Numerical prediction and analysis of motion response of high speed planning craft in regular waves

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Abstract

To accurately estimate the hydrodynamic performance of planning craft in waves, the high-speed sailing of planning craft in regular head waves was numerically simulated with multiple degrees of freedom by performing sea keeping model experiments. In the simulation, the FINE/MARINE software was adopted and the body-fitted mesh technique was employed.

The numerical results were then compared with the experimental data to verify the accuracy of the simulation. It is found that the numerical simulation can accurately and efficiently simulate the motion attitude and the hydrodynamic characteristics of the planning craft in high speed navigation in waves. Based on the time domain and frequency domain analysis method of the motion responses of the planning craft, the analysis of the influence of the period of incident wave and the natural frequency on the response of planning craft has been finished, which provide guidance and reference for the design of planning craft.

Key words： planning craft; motion response; regular wave; body-fitted mesh; numerical simulation

0 Introduction

As an important part of the field of high performance crafts, the planning craft has attracted more and more attention and application because of the superior combat performance. Owing to the strong nonlinear characteristics, such as overtopping and slamming of planning crafts in high speed sailing in waves, the accurate prediction of planing craft hydrodynamic and motion performance has become the focus of attention of scholars at home and abroad. With the development of computer hardware, the solution of ship hydrodynamics and motion response based on RANS equation has become the research direction of many scholars recently.

Hydrodynamic calculation research of planning crafts surface began with the towing test in Langley pool in 1940s, carried out by the National Advisory Committee for Aeronautics (NACA) [1].A lot of subsequent studies have been carried out based on the experimental data. Among these studies, Savitsky[2]-[4] presents a series of empirical or semi-empirical formulas for calculating the resistance of planning crafts based on the test results. In recent years，The modern CFD technique, which is aimed to solve the Reynolds time-average equation RANS in real time, is applied to the accurate prediction of hydrodynamic performance of surface high speed craft. According to the application of the 2D+t theory and the fully nonlinear boundary element method，Hui Sun and Odd M. F[5] calculated the added mass, damping coefficient and restoring force coefficient of the planning craft and presented the nonlinear time domain simulation of hydrodynamic and motion characteristics of planning craft, which shows that the hull hydrodynamic coefficients, pitch amplitude and the height of the center of gravity have a significant impact on the motion response of planning crafts. Based on experimental test, N.Santoro[6],etc have studied the hydrodynamic force and torque acting on the planning craft hull at high speed, focusing on the distribution of pressure at the bottom of the planning craft.

Su Yumin and Duan Wenyang[7]-[13] of Harbin Engineering University made a systematic study on the motion response of planning crafts in still water and regular waves by using self-programming and commercial software FLUENT, and then analyzed the hydrodynamic performance, motion performance and wake flow characteristics of planning crafts. Dong Wencai et al. [14] from Naval University of Engineering, studied the longitudinal motion in head sea regular waves of the deep V type planning craft, and analyzed the influence of wave factors on the longitudinal motion of planning craft.

This paper, based on FINE/MARINE software, carries out the numerical prediction of the longitudinal three degree of freedom motion response of the planning craft in the regular waves by utilizing six degree of freedom motion response module. In order to ensure the mesh quality of the planning craft in waves with large amplitude motion, the hydrodynamic characteristics, the motion response characteristics and the flow field distribution of the planning craft with different wave periods are quantitatively analyzed based on the body-fitted mesh technology, and the results are compared with the experimental results for verification.

1 Computational Model

1.1 Computational model and grid partition

According to the model of a certain type of planning craft, the SOLIDWORKS software is used to complete the 3-D modeling, and the HEXPRESS software is used for mesh generation. Then mesh encryption in the vicinity of hull and the free surface was conducted, among which the upper part is air domain while the lower part is water domain. Water domain is 10L * 4L * 3L, and the air domain is 10L * 4L * 1.5L. The craft bow is 3L away from the entrance and the stern is 6L away from the exit. In the computational domain, the standard wall function is used for the hull, the prescribed pressure (hydrostatic pressure) is used in upper boundary and the lower boundary, while the far field is adopted in the inlet boundary, the exit boundary and the bilateral boundary. Figure 1 is a schematic diagram of the computational domain and the hull surface grid division, and the main parameters of the planning craft model are shown in Table 1.

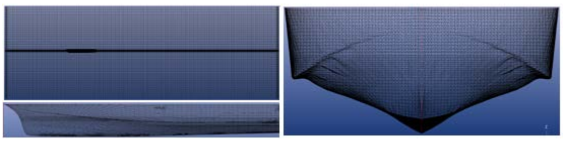


Figure 1. Diagrammatic sketch of the computational domain and the hull surface grid division

Table 1. Main parameters of planning craft model

Principal dimension	Parameter	Principal dimension	Parameter
Total length L/m	2.75	Length from center of gravity to stern l_g/m	1.048
Total width B/m	0.78	Craft weight m/kg	125.4
Draft d/m	0.17	Dead rise angle β/(°)	24.65
Longitudinal moment of inertia I_y /(kg•m^2)	53	Initial angle attack α/(°)	3

1.2 Calculation condition and numerical calculation method

Based on the FINE/Marine software, the parameter setting of the longitudinal three degree of freedom motion response prediction of the planning craft in the regular waves are as follows: 3-D unsteady two-phase flow, k-ω(SST-Menter) (SST-Menter) turbulence model(the value of k and ω is related to Reynolds number); while the speed of the planning craft is given, invoking the motion of the six degree of freedom motion, release the motion of heave and pitch freedom; the velocity inlet is used to make waves, and the body-fitted mesh technique was adopted in forward, heave and pitch motion; the turbulence equation is discretized by central difference (AVLSMART) scheme; the momentum equation is discretized by central difference (AVLSMART) scheme; the free surface is discretized by the mixed free surface capture and reconstruction (BRICS) scheme; the pressure velocity coupling algorithm is used. Calculation conditions are shown in Table 2.

