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Hydrodynamic Analysis of the Hull of a Scientific Research Vessel

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Abstract

In deep-sea exploration operations, hydrodynamic performance is not only reflected in the impact of marine environment on the hull of research vessels, but also related to the rationality of hull design.This article uses the AQWA module to conduct hydrodynamic analysis of ships under the influence of regular waves.Construct a simulation analysis model for a research vessel, and conduct hydrodynamic analysis on the hull model based on the potential flow theory in frequency domain analysis, including damping coefficients and additional mass in six degrees of freedom. And analyze the response laws and wave excitation forces under different wave directions.

Keywords

Hydrodynamic Analysis, AQWA, Additional Mass, Wave Force.

1. Introduction

China's marine scientific research mainly started in the late 1950s and has been going through a period of initial and expansion for nearly 70 years. It has now entered a period of vigorous development. Having advanced marine technologies is an important guarantee for safeguarding national maritime rights and interests. Many countries have made protecting the marine environment and developing marine resources a basic national policy, investing huge financial and material resources in marine exploration and resource development.

Shiming Wang[1] and other scholars have confirmed the influence of wave period, incident angle, and structural parameters on the hydrodynamic response of offshore platforms using AQWA software.

Zahra Tajali et al.[2]conducted hydrodynamic analysis on the interaction between multiple floating docks and incident waves, and designed a software capable of analyzing similar movements of multiple floating docks. Perform dynamic response and frequency domain analysis, considering the influence of relevant parameters on its motion response.

H. Chua et al.[3] investigated the hydrodynamic phase between parallel barges through the angle of gap surface response and applied forces. The interaction was numerically studied.

Hamid Reza Ghafari et al.[4]studied the hydrodynamic interactions of a semi submersible single column PSO under marine conditions in the Caspian Sea. The hydrodynamic load acting on the hull was determined using diffraction theory.

2. Establishment of Ship Model

2.1. Basic Parameters of the Ship's Hull

In deep-sea exploration operations, hydrodynamic performance is not only reflected in the impact of marine environment on the hull of scientific research vessels, but also related to the rationality of hull design. This article uses the AQWA module to conduct hydrodynamic analysis on a ship under the influence of regular waves.

AQWA is a software with a wide range of design fields and comprehensive functions in the field of hydrodynamic analysis and research. At present, there are two ways: the classic interface and the Workbench interface. The classic interface has stronger functionality but may have some difficulty in operation, while the latter provides some convenience but has certain limitations in analysis. This article adopts simulation analysis based on Workbench interface. It can use the basic dimensions of the hull to construct a basic model of the hull, and input ocean environmental parameters. Based on the three-dimensional potential flow theory, it can analyze the motion response of the ideal fluid under the influence of regular waves..

Due to the complexity of the actual ship structure, this study ignores its superstructure. Based on the basic parameters of the hull listed in Table (1), a simplified hull model as shown in Figure (1) was constructed using tetrahedral elements for mesh partitioning.

Table 1. Basic parameters of the ship's hull

Basic Parameters	numerical value
Total length of the ship	78.4m
moulded breadth	20.6m
molded depth	8m
Total displacement	6733t
loaded draft	5.6m

