+$  is set at 250, the  $\Delta t$  is set at 0.002 s. In this way both the accuracy and computational efficiency are guaranteed.

In the numerical simulation of seakeeping tests, the setting of calculation domains, grid parameters, and  $\Delta t$  are referenced to the Sections 4.1 and 4.2, meanwhile, in the wave conditions the flow field of the free surface is more complicated, the refinement region around the free surface needs to contain the entire wave surface and the vertical refinement grid should be not less than 10 layers. When the motion of the model in regular wave tends to stabilize and sails at least five wave lengths, the response amplitude operators of the model were obtained. The calculation grids of the numerical simulations of seakeeping tests are presented in Figure 13.



**Figure 13.** Calculation grids: (**a**) Domain grids; (**b**) Medium-profile local grids; (**c**) Surface grid on the hull; (**d**) Grid near free surface; (**e**) Free surface of regular wave.

The 3D model in the numerical simulation is quite the same as the model of USV01, which is shown in Figure 1, and regular wave conditions (1–6; Table 4) were adopted in the simulation. The response amplitude operators (RAOs) of the model, including the amplitude values of the heave, pitch angle and acceleration of the CG and bow and the average resistance under head wave conditions, were numerically predicted. After the model sailed steadily in regular wave at least five wavelengths, the curves of the motion response and resistance were acquired. The peak peak values of the motion response can be accessed directly, the average resistance is obtained by averaging the convergence resistance curve. The comparisons between the numerical and test results are presented in Table 8 and Figure 14, respectively.

	(a)					
	Heave/mm					g
$\lambda/L$	EFD	CFD	Deviation (%)	EFD	CFD	Deviation (%)
1.5	3.844	3.48	9.33	2.261	2.21	2.25
2.25	8.517	8.66	1.75	3.844	4.16	8.22
3	12.964	13.02	0.43	5.35	5.44	1.68
3.5	13.492	14.19	5.24	5.502	5.8045	5.49
4	13.341	13.98	4.8	5.051	5.151	1.97
5	11.456	12.39	8.15	3.915	4.273	9.14
			(b)			
	Acceleration	n of Center o	f Gravity (CG)/g	I	Acceleration o	f Bow/g
$\lambda/L$	EFD	CFD	Deviation (%)	EFD	CFD	Deviation (%)
1.5	0.905	0.825	8.83	2.11	1.931	8.48
2.25	0.98	1.003	2.34	2.355	2.205	6.36
3	0.829	0.849	2.41	1.809	1.705	5.74
3.5	0.678	0.637	6.04	1.356	1.351	0.36
4	0.527	0.494	6.26	0.979	0.925	5.51
5	0.301	0.310	2.99	0.527	0.485	7.97
			( <b>c</b> )			
			Resista	nce/N		
λ/L	EFD CFD				Dev	viation (%)
1.5	240.	.806	213.993	3		11.13
2.25	255.	255.584 225.988		8	11.58	
3	246.	246.725 223.342		2	9.47	
3.5	227.	227.517 199.802		2 12.18		12.18
4	221.	.607	193.844	4		12.52
5	217.178 190.169		9		12.43	

**Table 8.** Numerical and test results of the response amplitude operators (RAOs) and resistance: (a) Heave and pitch; (b) Acceleration; (c) Resistance.

The RAOs of numerical results presented a similar variation tendency with those of the tested results: they reach the maximum values in the resonance wave length region and then decrease.

By comparing the RAOs of the model in different conditions, the resonance region of the pitch and heave is quite the same (the region is in condition 4 ( $\lambda$ /L = 3.5)). Before reaching the resonance region, the encounter frequency Is larger than the natural frequency of pitching and heave; the resonance phenomenon does not occur and the values of amplitude are far less than 1. In the resonance region, the encounter frequency is the same as the natural frequency of heave and pitch (the frequency is 6.446 rad/s ( $\lambda$ /L = 3.5)), and the amplitudes reach the max. After reaching the resonance region, the wave slope angle decrease as the wave length increase, causing the amplitudes to decrease, but they always remain around 1.



**Figure 14.** Comparison of the numerical and tested results: (**a**) Amplitudes of the heave; (**b**) Amplitudes of the pitch; (**c**) Amplitudes of the acceleration of the CG; (**d**) Amplitudes of the acceleration of the bow; (**e**) Average values of the resistance.

