Vibration phenomena of serial-parallel platforms on ships

Zhang Lixun[1] Xu bai[2] Zhang Da[3] Zhu Yeqin[4] Gong Jiru[5]

[1-5]College of Mechanical and Electrical Engineering, Harbin Engineering University, China.

ABSTRACT

During the voyage, the ship is affected by waves, sea breeze and other factors, causing the ship to sway and produce vibration. The series-parallel three-degree-of-freedom stability platform is mainly a light guiding device for the sliding roll indicating system, which has the functions of isolating the hull pitching, rolling motion and adjusting the azimuth according to the direction of the helicopter. It is based on this function that makes the stable platform have a wide range of applications. This paper analyzes the overall structure and control scheme of the series-parallel platform, based on the wave spectrum density formula recommended by ITTC, digitally simulates the pitch and roll motion of the ship; performs dynamic and kinematic modeling analysis on the parallel platform, analyzes the interference and other phenomena. Based on dSPACE to build a semi-physical simulation platform, the HIL experiment is carried out on the prototype of the marine series-parallel stable platform. The stable platform is installed on the swinging platform, and the actual operating environment is simulated by the swinging table to simulate and analyze the actual operation.

1. INTRODUCTION

The ship series-parallel platform installed on ships with helicopters is a core light landing aids device which aids helicopter landing. During the voyage, the ship is affected by waves, sea breeze, current and other factors, causing the ship sway and equipment vibration with ship which affects ship's stability and is unable to keep relatively stable. Pitch and rolling endanger and affect ship most. Helicopters find difficulty during return to ship under the condition of night or low vision during the day. Therefore, most domestic and overseas ships with

---
[1] zhanglixun@hrbeu.edu.cn
[2] x862200137@163.com
[3] 429794147@qq.com
[4] 2939046824@qq.com
[5] 905765742@qq.com

helicopters are equipped with various guiding landing aid devices of which glide rolling indicating system is most widely operated.

The parallel platform of the ship is installed on a ship equipped with a helicopter to assist the helicopter to land. It is the core light-assisting device. When the ship is navigating at sea, it will be affected by waves, sea breeze, ocean currents, etc., causing the hull to sway, causing the equipment installed on the ship to follow, affecting its stability and not maintaining relative stability. The damage and impact of the pitch and roll on the ship are the greatest. . [3] Due to the low visibility of helicopters at night or during the day, there are many difficulties in returning the ship. Therefore, most ships equipped with helicopters at home and abroad are equipped with various guidance and descending devices, of which the slid~ing roll indicating system is The most widely used light assist device.

In 1904, Otto Schlick developed the first ship anti-rolling device to solve the problem of excessive roll angle during ship navigation and conducted related tests. This is the first device which successfully initiated research in the field of stable platforms are improved on this basis, which can be regarded as an upgraded version,which has successfully imitated research in the field of stable platform. The stable platform has a wide range of applications,covering air-based,ship-based,vehicle-based and various aerospace equipment and other related fields.It is mainly used to isolate the disturbance of these carriers and provide a stable environment installed in the carrier. Numerous military enterprises are engaged in development and production of the stable platform.

The stable platform design requires three rotational degrees of freedom, corresponding to the pitch and pitch motion freedom of the ship and the azimuth adjustment mechanism corresponding to the roll. The vibration of the parallel platform is now mainly reflected in the motion of pitch and roll, so we briefly introduce the relevant motion analysis here.
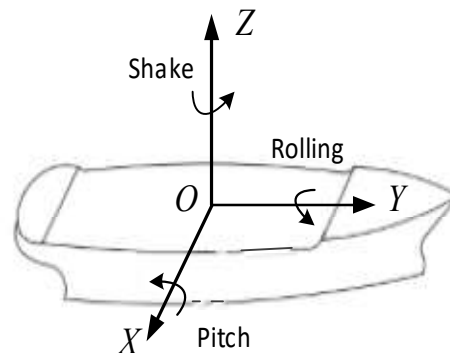