Table 2. Calculation condition table

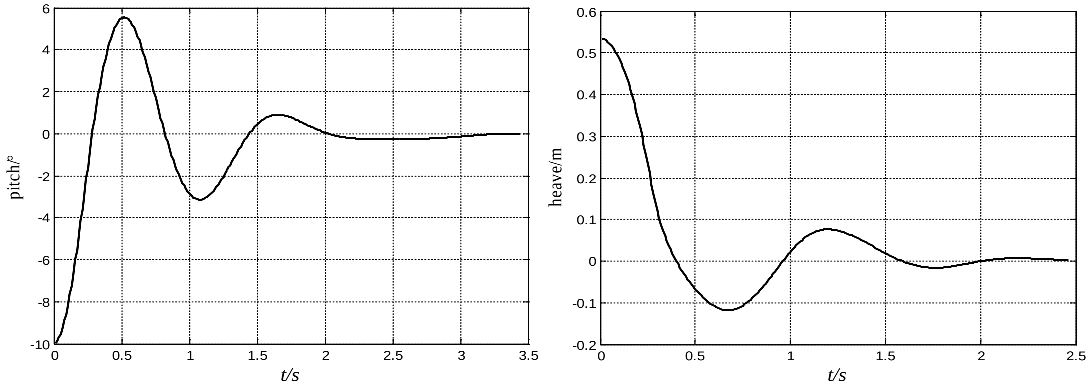
Number	H(m)	T(s)	V(m/s)	m（kg）	Fr_{∇}	λ(m)	T_e(m)	λ/L
A1		1.63				4.13	0.65	1.50
A2		1.88				5.50	0.81	2.00
A3		2.10				6.88	0.96	2.50
A4	0.20	2.30	3.86	125.4	1.74	8.25	1.11	3.00
A5		2.48				9.63	1.24	3.50
A6		2.66				11.00	1.37	4.00
A7		2.97				13.75	1.62	5.00

2 Calculation results and analysis

From the point of view of hydrodynamics, if the Volume Froude number $Fr_{\nabla} \geq 1.0$, the craft belongs to high-speed ship, including high speed displacement ship and power lift ship. For high-speed displacement ships whose Fr_{∇} is between 1.0 and 3.0, the main supporting force is the static buoyancy; For hydrodynamic lift type ships whose Fr_{∇} is no less than 3.0, the main supporting force is the hydrodynamic lift. As a result of high speed fluid acting on the hull surface, the splash phenomenon shows up at the interface of water and gas, and the influence of splash on the high speed ship in navigation should not be ignored. This paper studies the planning craft at the speed of 3.86m/s, Fr_{∇}=1.74.

2.1 Determination of the natural period of rolling, pitching and heaving

In the high speed navigation of planning craft, the composition of the motion response is complex. The natural period of three degrees of freedom, for which the restoring force exists, of the planning craft has an important influence on the motion response. As a result, the hydrostatic damping of the pitching and heaving of the planning craft is carried out to calculate the natural period of the planning craft. As can be seen from Figure 1, the natural period of pitching and heaving are respectively 1.08s and 1.0s.



（a）Pitch decay curve （b）Heave decay curve

Figure 1. Hydrostatic decay curve of planning boat

2.2 Calibration of incident wave elements

As a planning craft sails in the target wave environment, set a wave height observation point at the position of 2 times the length of craft in the forward direction of the planning craft, and real-time output wave height. Figure 2 shows the time history curves of different period (part time), where we can see that the error between incident wave height and target wave height is less than 5%, and the period is the same with the encounter period, indicating that the wave elements satisfy the calculation requirement.