The resonance region of the acceleration of the CG and bow is different (the region is in condition 2 ( $\lambda/L = 2.25$ )). Under the short wave length conditions ( $\lambda/L \le 2.25$ ), the vertical motion of the model is more intense due to the larger wave slope angle and wave disturbances, when the  $\lambda/L$  reaches 3.5,

the pitch motion become more intense due to the resonance phenomenon. This indicates that the resonance region of the acceleration shifts to the shorter wave length direction compared with that of heave and pitch, the natural frequency of the vertical motion of the vessel is larger than that of pitch and heave, and the natural frequency of vertical motion is 9.261 rad/s ( $\lambda$ /L = 2.25). Under any condition, the amplitudes of the acceleration of the bow are significantly greater than that of CG. This indicates that the bow will slap on the free surface during navigation, and the excessive value of bow acceleration may threaten navigation safety.

The deviation of the numerical method is mainly due to the deformation of the grid and the complex flow fields around the model. The relative deviations of the numerical methods are greatly affected by the wave conditions. Before reaching the resonance region, the deviation between the calculated and test values is small. However, when the waves reach the resonance region, the amplitudes of the heave and pitch increased gradually, the motion of the model in the waves become more intense, and the deviation become larger.

The maximum deviations of the calculated heave, pitch, and acceleration of the CG and bow are 9.33%, 9.14%, 8.83%, and 8.48%, respectively. The average deviations are 4.95%, 4.79%, 4.81%, and 5.73%, respectively. All the deviations of the RAOs are less than 10%. The deviations of the numerical results of the RAOs all become larger in their resonance regions. In the short wave length condition ( $\lambda$ /L = 1.5 and 2.25), the short encountering period increases the frequency of the vertical motion, and the amplitudes of the acceleration increase sharply. This makes the nonlinear characteristics of the vertical motion increase sharply, and the deviation between the numerical and test results become larger in these conditions. As for the pitch and heave, the variation in the deviations is similar to that of the acceleration, but the wave length of their resonance region is larger.

In terms of average resistance, the values of average resistance are similar in any condition, the deviation between the numerical and test values is similar in different conditions, and the numerical results of the average resistance of the vessel in regular wave are all lower than those of the test results. The maximum value is 12.54%, the average value is 11.55%. Meanwhile, compared with the RAOs, the deviation of the resistance is greater. In wave conditions, the proportion of hull wave-making resistance in the total resistance is large as the flow field around the hull becomes more complicated by the wave disturbance. The grids around the hull cannot accurately track the free surface, the complex flow field around the hull brings deviation to the numerical prediction of wave-making resistance, this makes the numerical result of the resistance mean a certain deviation compared with the experimental value, but the variation tendency are similar.

Summing up the above, the numerical method accurately predicted the variation trends of the model's motion response in regular wave. Compared with the corresponding test results, the relative deviations of the numerical results of the RAOs are less than 10%. This shows that the numerical method has a high accuracy in predicting the motion response of the model in regular wave. However, increasing nonlinear characteristics of the motion will make deviation of the numerical results become larger. Meanwhile, the complex flow field around the hull made it difficult to predict the wave-making resistance accurately and the deviation of the numerical results of the resistance are larger than that of the RAOs.

### 5. Numerical Simulation of Planing Craft in Regular Wave with Large Wave Height

Based on the numerical method which was been validated in Section 4, the low steaming of small planing craft under regular wave with large wave height is numerical analyzed.

The USV01 is designed for high-speed offshore navigation, its seakeeping is not enough to ensure safe navigation under regular wave with large wave height. The subsequent numerical simulation in large wave height conditions are not suitable to take USV01 as the simulation object.

A new small planing craft with better seakeeping is selected as the object of numerical simulation. The vessel's length is 6 m, displacement is 1.8t, the deadrise angle at the stern is 24 deg, and the model

scale is set at 1:3. The vessel has a larger deadrise angle and more drafts, in pitching and heave motion caused by wave disturbance, the hull can provide more damping.

To compare and validate the seakeeping performance of the new planing craft, the model of USV01 was scaled down to the same size and displacement as the new planing craft. Under the same wave conditions, the sailing of the two vessels under large wave height is predicted and compared.