Figure.1: The diagram of the ship motion

The roll and pitch motions are realized by parallel platforms. The parallel platform structure is shown in Figure 2. The optical device is located on the moving platform of the parallel platform, and two mutually perpendicular inertia units are installed at the end of the moving platform. Throughout the telescopic movement of the two electric cylinders, the entire parallel platform realizes two degrees of freedom rotation around the passive chain of the supporting column. One of the electric cylinders is connected to the lower platform through the rotating pair, and the other electric cylinder is connected to the lower platform through the hook hinge. The two electric cylinders are connected to the upper platform through the Hook hinge, and the rotating base is connected between the upper platform and the Hook hinge to realize the function of the ball joint.
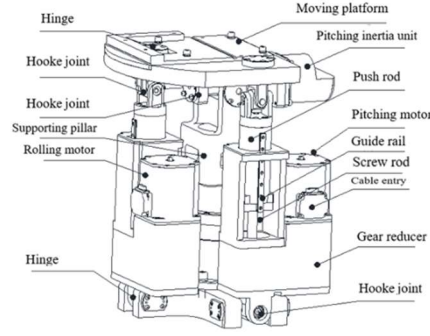
Figure 2: The structure diagram of the system control of the parallel platform

The system control of the parallel platform is briefly described here with a strategy diagram:
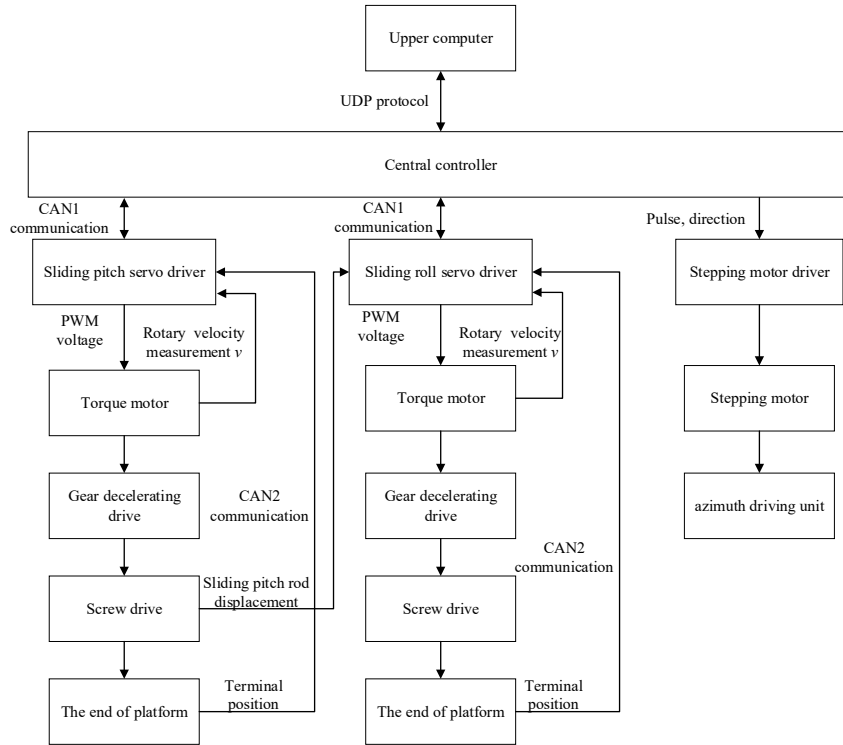

Figure 3: The strategy diagram of the system control

2. AZIMUTHAL MOTION ANALYSIS

First, we analyze the azimuth motion of the ship. For any point P on the ship, its motion is a superposition of pitch and roll motion, as shown in Figure 4. Let the ship's roll angle be α, the ship's pitch angle be β, the angle $\angle AOP=\gamma$, $\|OP\|=r$, and the angle $\angle P'OP=\psi$.
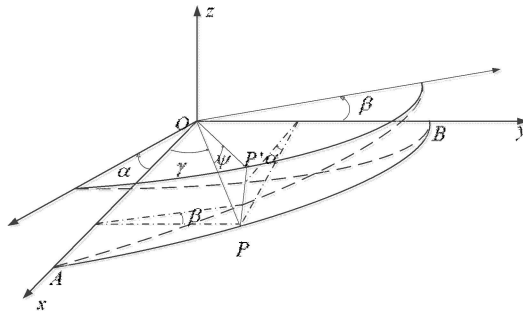
Point P is the point P' after the ship's roll and pitch motion, then the coordinates of point P, P' are expressed as：

$$P = \begin{bmatrix} rc\gamma \\ rs\gamma \\ 0 \end{bmatrix} = \begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix} \tag{1}$$