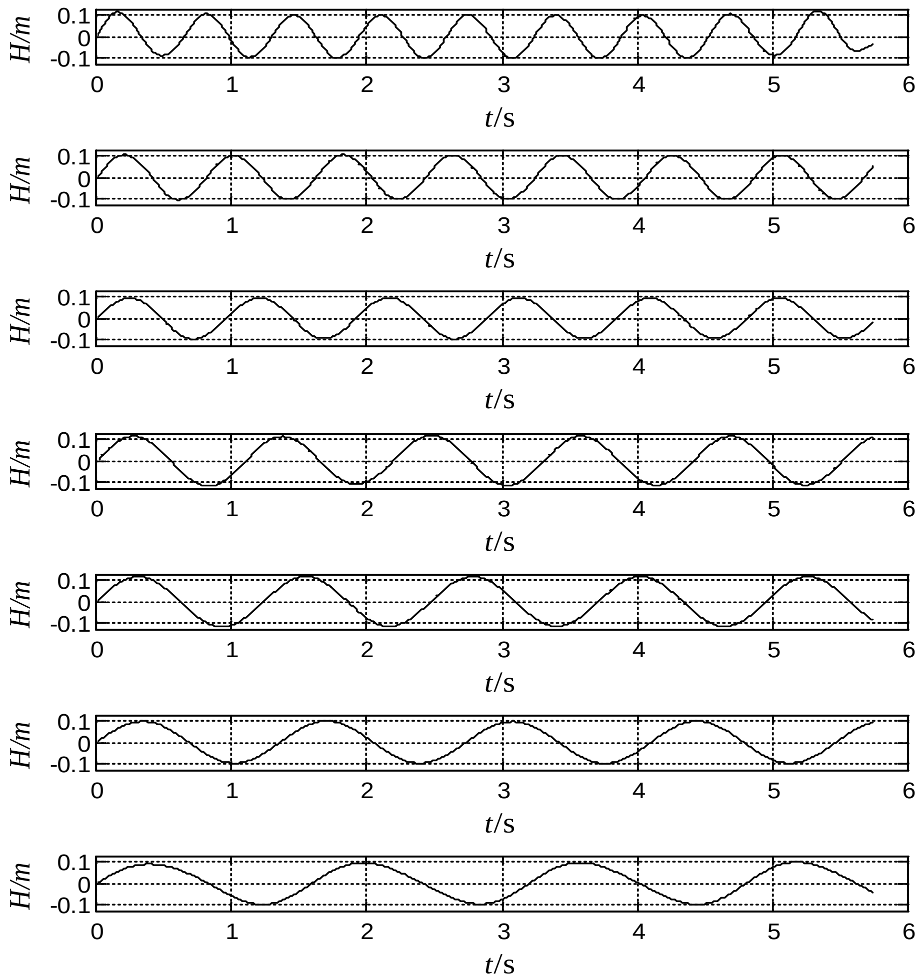


Figure 2. Wave duration curve of different period

2.3 Hydrodynamic performance of planning boat in waves

Figure 11 and Figure 12 show the variation curve of the resistance and dynamic lift of planning craft (for a period of time). It can be seen that the resistance and the dynamic lift force change with the periodic change of the wave when the planning craft is sailing in the waves. Figure 3 shows the load at the position where resistance and dynamic lift equilibrium (load is the average value of the duration curve). Figure 4 and figure 5 show the variation of the amplitude of the component of resistance and dynamic lift with wavelength.

Figure 3, figure 4 and figure 5 can be combined to reflect the change rule of the resistance and dynamic lift of the planning craft moves in waves with wavelength.

It can be seen from the figure that wavelength has little influence on the equilibrium position of the resistance (equivalent to the hydrostatic resistance), and the mainly affect its amplitude. Due to the high frequency characteristic of the two order slow drift force of waves, the amplitude of resistance decreases with the increase of wavelength.

When λ/L=1.5/2.0, resistance have remarkable high frequency characteristics, even shows quadruple-frequency phenomenon (refer to resistance spectrum in Figure 6 and Figure 8). The contribution of high frequency components to the resistance is large, especially when λ/L = 1.5, the high frequency resistance accounts for about 45% of the total resistance. The main reason for this phenomenon is: the wavelength is equal to the craft length so that overtopping occurred when the planning craft is sailing at high speed (verified in flow field Figure 16 (a)), and the hull slamming is remarkable. The strong nonlinear characteristics appear in the flow field around the hull.

When λ/L>2.0, the resistance is mainly composed of wave frequency components, as the contribution of high frequency components to the total resistance is less than 5%. The resistance value of the planning craft changes periodically with the peak value and the valley value of the encounter wave. For the same wave height, the longer the wavelength is, the smaller the wave steepness is, and the smaller the resistance change caused by waves is, Therefore, the resistance change amplitude decreases with the increase of wavelength.

As can be seen from the figure, the effect of the wavelength on the equilibrium position of the dynamic lift (which is equivalent to the dynamic lift in calm water) is not significant. As Fr_{∇} =1.74, the static buoyancy played a major role in the balance of the hull weight while dynamic lift accounted for about 10%;

When λ/L=1.5/2.0/3.0, dynamic lift have significant high frequency characteristics, even shows quadruple-frequency phenomenon (refer to dynamic lift spectrum in Figure 7, Figure 9 and Figure 10). The contribution of high frequency components to the dynamic lift is large, especially when λ/L = 1.5, the high frequency resistance accounts for about 55% of the total resistance. The main reason for this phenomenon is: the wavelength is equal to the craft length so that overtopping occurred when the planning craft is sailing at high speed (verified in flow field Figure 15 (a)), and the hull slamming is remarkable. The strong nonlinear characteristics appear in the flow field around the hull.

Different from the resistance characteristics, the dynamic lift appears triple frequency at λ/L=2.5, and there is a peak at the equilibrium position. As the encounter frequency of incident wave is close to the natural period of the pitching and heaving of the planning craft, the resonance phenomenon occurs.

When λ/L>2.5, the dynamic lift is mainly composed of wave frequency components while the contribution of high frequency components to dynamic lift is about 20%. The dynamic lift value of the planning craft changes periodically with the wave. For the same wave height, the longer the wavelength is, the higher the wave lift capacity increases with the increase of wavelength, So the dynamic lift amplitude increases with the increase of wavelength.