The scaled model of USV01 is selected as prototype. The new vessel improved in seakeeping compared with the prototype, the new vessel is named as improved vessel.

The hull and specific parameters of the improved vessel are presented in Figure 15 and Table 9, respectively.



Figure 15. Threedimensional (3D) model and line plan of the improved vessel.

Main Feature	Symbol	Value
Model scale	k	1:3
Length overall	L	2 m
Beam overall	В	0.54 m
Mouded depth	h	0.256 m
Displacement	$\Delta$	66.67 kg
Draft	d	0.147 m
Longitudinal position of the center of gravity	LCG	0.82 m

Deadrise angle

**Table 9.** Model parameters of the improved vessel.

The model of USV01 is scaled down to the size shown in Table 10, but the shape remains the same. The low steaming of the two vessels in the same conditions is numerically simulated. The regular wave conditions refer to moderate sea conditions. The wave height of the moderate sea conditions ranges from 1.25 m to 2.5 m. In the numerical simulation, the scale ratio is 1:3, the wave height of regular wave is set at 0.45 m, and the wave length range from 2 L to 6 L. The parameters of regular wave are shown in Table 11.

β

24 deg

Symbol	Value
L	2 m
В	0.67 m
h	0.23 m
Δ	66.67 kg
d	0.118 m
LCG	0.82 m
β	18 deg
	Symbol L B h Δ d LCG β

**Table 10.** Model parameters of the prototype.

No	U (m/s)	Fn	H (m)	λ/L	λ (m)	ω (rad/s)	Η/λ
7	2	0.46	0.45	2	4	7.316	0.1125
8	2	0.46	0.45	3	6	5.391	0.075
9	2	0.46	0.45	4	8	4.390	0.05625
10	2	0.46	0.45	5	10	3.749	0.045
11	2	0.46	0.45	6	12	3.324	0.0375

**Table 11.** The matrix of regular wave with large wave height.

6. Results

# 6.1. The Influence of Wave Length on the Navigation Configuration

To study the seakeeping of the two vessels, the sailing of the prototype and improved vessel in conditions 7 to 11 were simulated, their motion responses were compared. The comparisons are presented in Table 12 and Figure 16, respectively.

		(a)		
	Amplitude of Heave (m)		Amplitude	of Pitch (deg)
λ/L	prototype	improved vessel	prototype	improved vessel
2	0.103	0.118	6.825	7.895
3	0.213	0.209	8.764	10.685
4	0.228	0.209	9.653	9.44
5	0.233	0.208	8.942	7.835
6	0.235	0.207	7.483	6.195
		(b)		
	Amplitude of Ac	celeration of CG (g)	Amplitude of Ac	celeration of Bow (g)
λ/L	prototype	improved vessel	prototype	improved vessel
2	0.574	0.651	1.017	1.278
3	0.677	0.659	1.411	1.309
4	0.531	0.503	0.871	0.783
5	0.398	0.367	0.617	0.549
6	0.272	0.251	0.451	0.347

Table 12. RAOs of the prototype and improved vessel: (a) Heave and pitch; (b) Acceleration

Figure 16 indicates that the motion tendency of the prototype and improved vessel are similar: As the wave length increased, the amplitudes of the pitch and acceleration began to decrease gradually after reaching the resonance region, while the amplitudes of heave tend to remain stable.



**Figure 16.** The comparison of the RAOs of the prototype and improved vessel: (**a**) Amplitude of the acceleration of the CG; (**b**) Amplitudes of the acceleration of the bow; (**c**) Amplitudes of the heave; (**d**) Amplitudes of the pitch.

The dimensionless amplitudes of the pitch and heave in the short wave length conditions (conditions 7 and 8) are less than 1. This indicates that, in these conditions, no resonance occurred during the sailing and the heave amplitudes are far lower than those of the wave amplitude. Meanwhile, the vessel's pitching motion lag behind the sinusoidal motion of regular wave, the large wave height allows the prototype to plough through the wave before reaching the crest, the vessel is in the wave-piercing status. In these conditions, the heave and pitch amplitudes are small, while that of the acceleration are large, this indicates that the vertical motion is intense. The wave-piercing navigation is accompanied by a heavy green water, and the navigation safety will be threatened. The simulation of the wave-piercing navigation of the vessel is presented in Figure 17.