$$P' = \begin{bmatrix} c\alpha & 0 & s\alpha \\ 0 & 1 & 0 \\ -s\alpha & 0 & c\alpha \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\beta & -s\beta \\ 0 & s\beta & c\beta \end{bmatrix} \begin{bmatrix} rc\gamma \\ rs\gamma \\ 0 \end{bmatrix} = \begin{bmatrix} rc\gamma c\alpha + rs\gamma s\alpha s\beta \\ rs\gamma c\beta \\ -rc\gamma s\alpha + rs\gamma c\alpha s\beta \end{bmatrix} = \begin{bmatrix} P_x' \\ P_y' \\ P_z' \end{bmatrix} \tag{2}$$

From $\| \vec{x} \bullet \vec{y} \| = \| \vec{x} \| \cdot \| \vec{y} \| \cdot \cos\varphi$, available

$$\psi = \arccos\left(\frac{\| OP \bullet OP' \|}{\| OP \| \cdot \| OP' \|}\right) \tag{3}$$

The angle obtained by the Equation (3) is an angle size, and the angle direction cannot be represented. Therefore, we can find that the relationship between α, β, γ and ψ is

$$\psi = \arccos(\chi)\mathrm{sgn}(\varsigma) \tag{4}$$

Where $\chi = \cos^2\gamma \cos\alpha + \cos\gamma \sin\gamma \sin\alpha \sin\beta + \sin^2\gamma \cos\beta$,

$\varsigma = \sin\gamma \cos\alpha \sin\beta - \cos\gamma \sin\alpha$.

It is known that the ship's roll angle is α, the ship's pitch angle is β, and the azimuth angle γ, then the parallel platform tilts the electric push rod angle θ, and the parallel platform rolls the electric push rod angle ϕ respectively.

$$\theta = \arccos(\chi_1)\mathrm{sgn}(\varsigma_1) \tag{5}$$

$$\phi = -\arccos(\chi_2)\mathrm{sgn}(\varsigma_2) \tag{6}$$

Where $\chi_1 = \cos^2(\gamma + \frac{\pi}{2})\cos\alpha + \cos(\gamma + \frac{\pi}{2})\sin(\gamma + \frac{\pi}{2})\sin\alpha \sin\beta + \sin^2(\gamma + \frac{\pi}{2})\cos\beta$;

$\varsigma_1 = \sin(\gamma + \frac{\pi}{2})\cos\alpha \sin\beta - \cos(\gamma + \frac{\pi}{2})\sin\alpha$;

$\chi_2 = \cos^2\gamma \cos\alpha + \cos\gamma \sin\gamma \sin\alpha \sin\beta + \sin^2\gamma \cos\beta$;

$\varsigma_2 = \sin\gamma \cos\alpha \sin\beta - \cos\gamma \sin\alpha$.

Similarly,

$$\alpha = -\arccos(\chi_3)\mathrm{sgn}(\varsigma_3) \tag{7}$$

$$\beta = \arccos(\chi_4)\mathrm{sgn}(\varsigma_4) \tag{8}$$

Where $\chi_3 = \cos^2(-\gamma)\cos\phi + \cos(-\gamma)\sin(-\gamma)\sin\phi \sin\theta + \sin^2(-\gamma)\cos\theta$;

$\varsigma_3 = \sin(-\gamma)\cos\phi \sin\theta - \cos(-\gamma)\sin\phi$;

$$\chi_4 = \cos^2(\frac{\pi}{2} - \gamma)\cos\phi + \cos(\frac{\pi}{2} - \gamma)\sin(\frac{\pi}{2} - \gamma)\sin\phi\sin\theta + \sin^2(\frac{\pi}{2} - \gamma)\cos\theta\ ;$$

$$\varsigma_4 = \sin(\frac{\pi}{2} - \gamma)\cos\phi\sin\theta - \cos(\frac{\pi}{2} - \gamma)\sin\phi\ .$$

Orientation mechanism movement, change the azimuth angle, thereby affecting the input angle of the parallel platform tilting electric push rod, the parallel platform panning the electric push rod input angle; according to the parallel platform, the electric push rod input angle is swung, the parallel platform is tilting the electric push rod input The angle, as well as the azimuth angle, determine the ship's roll angle and the ship's pitch angle.