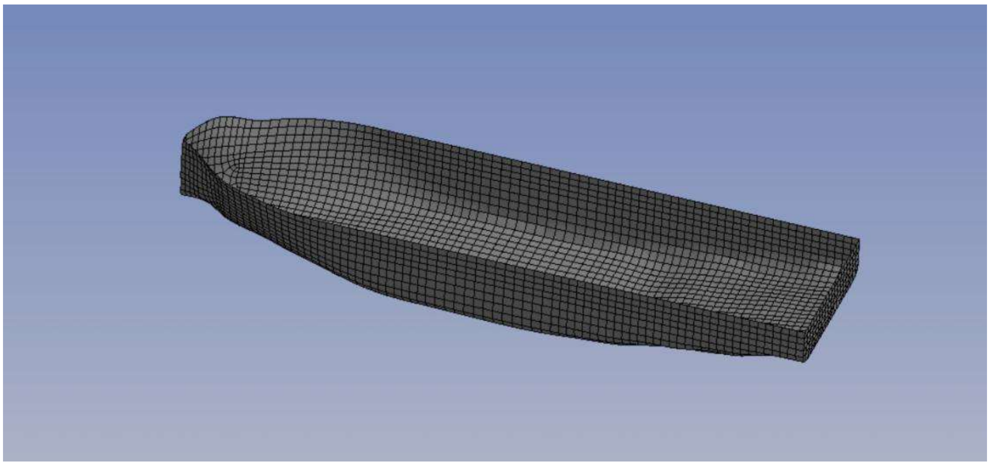

Fig. 1 Simple Ship Model

AQWA, as a mainstream hydrodynamic analysis platform, is widely used for evaluating the dynamic characteristics of various marine engineering structures. The calculation process can automatically consider the effect of waves on the structure under different sea conditions, so there is no need to input additional sea conditions when solving the RAO parameters of the ship. This software adopts a frequency domain based method, which can solve the response characteristics of floating structures in the frequency domain, covering static water stiffness, additional mass, radiation damping, and first-order wave forces. These coefficients are the core parameters for conducting motion response analysis under different sea conditions.

2.2. Free Movement of the Ship's Hull

During the navigation and operation of ships at sea, complex sea conditions such as wind, waves, and ocean currents can have a sustained impact on the hull, causing six degrees of freedom motion around its center of gravity. These six degrees of freedom include three types of translation and three types of rotation: longitudinal oscillation refers to the forward and backward displacement of the hull along the X-axis direction, lateral oscillation refers to the left and right displacement along the Y-axis direction, and vertical oscillation refers to the up and

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down displacement along the Z-axis direction; And pitch corresponds to pitch rotation around the X-axis, roll refers to lateral tilt rotation around the Y-axis, and bow represents the yaw motion of the hull around the Z-axis. The six degrees of freedom motion not only describes the basic dynamic characteristics of ships when they are subjected to environmental disturbances at sea, but also serves as an important foundation for conducting ship maneuverability analysis and hydrodynamic research.

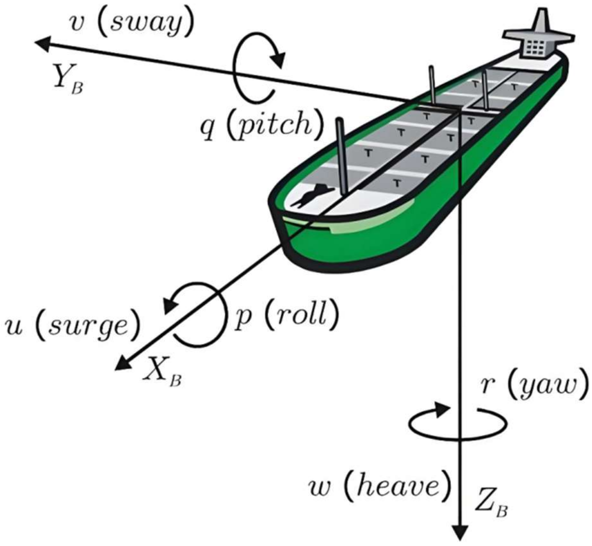

Fig. 2 Six degrees of freedom for ships

Table 2. Six degrees of freedom for ships

type	X-axis	Y-axis	Z-axis
displacement	surge	Sway	Heave
rotate	roll	pitch	Yaw

During the navigation process, the ship will experience coupling effects with surrounding fluids due to wave motion. According to the theory of ship motion, the torque and force experienced are:

$$M_c = \int (r - r_c)^2 \mathrm{n}\, dS$$

$$\mathrm{F} = \int (\tau - \mathrm{pI})\mathrm{n}\, dS - mg$$

In the formula: M_c- The hull is subjected to external torque; F- External forces acting on the hull of the ship; m- Drainage volume; p- Fluid pressure; τ- Shear force; r- Coordinate vector of any point on the surface of the ship; r_c- The coordinate vector of the ship's rotation center.

According to Newton's second law, the equations of motion for the six degrees of freedom of the ship's hull are obtained using the centroid motion theorem and the moment of momentum theorem.

$$\frac{\mathrm{d}}{\mathrm{dt}}(\mathrm{mv_c}) = \mathrm{F}$$

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$$\frac{d}{dt}([I_C * \omega_c]) = M_C$$

In the formula: v_c- ship's linear velocity vector; ω_c- Ship rotation angular velocity vector; I_C- Inertial moment tensor of ship hull.