When the wave length reaches 4 L, the dimensionless amplitudes of the heave and pitch float around 1, indicating that in these conditions, the response of vessel to wave disturbance is better. The vessel starts to depart from the wave-piercing status. As the wave length increases, the encountering period increases, and the nonlinear characteristics of the motion begins to decrease. The vessel can normally pass through the crests and troughs of regular wave. At this time, the vessel is in a normal navigation configuration. However, the speed of the vessel in regular wave is too low to provide sufficient dynamic lift, and the vessel is in the hull-borne status. In this navigation configuration, the heave amplitude is greatly affected by the wave height and tends to be stable in the condition of an invariant wave height. The amplitudes of the pitch are greatly affected by the wave slope angle. Figure 18 shows the hull-borne status of the vessel. The model of the vessel can pass the crest smoothly, and the green water phenomenon did not occur.



**Figure 17.** The simulation of the sailing of the improved vessel in the wave-piercing status: (**a**) Free surface; (**b**) Gas–liquid phase diagram; (**c**) Free surface representation of the hull.



**Figure 18.** The simulation of the sailing of an improved vessel in the hull-borne status: (**a**) Free surface; (**b**) Gas–liquid phase diagram; (**c**) Free surface representation of the hull.

The dimensions of the improved vessel are the same as those of the prototype, and the motion trends are consistent in the same condition, both of which have the wave-piercing status and hull-borne status.

In the wave-piercing status, the RAOs of the improved vessel are slightly larger than those of the prototype, and while the two vessels are similar in size, the large deadrise angle of the improved vessel makes its pitching period shorter, allowing the vessel to better respond to wave disturbances. Due to the large wave height and short encountering period, the improved vessel is also in the wave-piercing status, and because of the good response of the improved vessel to the waves, the phenomenon of green water on deck during navigation will be greatly reduced. Therefore, the seakeeping of the improved vessel is better than that of the prototype in wave-piercing status.

When the vessels are in the hull-borne status, the amplitudes of the heave and pitch become larger, compared with those in the wave-piercing status, and the amplitude of the acceleration decreases sharply. Due to the better seakeeping of the improved vessel, the hull is able to provide more pitch damping under the regular wave, compared with the prototype. After entering the hull-borne status, the RAOs of the improved vessel are all smaller than those of the prototype in the same wave conditions.

Summing up the above, the improved vessel provides a better seakeeping performance in both the wave-piercing and hull-borne statuses. In the wave-piercing status, the design of the improved vessel can effectively reduce the occurrence of wave-piercing and green water; in the hull-borne status, the RAOs of the vessel sailing in regular wave are reduced.

### 6.2. The Influence of Speed on the Navigation Configuration

To study the influence of speed on the RAOs of improved vessel, the sailing of the improved vessel at different speeds and with different wave lengths was simulated. Another speed (U = 3 m/s) is selected. The wave matrix is shown in Table 13.

The sailing of the improved vessel in conditions 7–11 and 12–16 were numerically simulated and compared. The amplitude values of the motion response of model are obtained, and a dimensionless treatment is also carried out. A comparison of the RAOs of the vessel at two speeds is presented in Table 14 and Figure 19, respectively.

No	U (m/s)	Fn	H (m)	λ/L	λ (m)	ω (rad/s)	Η/λ
12	3	0.69	0.45	2	4	8.897	0.1125
13	3	0.69	0.45	3	6	6.440	0.075
14	3	0.69	0.45	4	8	5.177	0.05625
15	3	0.69	0.45	5	10	4.392	0.045
16	3	0.69	0.45	6	12	3.845	0.0375

**Table 13.** The parameters of regular wave, in which U = 3 m/s.

Table 14. RAOs of the improved	l vessel at different speeds	and with different wave	e lengths: ( <b>a</b> ) Heave
and pitch; ( <b>b</b> ) Acceleration.			