3. AZIMUTH MOTION SIMULATION

The MATLAB/Simulink toolbox[4] is used to analyze the influence of the input angle of the parallel platform on the given ship's roll, pitch angle and azimuth changes; the pitch, roll angle and orientation of the parallel platform are known. In the case where the angle is known, the ship's roll and pitch angles are solved to realize the functional requirements of the ship's angle of motion during the movement.

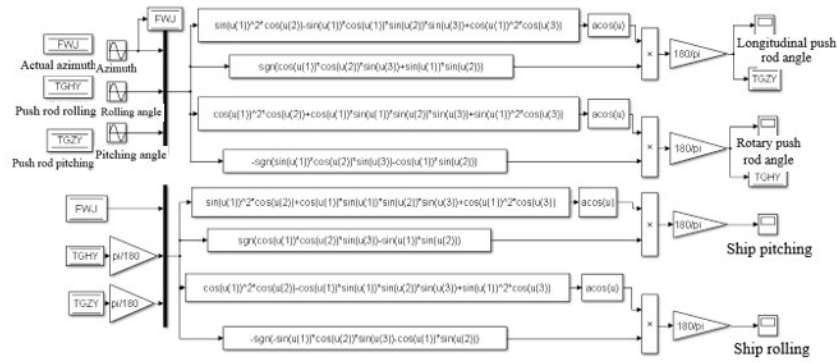The block diagram of establishing Simulink is shown in Figure 5.

Figure 5: Azimuth motion simulation block diagram

Input ship roll, pitch motion $\alpha = 6\sin(2\pi \times 0.25 \times t)$, $\beta = 15\sin(2\pi \times 0.125 \times t)$, azimuth motion $\gamma = 90\sin(2\pi \times 0.025 \times t)$, the motion law of pitch and roll of parallel platform is shown in Figure 7.
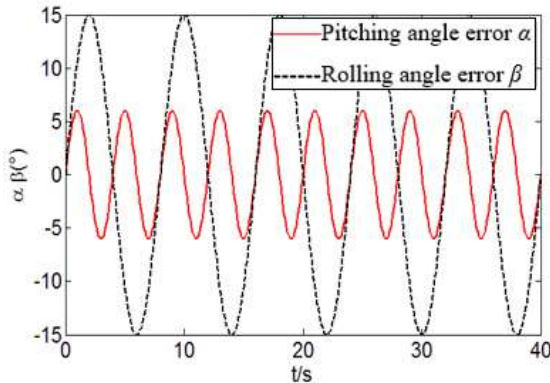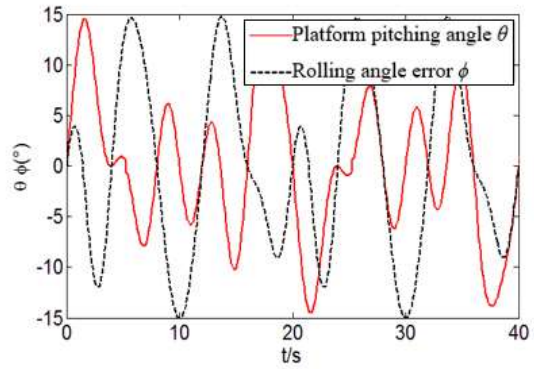

Figure 6: Ship angle input curve

Figure 7: Series-parallel platform motion angle curve

According to the motion law of the pitch and roll angles of the parallel platform in Figure 7, and the azimuth variation law, the ship roll and pitch curves are obtained as shown in Figure 8, and the error curve is shown in Figure 9.
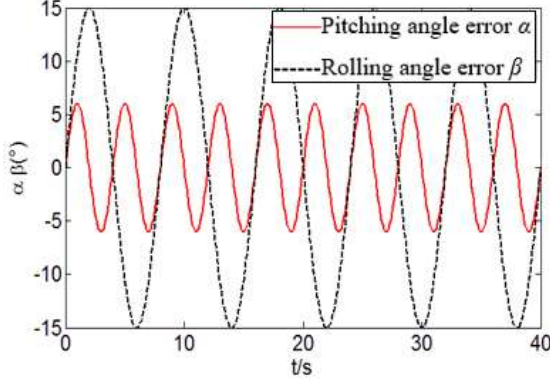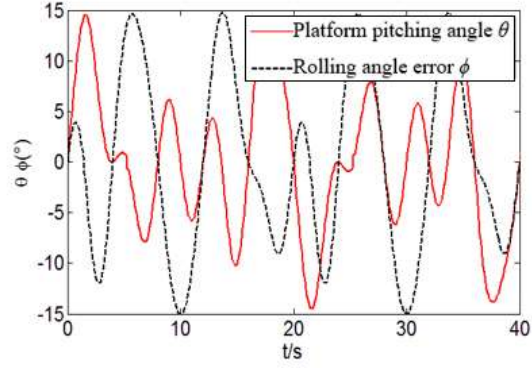