In the process of ship hydrodynamic simulation, the motion parameters can be obtained through the above formula. The interaction between the flow field and the hull is mutual, with forces and moments driving the movement of the hull, and feedback from the hull movement acting on the flow field, reflecting the interactive transfer of energy.

In ship and ocean engineering, because the potential flow theory of AQWA cannot calculate viscous damping, the additional mass obtained directly from the potential flow theory, especially for roll, often needs to be corrected to make it more in line with physical laws or experimental data. If the roll response (RAO) calculated directly using AQWA is used, the results will significantly overestimate the roll amplitude because the software did not consider sufficient roll damping. For other degrees of freedom (such as heave, pitch, etc.), no modifications are needed because the potential flow theory is already quite reliable in calculating these degrees of freedom. Therefore, place the center of gravity of the correction on the roll.

Calculation of additional damping:

$$\text{Damping} = 2\zeta\sqrt{(M + \Delta M) * K}$$

$$\zeta = \frac{\ln(2)}{2\pi * n}$$

In the formula: ζ- critical damping ratio, the exact value is obtained through numerical simulation and emulation; M- Structural quality, here refers to the displacement of the vessel; ΔM- Additional quality; K- restoring stiffness; N- The number of complete cycles required for halving the amplitude in a free decay experiment.

3. Analysis of Ship Hydrodynamic Performance

3.1. Damping Coefficient and Additional Mass

As shown in Figs (3) and (4), the damping coefficient and additional mass of the hull exhibit different variation patterns in six degrees of freedom.

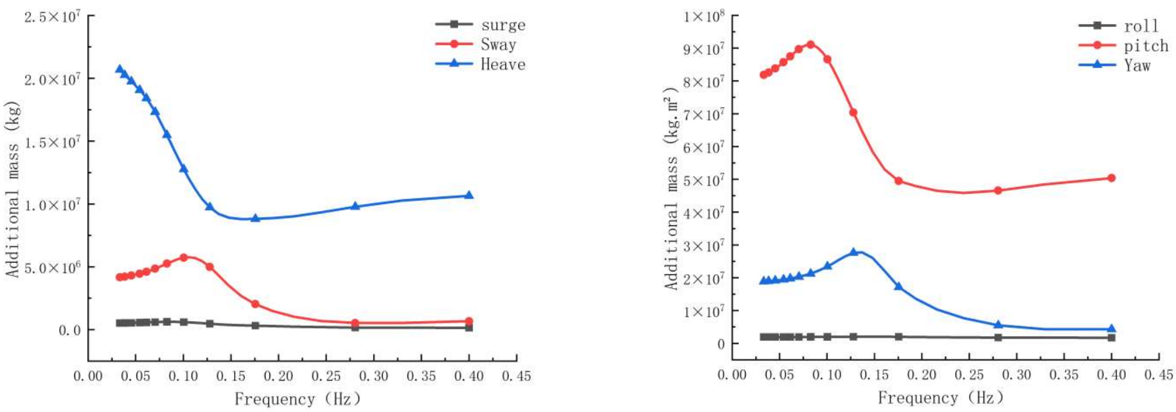

Fig. 3 Damping coefficient of the ship in six degrees of freedom when fully loaded

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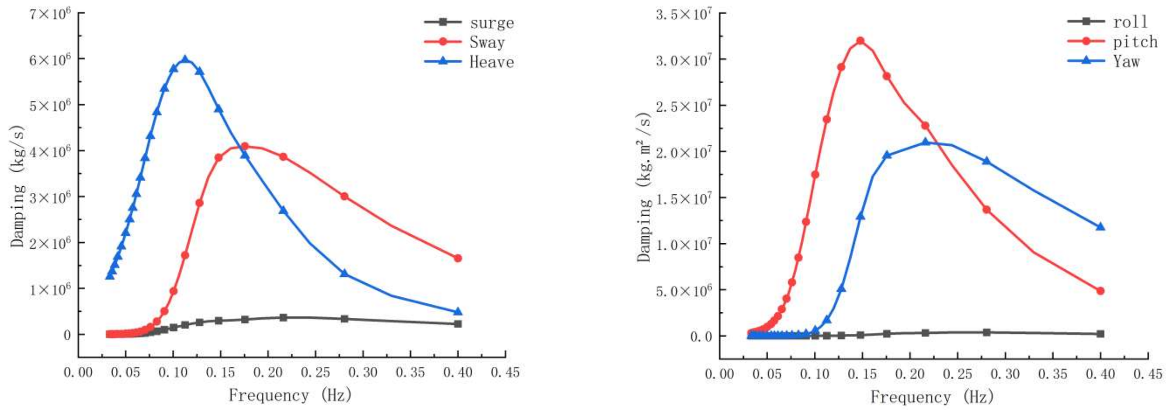