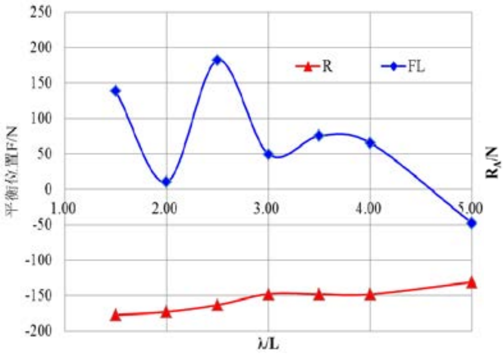


Figure 3. Load change curves with wavelength at resistance and dynamic lift equilibrium position

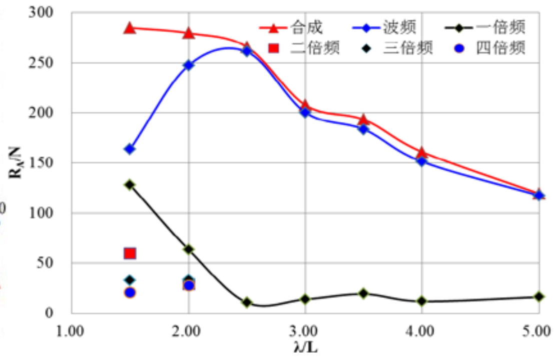


Figure 4. Resistance amplitude versus wavelength curve

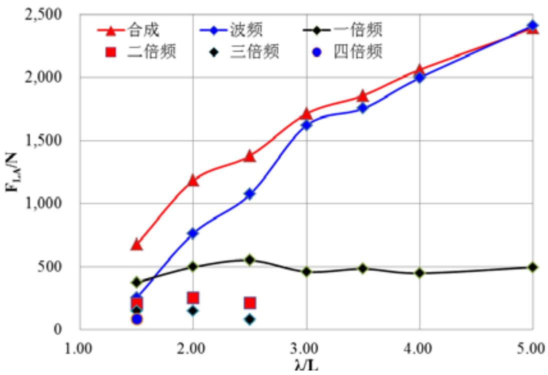


Figure 5. Dynamic lift amplitude versus wavelength curve

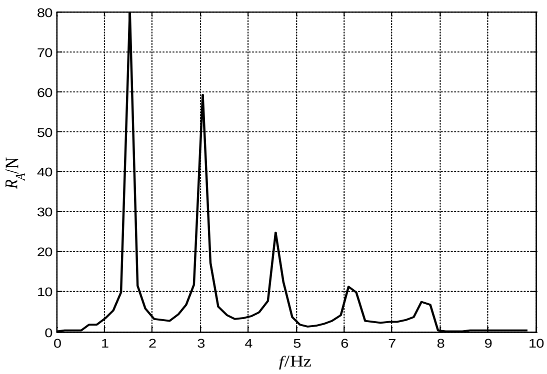


Figure 6. Resistance spectrum whenλ/L=1.5

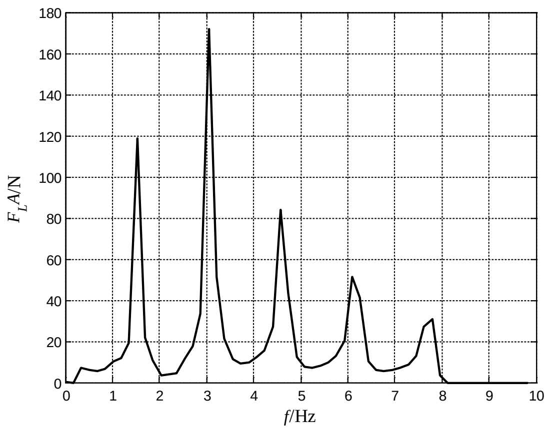


Figure 7. Dynamic lift spectrum whenλ/L=1.5

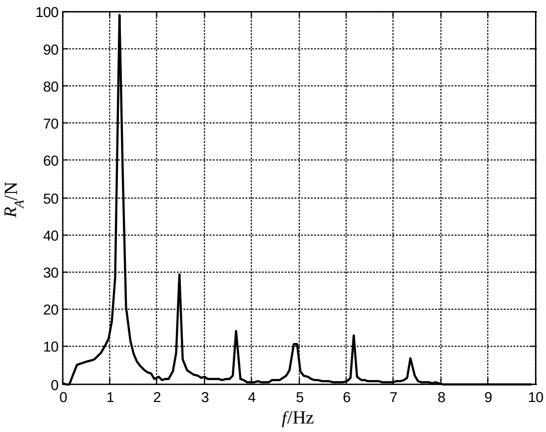


Figure 8. Resistance spectrum whenλ/L=2.0

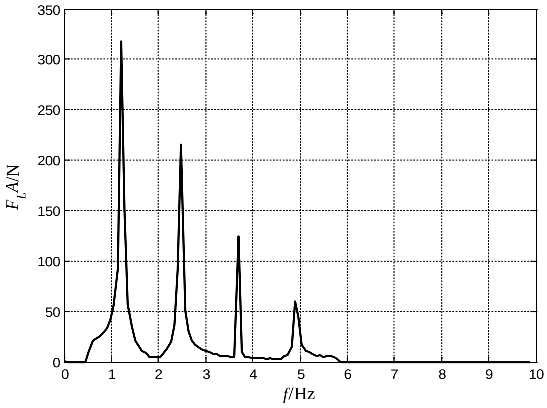


Figure 9. Dynamic lift spectrum whenλ/L=2.0

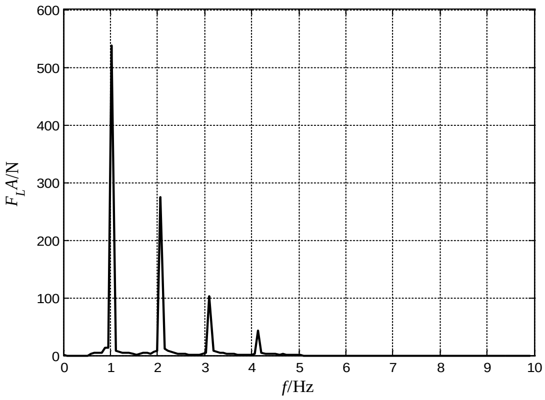
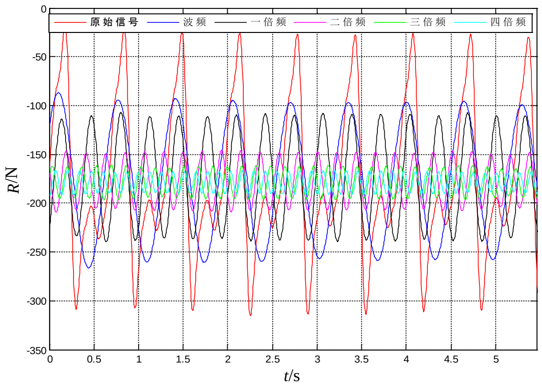
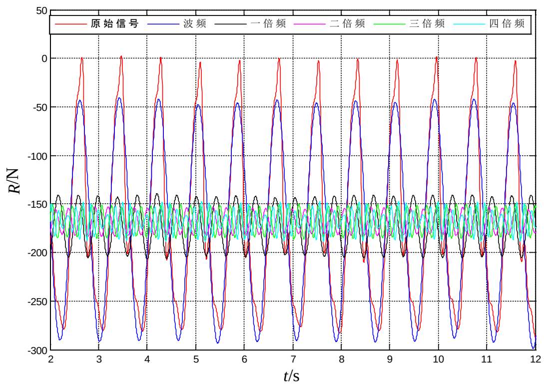


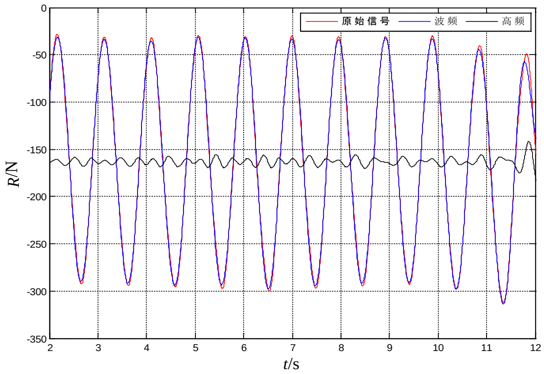
Figure 10. Dynamic lift spectrum when λ/L=2.5