Figure 8: Inverse solution of ship motion angle curve

Figure 9: Inverse solution of ship motion deviation curve

In summary, it can be seen that the influence of azimuth motion on the parallel platform is the input change of the pitch and roll angle of the parallel platform.

4. KINEMATICS ANALYSIS OF PARALLEL PLATFORMS

The ship series-parallel platform consists of upper and lower platforms and two electric cylinders. The electric cylinder and the upper platform are connected to the A1 and A2 through the ball joint. The lower platform and the rotating pair are connected to the B1 point. The lower platform and the tiger are connected. The hinge connection is made at point B2, as shown in Figure 10. Through the expansion and contraction of the two electric push rods, the influence of the rolling and pitching motion of the ship on the upper platform is isolated, so that the upper platform maintains a relatively stable horizontal level.
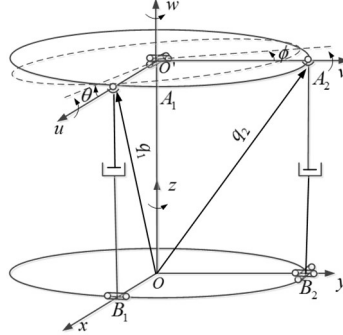

Figure 10 Structural scheme of mechanism of series-parallel stable platform

The kinematics of the parallel platform is divided into the following two basic problems: one is that the telescopic displacement of the electric push rod is known to solve the output angle of the moving platform; the other is that the output angle of the moving platform is known to solve the telescopic displacement of the electric push rod.

5. DYNAMIC SIMULATION ANALYSIS OF PARALLEL PLATFORM

It is known that the cylinder mass $m_1 = 3$ kg, the putter mass is $m_2 = 1.25$ kg, the stable platform load $m_f = 12$ kg, the load moment of inertia

$$I_f = \begin{bmatrix} 0.125 & \\ & 0.102 \end{bmatrix} \text{kg/m}^2 ,$$ the moving platform mass is $m_p = 7.2$ kg, the moment of inertia is $I_p = \begin{bmatrix} 0.0871 & \\ & 0.0871 \end{bmatrix} \text{kg/m}^2$, the cylinder's moment of inertia is $I_1 = 0.0122$ kg/m^2, and the pitching moment of inertia is $I_2 = 0.028$ kg/m^2. Substituting each parameter into the formula, the curve of the generalized force can be obtained as shown in Figure 11.
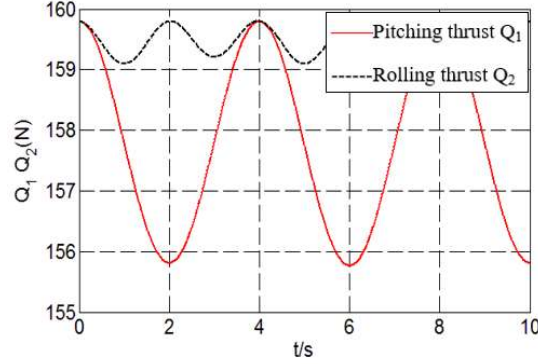

Figure 11: Push rod thrust output curve

6. WAVE MODEL AND SIMULATION

When the ship is driving in the sea, it is affected by the waves, and the ship will vibrate. It is generally assumed that the waves travel only in a fixed direction, and that their peaks and trough lines are parallel to each other and extend indefinitely. The nature of the waves can be summarized as follows[6]: the fully developed ocean wave is a stochastic process with stable and erratic properties; the instantaneous wavefront elevation of the ocean wave has a statistical distribution of normal distribution, and the amplitude obeys the Rayleigh distribution; Irregular waves can be superimposed by a plurality of unit regular waves that are independent of each other and have different wavelengths, amplitudes, and random phases[7].