Fig. 4 Additional mass in six degrees of freedom of the vessel when fully loaded

The variation law of damping coefficient is relatively consistent, mainly showing an increase followed by a decrease with increasing frequency, and a peak appears at 0.1-0.15Hz.

For movements in the three degrees of freedom of sway, pitch, and yaw, the overall trend of additional mass with increasing frequency is to first increase and then slowly decrease. For movements in the two degrees of freedom of sway and pitch, the change in additional mass with frequency is not significant. For movements in the heave degrees of freedom, the additional mass first decreases and then slowly increases with increasing frequency.

3.2. Hydrodynamic Analysis

By conducting frequency domain analysis on ships in AQWA, the response patterns of the hull under different wave directions can be obtained, providing support for subsequent time-domain calculations. The core of frequency domain computation is to determine the amplitude response operator (RAO) for different wave direction angles. The RAO parameter not only reflects the motion response of the ship under wave action, but also provides important basis for evaluating the stability and seaworthiness of the ship in complex sea conditions. The wave frequency range is selected as 0-0.4Hz. Since the simplified model of the hull established based on the hull line values is symmetrical about the x-axis, the wave angle can be considered as 0-180 °, which is divided into five parts: 0°, 45°, 90°, 135°, and 180°.

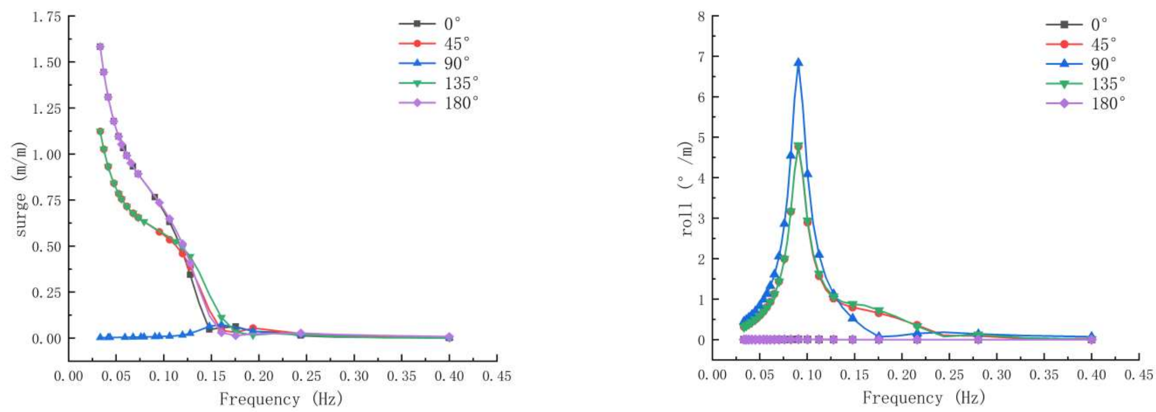

Fig. 5 RAO curve in the surge and roll

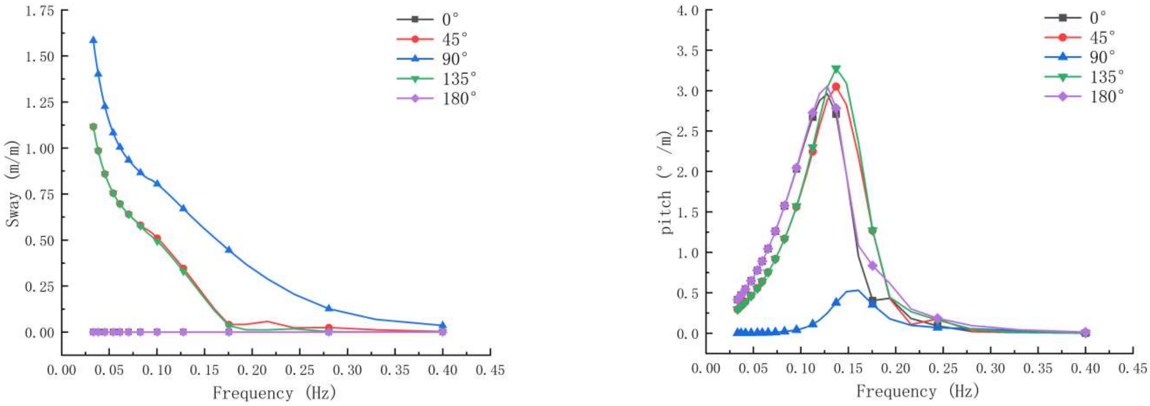

Fig. 6 RAO curve in the Sway and pitch

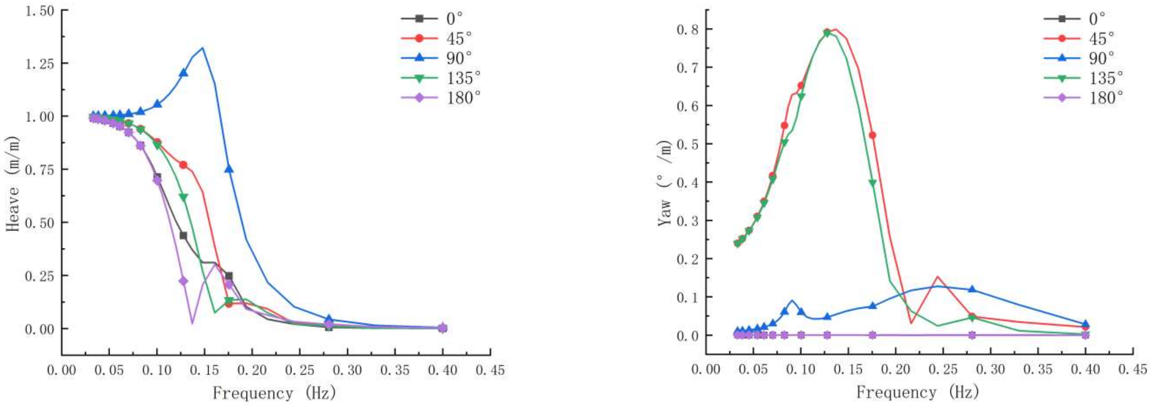

Fig. 7 RAO curve in the Heave and Yaw