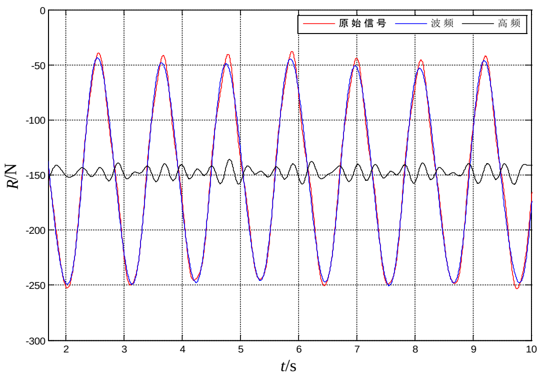
（a）λ/L=1.5



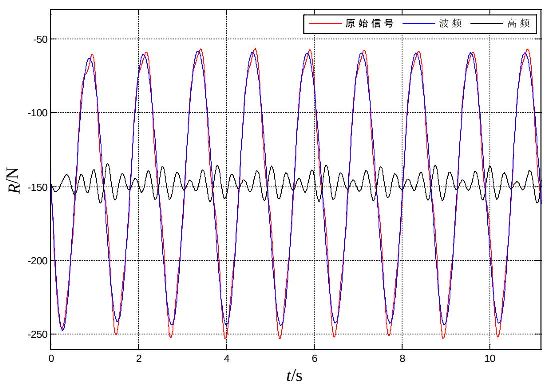
（b）λ/L=2.0



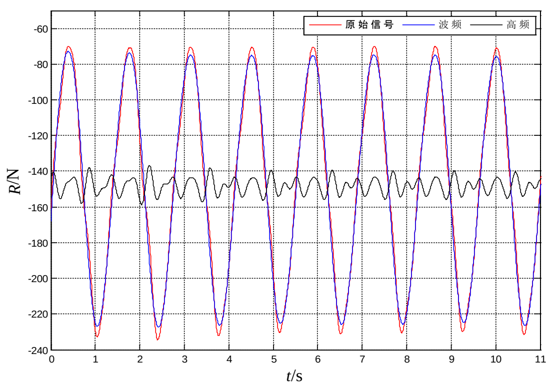
（c）λ/L=2.5



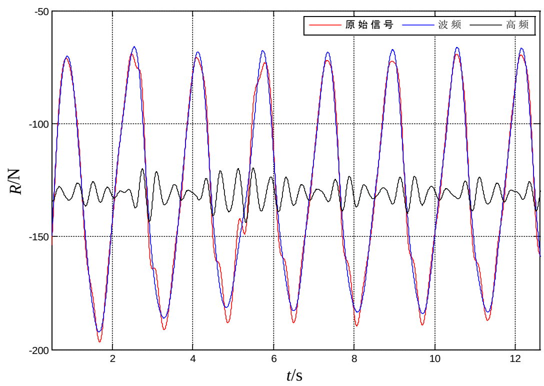
（d）λ/L=3.0

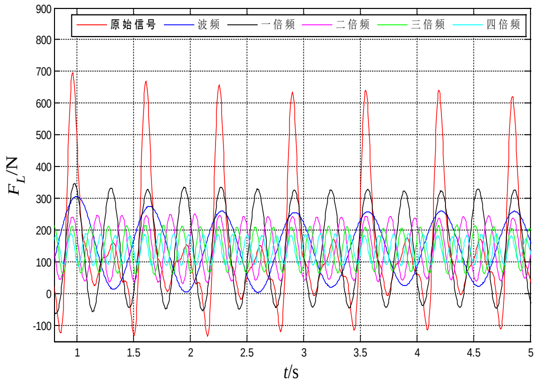


（e）λ/L=3.5



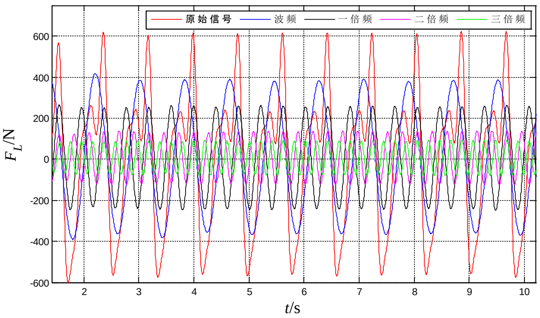
（f）λ/L=4.0

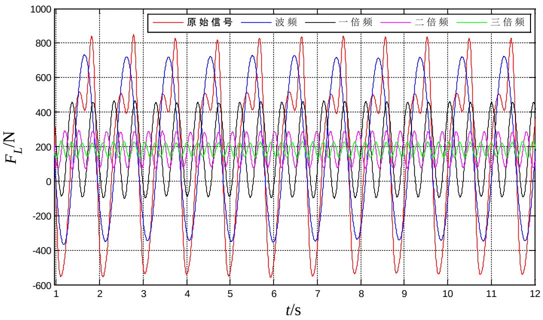




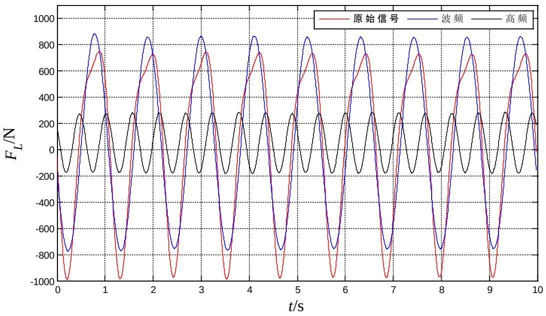
（g）λ/L=5.0 （a）λ/L=1.5

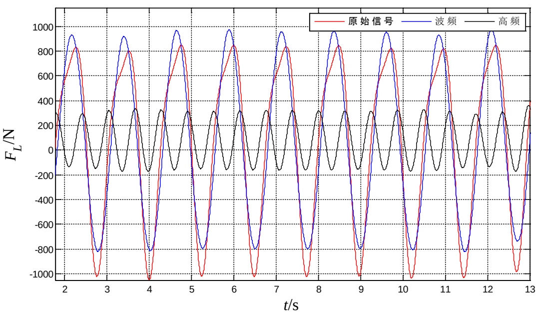
Figure 11. Duration curves of resistance components at different wavelengths



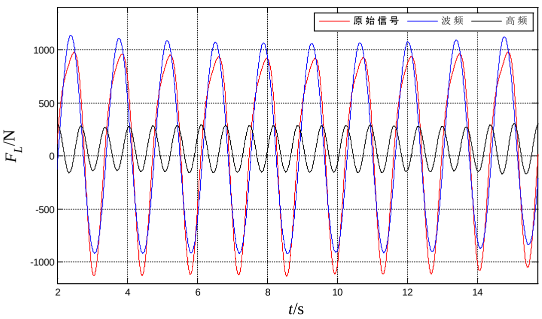


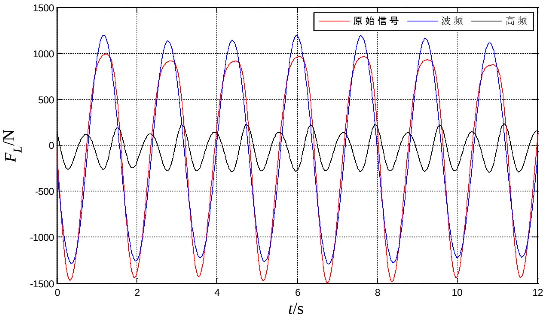
（b）λ/L=2.0 （c）λ/L=2.5





（d）λ/L=3.0 （e）λ/L=3.5





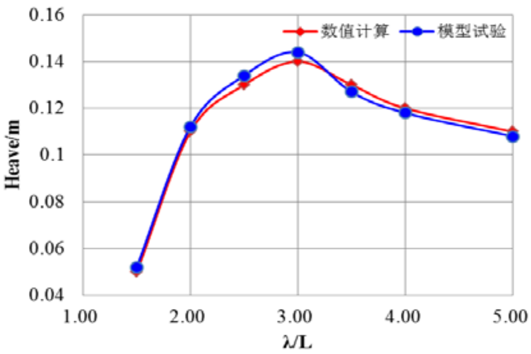
（f）λ/L=4.0 （g）λ/L=5.0

Figure 12. Duration curves of dynamic lift components at different wavelengths

2.4 Analysis of the motion response characteristics of planning boat in waves

Figure 15 shows the time history curve of heave and trim angle (a certain period of time). It can be seen from the figure that if λ/L=1.5/2.0/3.0, there is obvious high frequency components in the motion of heave and trim angle, and the high frequency component accounts for about 10%, which is consistent with the change characteristic of dynamic lift; when λ/L>2.5, the heave and the trim angle is mainly composed of wave frequency, with high frequency components accounting for less than 3%.