		(a)		
	Amplitude o	of Heave (m)	Amplitude o	of Pitch (deg)
λ/L	Fn = 0.46	Fn = 0.69	Fn = 0.46	Fn = 0.69
2	0.118	0.097	7.895	6.597
3	0.209	0.232	10.685	10.434
4	0.209	0.246	9.44	10.225
5	0.208	0.244	7.835	8.673
6	0.207	0.242	6.195	7.465
		(b)		
	Amplitude of Acc	eleration of CG (g)	Amplitude of Acce	leration of Bow (g)
λ/L	Fn = 0.46	Fn = 0.69	Fn = 0.46	Fn = 0.69
2	0.651	0.771	1.278	2.059
3	0.659	0.918	1.309	2.709
4	0.503	0.752	0.783	1.403
5	0.367	0.612	0.549	0.783
6	0.251	0.481	0.347	0.574



**Figure 19.** Comparison of the RAOs at two speeds: (a) Amplitudes of the acceleration of the CG; (b) Amplitudes of the acceleration of the bow; (c) Amplitudes of the heave; (d) Amplitudes of the pitch.

As Figure 19 shows, there are still two kinds of navigation configurations: the wave-piercing and hull-borne statuses. Comparing the RAOs of the improved vessel in the same wave condition at different speeds, speed has an obvious effect on the RAOs of the vessel. In terms of heave, when  $\lambda/L > 3$ , the vessel is in the hull-borne status. Increasing the speed makes the hull generate more dynamic lift, and this greatly increase the heave amplitudes of the vessel. However, when the wave length decreases, the vessel goes into the wave-piercing status, and the effect of the speed on the heave is opposite to that in the hull-borne status. Meanwhile, the effect of the speed on pitch is consistent with that of the heave in any condition, but the effect is weaker. In terms of the acceleration, the acceleration amplitudes of t vessel at 3 m/s (Fn = 0.69) are larger than that of the vessel at 2 m/s (Fn = 0.46) in any condition, and the speed has a more obvious influence on the acceleration, compared with the heave and pitch.

For further study, the influence of speed on the RAOs of improved vessel in the wave-piercing and hull-borne statuses have been numerically predicted. The wave conditions where the wave height is 0.45 m,  $\lambda/L = 3$  and 6 are selected,  $\lambda/L = 3$ , the improved vessel is in the wave-piercing status, and when  $\lambda/L = 6$ , the improved vessel is in the hull-borne status. The wave matrix is shown in Table 15. The RAOs of the improved vessel are obtained, based on the numerical method, and a comparison of RAOs at different speeds is presented in Figure 20 and Table 16.

No	U (m/s)	Fn	H (m)	λ/L	λ (m)	ω (rad/s)	Η/λ
17	2	0.46	0.45	3	6	5.391	0.075
18	3	0.69	0.45	3	6	6.440	0.075
19	4	0.92	0.45	3	6	7.489	0.075
20	5	1.15	0.45	3	6	8.539	0.075
21	6	1.39	0.45	3	6	9.594	0.075
22	2	0.46	0.45	6	12	3.324	0.0375
23	3	0.69	0.45	6	12	3.845	0.0375
24	4	0.92	0.45	6	12	4.367	0.0375
25	5	1.15	0.45	6	12	4.888	0.0375
26	6	1.39	0.45	6	12	5.411	0.0375

Table 15. The regular wave matrix at different speeds.



**Figure 20.** Comparison of the RAOs under different navigation configurations: (**a**) Amplitudes of the acceleration of the CG; (**b**) Amplitudes of the acceleration of the bow; (**c**) Amplitudes of the heave; (**d**) Amplitudes of the pitch.

Fn 0.46 0.69 0.92 1.15 1.39

Fn

0.46

0.69

0.92

1.15

1.39

 $\lambda/L = 3$ 

0.659

0.918

1.583

2.193

2.436

		(a)			
	Amplitude of Heave (m)		Amplitude of Pitch (deg)		
	$\lambda/L = 3$	$\lambda/L = 6$	$\lambda/L = 3$	$\lambda/L = 6$	
	0.209	0.207	10.685	6.159	
	0.232	0.242	10.434	7.465	
	0.196	0.255	8.745	7.651	
	0.171	0.2704	6.951	8.408	
	0.142	0.3035	6.115	9.483	
		(b)			
Amplitude of Acceleration of CG (g)			Amplitude of Acce	eleration of Bow (g)	

 $\lambda/L = 3$ 

1.309

2.709

4.022

4.788

4.871

Table 16. The RAOs of the improved vessel at different speeds: (a) Heave and pitch; (b) Acceleration.