From Fig. (5), it can be observed that the longitudinal and lateral response curves have obvious symmetry, such as the response amplitudes in the 45° and 135° directions being basically the same, which is closely related to the symmetrical structure of the ship itself.

Overall, the RAO of ship heave and sway gradually decreases with the increase of wave frequency, and reaches a turning point at approximately 0.15Hz. After reaching a peak near 0.15Hz, it sharply decreases and eventually approaches zero. When the wave angle is set to 0° or 180°, the amplitude of lateral oscillation can be almost ignored; When the wave angle is set to 90°, the amplitude of longitudinal oscillation can be almost ignored. The overall response curve of roll amplitude shows a "conical" trend. Under the condition of 90° transverse waves, the roll amplitude is most significant, forming a peak around 0.1Hz.

From Fig. (6), it can be seen that the pitch response shows significant differences with the variation of wave angle. All five wave angles exhibit peak characteristics, with pitch in the 135° direction being the most significant, reaching a maximum value of 3.3°/m around 0.1Hz. In contrast, the 90° wave angle has the weakest impact on pitch response, with a maximum peak value of only 0.53°/m.

The results in Fig. (7) indicate that the heave response is different from the longitudinal and lateral oscillations, and its curve does not have symmetry. In the initial frequency stage, the response amplitude at all wave angles is 1m. The bow roll amplitude response shows significant differences at different wave angles. Among them, the bow sway response in the 45° and 135° directions is the strongest, reaching peak values in the range of 0.12-0.15Hz, and exhibiting

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different behaviors in the high frequency range. A second small extremum appears in the 135° direction.