Therefore, the wave height of a random wave can be expressed as

$$\zeta_t = \sum_{i=1}^{N} a_i \cos(k_i x + \omega_i t + \xi_i) \qquad (9)$$

The corresponding wave dip model is

$$\alpha_t = \sum_{i=1}^{N} \alpha_i \cos(k_i x + \omega_i t + \xi_i) \qquad (10)$$

Where a_i, x, k_i, ω_i, ξ_i, α_i respectively represent the amplitude, current position, wave number, angular frequency, initial phase, wave inclination angle of the i-th harmonic, and N represents the total number of harmonics. The relationship of k_i, ω_i, ξ_i can be expressed as:

$$k_i = \frac{2\pi}{\lambda_i} = \frac{\omega_i^2}{g} \qquad \omega_i = \frac{2\pi}{T_i} \qquad f(\xi_i) = \begin{cases} \frac{1}{2\pi} & (0 < \xi_i < 2\pi) \\ 0 & \text{else} \end{cases}$$

In practical applications, the concept of wave energy spectrum is often used to describe ocean waves. The essence of the wave energy spectrum $S_\xi(\omega)$ is to reflect the energy density.At present, the wave energy spectrum usually adopts the wave spectral density formula recommended by ITTC (International Ship Model Pool Conference), expressed as

$$S_\xi(\omega) = \frac{A}{\omega^5} \exp(-\frac{B}{\omega^4}) \tag{11}$$

Then the wave height of the random wave can be expressed as

$$\zeta_t = \sum_{i=1}^{N} \sqrt{2S_\zeta(\omega_i)\Delta\omega_i} \cos(\omega_i t + \xi_i) \tag{12}$$

Wave dip can be expressed as

$$\alpha_t = \sum_{i=1}^{N} \frac{\omega_i^2}{g} \sqrt{2S_\zeta(\omega_i)\Delta\omega_i} \cos(\omega_i t + \xi_i) \tag{13}$$

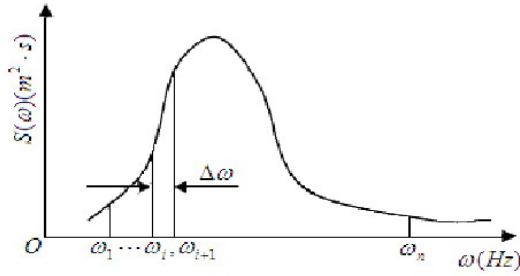The spectrum distribution frequency of the wave spectrum is shown in Figure 12.

Figure 12: The spectrum distribution frequency of the wave spectrum

In the five-level sea state, the sense wave height is $\zeta_{\omega/3}$=4m, and when the main frequency band is $[0.24, 2.4]$ rad/s, take $\omega = 0.08$ rad/s. The wave energy spectrum, wave height and wave inclination curve obtained by MATLAB simulation are as follows.
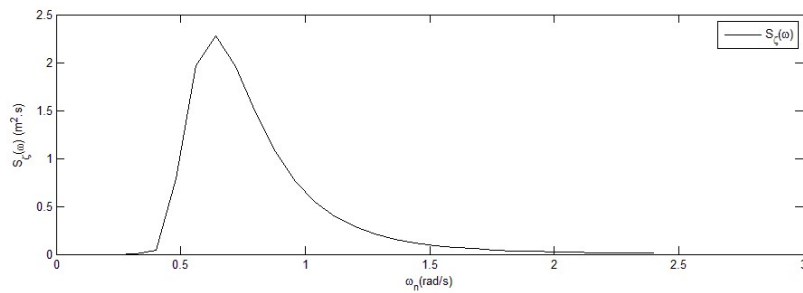