As Figure 20 shows, the effect of increasing the speed is completely opposite to that of changing the navigation configuration. In the conditions where the wave length is 3 L, U = 2 m/s (Fn = 0.46), and the vessel is in the wave-piercing status, the amplitudes of the heave and pitch decrease sharply as the speed increases. When the wave length reaches 3 L, the period of the encounter decreases with the increasing of the speed, while the pitch period of the vessel remains unchanged. This means that, with the increasing of the speed, the gap between the encounter period and the resonance period increases, and the resonance phenomenon gradually becomes weaker, the amplitudes begin to decrease, the nonlinear characteristics of pitch increase, and the wave-piercing phenomenon of the vessel becomes more obvious, leading to more green water.

 $\lambda/L = 6$ 

0.251

0.481

0.557

0.712

1.038

In the hull-borne status ( $\lambda/L = 6$ ), the amplitudes of the heave and pitch both increase with the increasing of the speed. Compared with the wave-piercing status, amplitudes of the vessel in the hull-borne status are much higher than those in the wave-piercing status. With the increasing of the speed, the lift force received by the craft gradually increases, making the RAOs of the vessel in regular wave increase obviously.

In terms of the acceleration, the influence of the speed in different navigation configurations is quite the same, while in the wave-piercing status, the influence of the speed on the acceleration is more obvious. The amplitudes of the acceleration of the vessel increase with the increasing of the speed in any condition, and the increase will become sharp at a high speed. The amplitudes of the acceleration of the vessel in the wave-piercing status ( $\lambda/L = 3$ ) are always larger than that in the hull-borne status ( $\lambda/L = 6$ ). This shows that in the wave-piercing status, the pitching motion is more intense, and the nonlinear characteristics of the motion increase. The influence of the speed on the acceleration of CG and bow is consistent. However, the amplitude of the acceleration of the bow increases quite sharply as the speed continues to increase, indicating that the nonlinear characteristics of the motion of the bow at a high speed increase sharply, which will greatly endanger the navigation safety.

Summing up the above, increasing the speed will increase the nonlinear characteristics of the motion in any condition: in the wave-piercing status, the occurrence of wave-piercing and green water will become more serious, in the hull-borne status, the RAOs will increase sharply. This indicates that reducing the speed is the most effective means to ensure navigation safety under regular wave with large wave height.

 $\lambda/L = 6$ 

0.347

0.574

0.766

1.276

2.381

### 7. Conclusions

This paper presents a seakeeping analysis of planing craft, based on numerical and experimental methods. In order to validate numerical method, the sailing of USV01 was numerically simulated, based on the RANS solver and overset method. The numerical results of the RAOs were compared with the corresponding test results, and the overall uncertainty was within 10%. The deviation of the numerical method became slightly larger in the resonance region, especially for the acceleration. These results indicate that the numerical method has a high accuracy in simulating the seakeeping test of planing craft. Additionally, the numerical prediction of wave-making resistance has a slightly larger deviation due to complex flow field around the hull.

For further study on the seakeeping performance of vessels in regular wave with large wave height, a new small size planing craft with better seakeeping performance is selected for numerical simulation, and the vessel is named as improved vessel, the model of USV01 shrunk to the same size as improved vessel and named as prototype. The low steaming of the prototype and improved vessel in the same conditions were numerically simulated and compared. Under the influence of the large wave height and different wave lengths, there are two navigation configurations in the sailing of the vessels: The wave-piercing and hull-borne status. In the wave-piercing status, the vessel's pitching motion lags behind the sinusoidal motion of regular wave, and there is no resonance phenomenon. The pitch and heave amplitudes are small, and the vessel traverses the waves, accompanied by severely green water. In the hull-borne status, the amplitudes of the pitch and heave are affected by the wave conditions. Compared with the prototype, the improved vessel shows a better seakeeping performance in both navigation configurations: in the wave-piercing status, the phenomenon of green water will be greatly reduced with the improved vessel, and in the hull-borne status, the RAOs of the improved vessel are lower than those of the prototype in the same wave conditions. For further study, the influence of the speed on the RAOs of the improved vessel in different navigation configurations will be analyzed. The increasing of the speed increases the nonlinear characteristics of the vessel's motion in regular wave and in both the wave-piercing and hull-borne statuses. However, in different navigation configurations, the effect of the speed on the RAOs will be different, and reducing speed is the most effective means to ensure the navigation safety of planing craft under regular wave with large wave height.

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