3.3. First-order Wave Force

The first-order wave force, also known as wave excitation force, generally refers to the force and moment generated on the wet surface of the ship when it is subjected to external fluid action in regular waves, also known as wave interference force. It consists of two types of force components: one is the Froude Krylov force, which originates from the unsteady pressure exerted on the hull by incident waves that are not disturbed by floating bodies; The second is the wave diffraction force, which is caused by the disturbance of the wave field due to the presence of the hull, resulting in additional forces in the altered pressure field.

Due to the presence of floating bodies, incident waves undergo scattering and reflection, thereby altering the wavefield distribution around them. The additional load generated by the changed wave pressure field acting on the surface of the floating body is the diffraction force. Diffraction force can be regarded as a correction term introduced by a floating body on the disturbance of the original wavefield based on the Froude Krylov force.

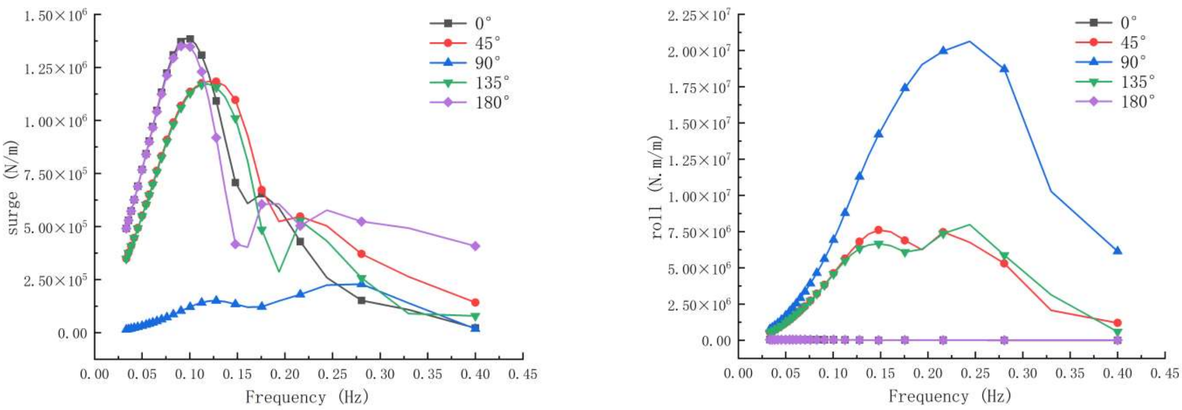

Fig. 8 First-order wave force in the surge and roll

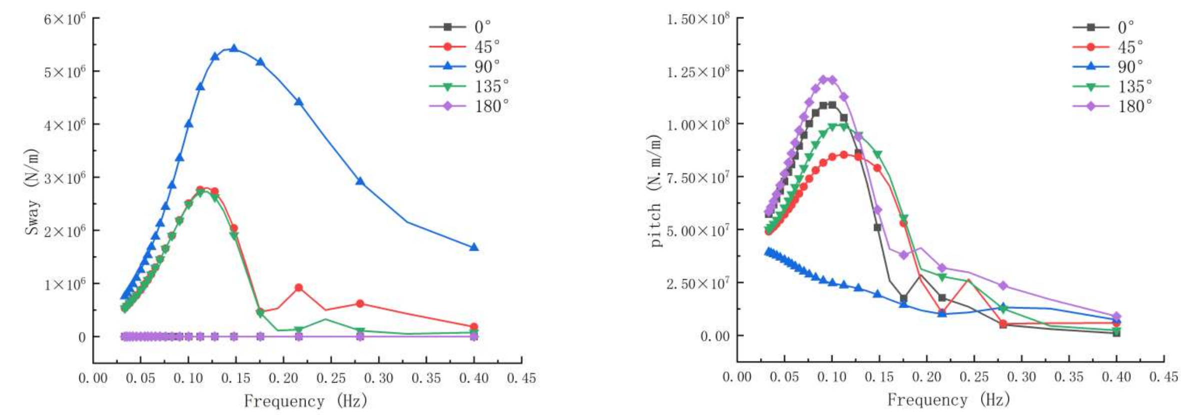

Fig. 9 First-order wave force in the Sway and pitch

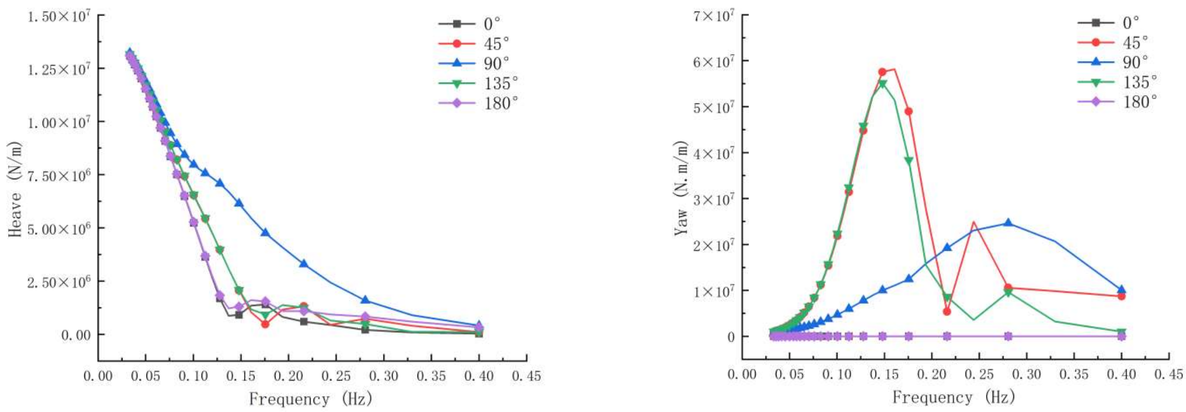

Fig. 10 First-order wave force in the Heave and Yaw

From Fig. (8), it can be seen that the first-order wave excitation force in the longitudinal oscillation direction exhibits obvious wave characteristics. In the low-frequency region, as the angle of the incident wave approaches the direction of the upstream or downstream wave, the rate of increase in wave excitation force accelerates and enters the peak stage earlier, with the maximum peak occurring under the upstream wave (0°) condition. The first-order wave excitation force of roll exhibits a certain pattern with the variation of frequency and wave direction angle. As the frequency increases, the curves at all angles enter the peak region, but the peak gradually decreases as the incident angle approaches 0° and 180°. After entering the high-frequency range, the curve tends to decay as a whole.