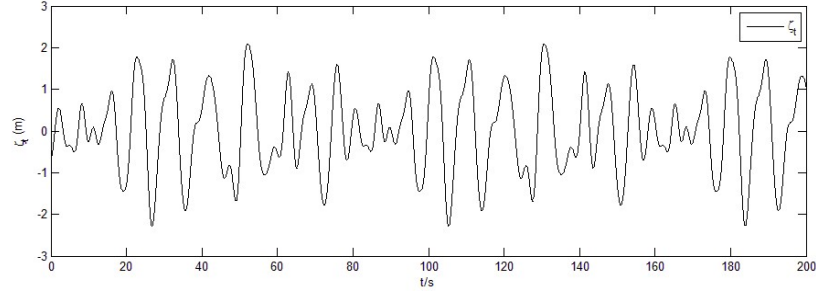*Figure 13: The wave energy spectrum mock curve*
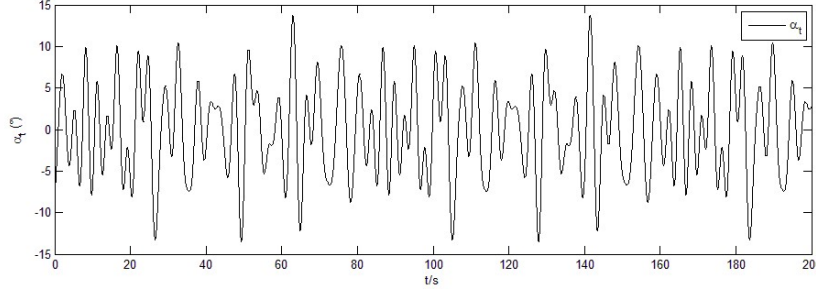
Figure 14: The wave height mock curve

Figure 15: The wave inclination mock curve

7. SHIP MOTION ANALYSIS AND SIMULAITON

The vibration of the ship is mainly caused by the movement of the ship. We can analyze the motion of the ship and analyze the force of a certain position of the ship during the rolling process according to Newton's second law. The roll motion model is[7]:

$$(J_\phi + J_\phi)\frac{d^2\phi}{dt^2} + 2N_\phi \frac{d\phi}{dt} + Dh\phi = M_\phi \qquad (14)$$

The rolling moment M_ϕ is the main moment that causes the ship to roll, and the relationship with the wave inclination α_t is

$$\triangle J_\phi \frac{d^2\alpha_t}{dt^2} + 2N_\phi \frac{d\alpha_t}{dt} + Dh\alpha_t = M_\phi \qquad (15)$$

Perform Laplace transform to get $G(s)$

$$G(s) = \frac{\phi(s)}{\alpha_t(s)} = \frac{\triangle J_\phi s^2 + 2N_\phi + Dh}{(J_\phi + \triangle J_\phi)s^2 + 2N_\phi s + Dh} = \frac{\omega_\theta^2(\frac{\triangle J_\phi}{Dh}s^2 + \frac{2\xi_\theta}{\omega_\theta}s + 1)}{s^2 + 2\xi_\theta\omega_\theta s + \omega_\theta^2} \qquad (16)$$

Where $\omega_\theta = \sqrt{\dfrac{Dh}{J_\phi + \triangle J_\phi}} = \dfrac{2\pi}{T_\phi}$, $\xi_\theta = \dfrac{N_\theta}{\sqrt{Dh(J_\phi + \triangle J_\phi)}}$ 。

It is known that the ship rolls the natural period $T_\phi = 12s$ and uses the wave inclination angle $\alpha_t(t)$ as the input signal. The traverse motion output angle curve obtained by MATLAB is shown in Fig. 16.
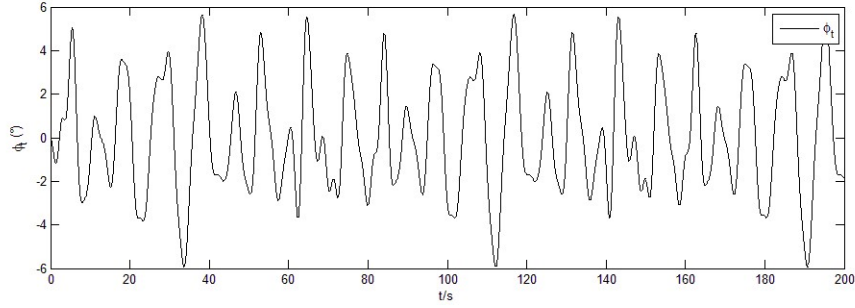
Figure 16: The simulation curve of the ship roll motion