Figure 13 and figure 14 show the variation of the amplitude of the heave and the trim angle with the wavelength. And the numerical results are compared with the experimental data, which indicates they are in good agreement. The error is generally less than 5%. It can be seen from the figure that the amount of heave and trim angle increases with the wavelength and then decreases, and the response reaches the maximum at λ/L=3.0. The resonance phenomenon occurs when the frequency is close to the wave encounter period and the natural period of heave and pitch.



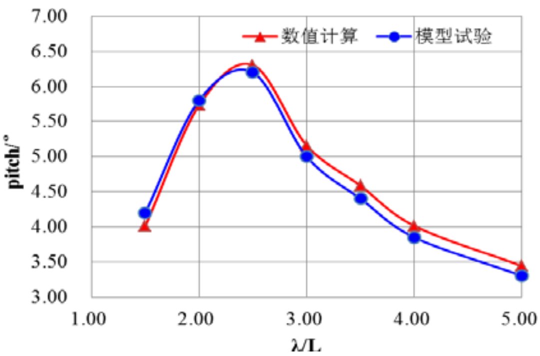
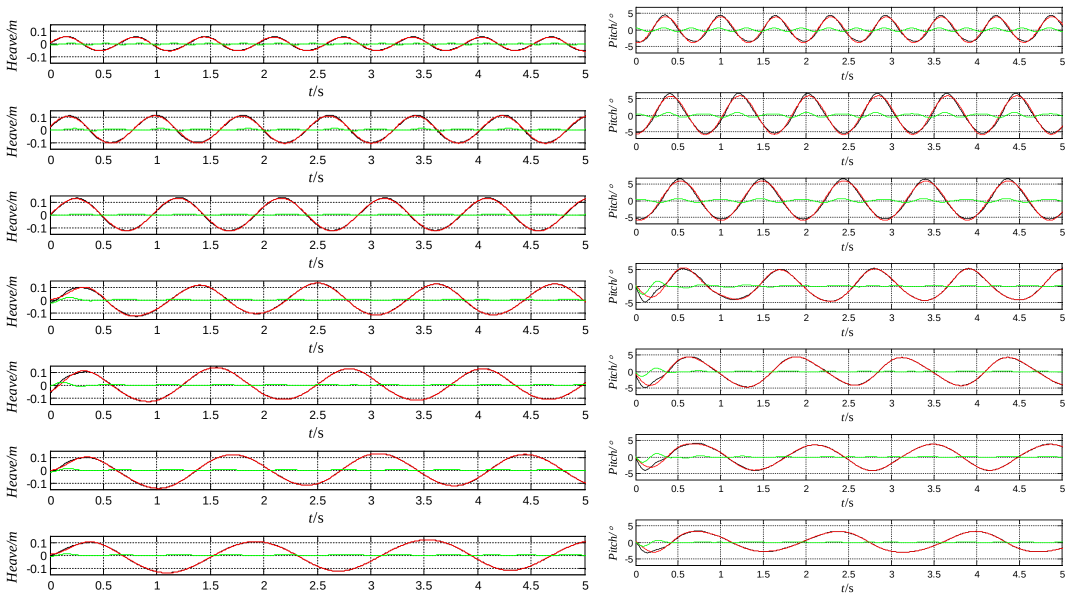


Figure 13. Comparison between the calculation results and experiment data of the heave

Figure 14. Comparison between calculation results and experiment data of the trim angle amplitude



（a）heave **（b）trim angle**

Figure 15. Duration curves of heave and trim angle at different wavelengths

2.5 Flow field distribution of planning boats in waves

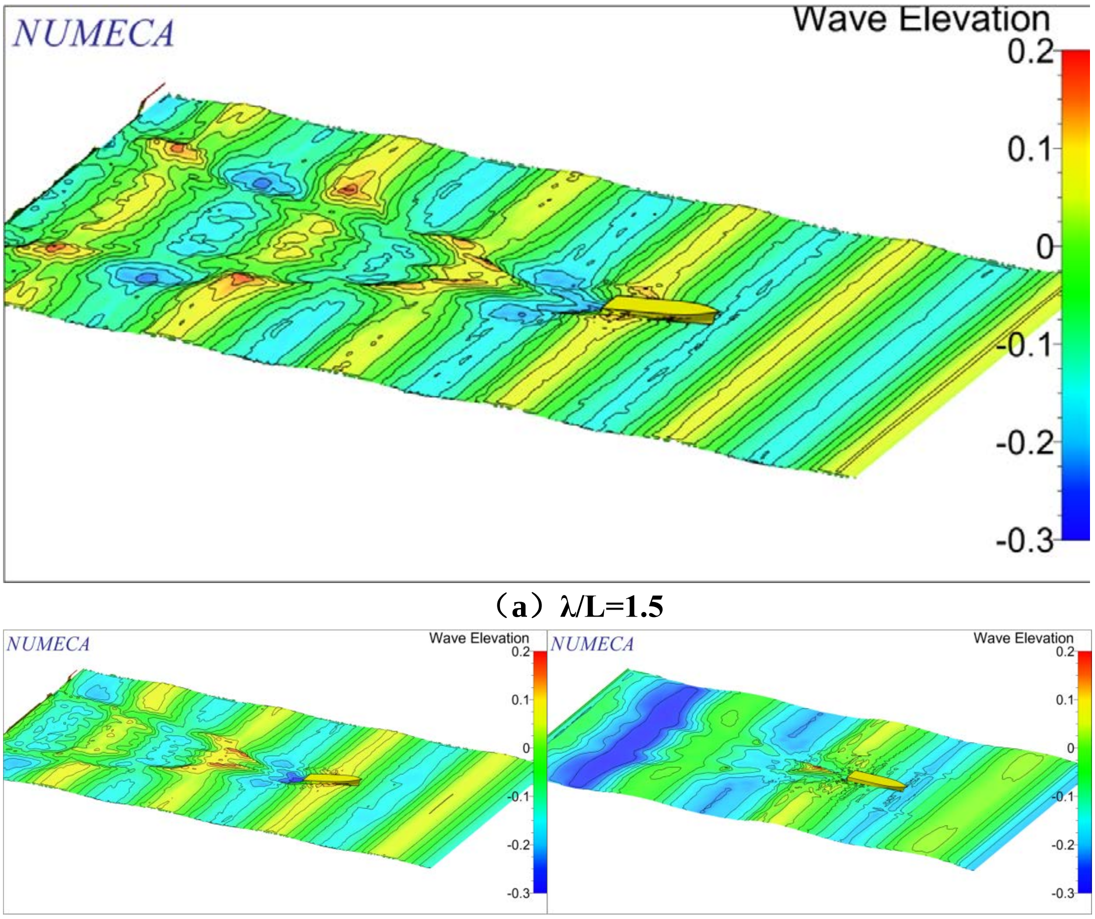
Figure 15 shows the wake field wave clouds map of planning crafts with different wavelength. From the figure we can obviously see that, when the planning craft is sailing in waves at high speed, the craft hull has a negative effect on the flow. The wake field has the following characteristics:

（1）The water flowing out from both sides of the hull, resulting in a large number of splash and spray.

（2）A cavity forms at the trailing edge of the hull.

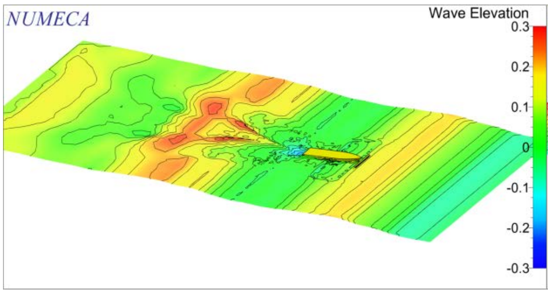
（3）Scattered wave and shear wave from a "chicken wake flow" at the hull tail edge, causing the superposition of incident wave and traveling wave system. As a result, the 3-D wave crest of the longitudinal profile of the planning craft is appeared in the wake field.

（4）When λ/L=1.5/2.0, overtopping phenomenon occurs.

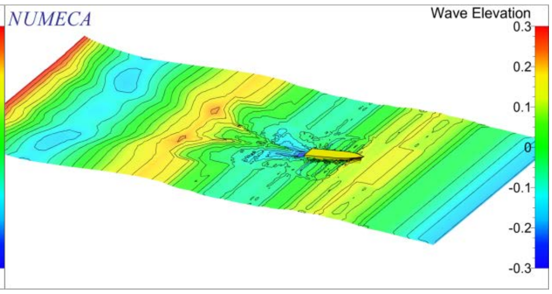


（a）λ/L=1.5

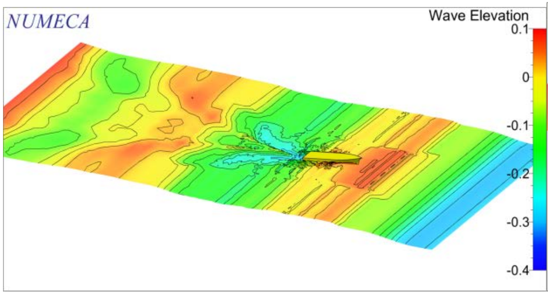
（b）λ/L=2.0 **（c）λ/L=2.5**



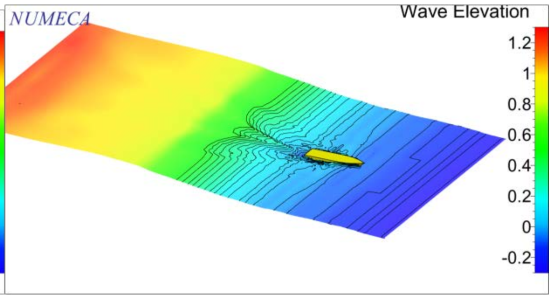
（d）λ/L=3.0



（e）λ/L=3.5



（f）λ/L=4.0



（g）λ/L=5.0

Figure 16. The waveform of the stern flow field

3 Conclusion

In this paper, based on the FINE/MARINE software, the numerical simulation of the longitudinal motion response of high speed planning craft, with the application of six degree of freedom motion response module, has been conducted. The numerical results are compared with the model tests and the following conclusions are obtained：

1）The results of numerical simulation of the motion response of high speed planning craft are in good agreement with the experimental values, with an error less than 5%.

2）When λ/L=1.5/2.0, overtopping and slamming happens on the planning craft. The composition of the load acting on the planning craft is complex, which has a great influence on the motion response.

3）When λ/L=1.5/2.0, The high frequency component has a great contribution to the resistance and the dynamic lift of the planning boat, which should be given more attention. When λ/L>2.5, it mainly consists of wave frequency component. The high frequency component is so little that can be ignored.

4）The Fine/Marine software can be used to deal well with the nonlinear problems such as overtopping and slamming.

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