From Fig. (9), it can be seen that the first-order transverse wave excitation curve exhibits diverse characteristics with different wave incidence angles. The smaller the incident angle, the higher the initial value of the wave excitation force, the faster the rise speed, and the larger the peak amplitude. The overall pattern of the first-order wave excitation curve in the pitch direction is similar to that in the heave direction. In the low-frequency stage, the initial value of wave excitation force increases with the increase of incident angle, and the growth rate of the curve also accelerates, entering the peak range earlier.

From Fig. (10), it can be seen that the first-order wave excitation force in the heave direction generally shows a monotonic decreasing trend throughout the entire frequency range. At the initial frequency stage, the initial values of wave excitation force under the five wave incidence angle conditions are basically the same. As the frequency increases, the wave excitation force gradually decreases, and the larger the incident angle, the faster its attenuation speed. At an incident angle of 67.5°, the maximum peak of the bow roll direction curve appears at 0.2Hz, indicating that the ship is most strongly excited at this angle.

4. Conclusion

This chapter constructed a simplified hull model in the Design Modeler module based on the actual ship type parameters, and analyzed the motion performance and hydrodynamic response of the ship under regular wave excitation using AnsysAQWA. Firstly, the mechanism of ship motion is introduced, and a motion coordinate system and mathematical model are established to derive the motion equation of the ship. Subsequently, key hydrodynamic parameters such as additional mass, damping coefficient, motion response operator, and first-order wave excitation force were calculated. By analyzing the response characteristics of six degrees of freedom under different wave incidence angles, the variation laws of ship motion in various wave directions were studied. The results show that the calculated response amplitude

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and variation trend meet the design requirements of the ship, indicating that the model is established reasonably and the calculation results are reliable, providing effective data support for subsequent time-domain motion simulation and safety evaluation.

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