Similar to the roll motion, it is known that the ship's pitch natural period，$T_\phi = 8s$ $\alpha_t(t)$ is used as the input signal, and the output angle curve of the pitch motion obtained by MATLAB is shown in Fig. 17.
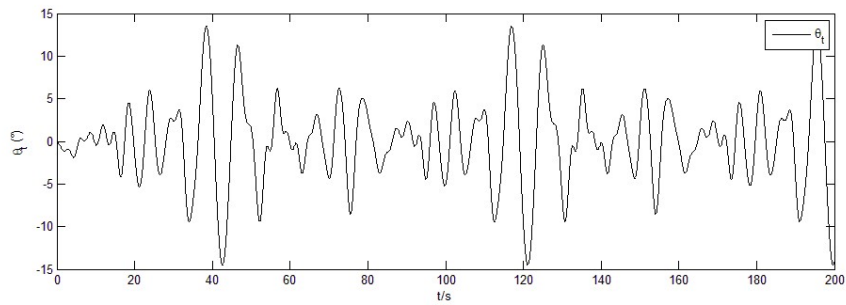

Figure 17: The simulation curve of the ship pitch motion

Using DSPACE to build a semi-physical simulation platform, the HIL (hardware-in-the-loop) experimental study is carried out on the prototype of the marine series-parallel stable platform. By using the table to simulate the actual operating environment, the swing table can realize different amplitude and periodic sinusoidal motion, which will be stable during installation. The pitch direction movement of the platform is perpendicular to the rocking table axis, simulating the ship's pitch direction motion. The two directions are rotated by azimuth rotation to simulate the actual application scenarios.

The HIL experimental system consists of three main components: a real-time processor, an I/O interface, and an operator interface, as shown in Figure 18.

Figure 18: The schematic diagram of HIL

8. Conclusion:

In this article, first, we analyzed the overall structure of the series-parallel platform, and analyzed the motion of the ship series-parallel platform. Based on the wave-wave density formula recommended by ITTC, the ship's pitch and roll motions were carried out. Dynamics and kinematics analysis, the vibration of the ship's series-parallel platform is mainly generated during the movement process, and our analysis of the motion situation can more clearly determine the details of the vibration. The vibration phenomenon is one of the main reasons for the damage of the machine. We analyze the actual surge of the ship in the waves, which is

helpful to understand the vibration of the ship's series-parallel platform. Therefore, we mainly analyze the actual surge of the ship.

10. REFERENCES

[1] Mccormick J B. *Anti-roll device*[D]. US, 1962.

[2] Matthews J. *Horizontal vibration isolation system*[D]. US, 2011.

[3] Kennedy P J, Kennedy R L. *Direct versus indirect line of sight (LOS) stabilization*[J]. IEEE Transactions on Control Systems Technology, 2003, 11(1):3-15.

[4] Dickinson A W, Abolmaesumi P, Gobbi D G, et al. SimITK: *visual programming of the ITK image-processing library within Simulink*[J]. Journal of Digital Imaging, 2014, 27(2):220-230.

[5] Wahab R, Hubble E N. *Simplified Theoretical Methods of Predicting the Motions of a Catamaran in Waves*[J]. Ship Motion, 2006, 15(2):11-17.

[6] Harman T L. *The Student Edition of SIMULINK: Dynamic System Simulation for MATLAB*[M]. Prentice Hall PTR, 2007.

[7] Li Ming, Zhang Renqiang. *Modeling and parameter optimization of passive vibration damping for inertial stability platform*[J]. Electronic Design Engineering, 2018, 26(02): 1-5.

[8]ZHOU Zhifeng, SHI Xuwei, YU Zhuqing. *Structural Design and Finite Element Analysis of Airborne Antenna Stabilization Platform*[J].Manufacturing Automation, 2017, 39(11): 60-64.

[9] Li Lin. *Research on Vibration Reduction Technology of Photoelectric Stabilization Platform* [D]. Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, 2017.

[10] Hong Jin. *Research on the stable structure of the laser communication turntable of the moving platform* [D]. Changchun University of Science and Technology, 2015.

[11] Liu Sichao. *Research on Vibration Drift Performance of Gyro Stabilized Platform*[J]. Tactical Missile Technology, 2014(02): 91-94.

[12] Liang Wei. *Vibration Analysis and Vibration Reduction Design of Ship Stabilization Platform*[J]. Electromechanical Information, 2011(21): 169-170.

[13] Ai Yunhui, Zhou Qingkun, Jin Zhongqing. *Vibration Analysis and Vibration Reduction Design of Shipborne Antenna Stabilization Platform*[J]. New Technology & New Process, 2006(02): 61-64.