Motion response analysis of mining vessel based on ANSYS/AQWA

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Abstract. To analyse the motion response of mining vessel under complex sea conditions and provide theoretical support for the design of heave compensation system, the hydrodynamic analysis software AQWA of three-dimensional potential flow theory was used to analyse the time-frequency response characteristics of mining vessel under the coupling of wind, wave and flow. The response amplitude operator (RAO) of the hull at different wave angles and the six-degree-of-freedom motion response of the hull at different currents were obtained. The results show that the wave angle has an influence on the RAO in the six degrees of freedom, but the frequency corresponding to the RAO peak is relatively close; the time domain analysis results show that the hull roll motion response is larger than the pitch; the maximum response angle of the roll is up to 4°; the effect of sea current velocity on swing, sway, and heave direction is different; the statistical average of wave force in different degrees of freedom is also affected by the wave angle. The simulation results in this paper can provide theoretical guidance for the design of multi-dimensional wave compensation system in mining system. Therefore, when designing wave compensation system, it is necessary to consider the influence of different situations.

1. Introduction
The mining vessel is the sea support portion of the deep sea mining system [1]. For large-scale actual mining operations, the entire mining system needs to remain stable under complex sea conditions. Moreover, in the early stage of theoretical research, its motion state is directly related to the structural design of the underwater operating subsystem and the analysis of fatigue strength. When the sea conditions is extremely complex, the mining production can even be stopped directly.

The size of the main body of the mining vessel is too large, and the external load response prediction is usually carried out by theoretical calculation and computer simulation. Bu Shuxia [2] analyzed the motion response of a damaged vessel in a wave based on the potential flow theory and the modified Bernoulli equation. He Guanghua [2] established a time-domain analysis model of vessel's strong nonlinear motion response based on CIP(Constrained Interpolation Profile) method, which shows that the vessel's strong nonlinear response model based on self-programming has good convergence and accuracy. Chen Zhanyang [4] used a segmented mode oblique wave test on container vessels to study...
the bending moment response and slamming pressure of each wave, and found that high frequency chattering is most sensitive to the wave front state. Tomoki Takami [5] analyzed the rigid body motion patterns and hydrodynamic responses of vessels in different and different local conditions based on the CFD-FEA (Computational Fluid Dynamic-Finite Element Analysis) coupling algorithm. JFM Gadelho [6] used open source hydrodynamics simulation software OpenFOAM to analyze the hydrodynamic coefficients of the heave motion of hulls in three-dimensional deep and shallow water layers. The study shows the additional mass and impact force coefficients obtained through numerical calculations. The coefficients obtained by the traveling wave boundary method have good consistency. Jung-Hyun Kim [7] used the 3D Rankine panel method to analyze the sea surface wave resistance of the 6750-TEU container vessel, and the numerical simulation results are in good agreement with the experimental results.

However, little research has been done on the motion response of mining vessels in waves. In this paper, the three-dimensional potential flow theory is simulated by the marine dynamics module AQWA in ANSYS, and its six-degree-of-freedom motion response is analyzed. Figure 1 is the mining system which contains the mining vessel.

![Mining System Diagram](image)

**Figure 1.** Schematic diagram of the mining system

2. **Mathematical model analysis**

2.1. **potential flow theory**

In ideal fluid, the velocity potential function is often used to describe the velocity distribution in the flow field. When the vessel interacts with the waves, the wave flow field around the hull can be expressed by the velocity potential \( \phi \). According to the Haskind study, the fluid force on the hull section can be obtained from the velocity potential, and the hull motion and wave force can be obtained. The velocity potential \( \phi \) \((x, y, z, t)\) is under the linear assumption, and its solution conditions are as follows [8].

\[
\begin{align*}
\nabla^2 \phi &= 0 \\
\frac{\partial^2 \phi}{\partial t^2} + g \frac{\partial \phi}{\partial z} &= 0 \\
\frac{\partial \phi}{\partial n} &= v(t) n_j \\
\frac{\partial \phi}{\partial z} &= 0
\end{align*}
\]

The initial condition for the time domain problem is:

\[
\begin{align*}
\phi &= 0 \ (t < 0) \\
\frac{\partial \phi}{\partial t} &= 0 \ (t = 0, z = 0)
\end{align*}
\]
The incident wave velocity potential is the velocity potential describing the wave motion, ignoring the hull motion and the reflection of the waves [9]. The effect of the motion of the hull caused by waves on the surrounding flow field is the radiation potential. In this paper, the motion response of a mining vessel under waves is studied. In the initial state, the hull is stationary, so the radiation potential is not considered. Wave motion encounters an impenetrable hull surface and produces reflections, which are called diffracted waves. The heave and pitch motion generated by the hull under the action of external waves, the velocity potential around it can be superimposed by the following two velocity potentials:

\[ \phi = \phi_w + \phi_D + \phi_R \]  

Where: \( \phi_w \) is the incident wave velocity potential; \( \phi_D \) is the diffraction wave velocity potential; \( \phi_R \) is the radiation wave velocity potential, and the \( \phi_R \) can be ignored.

The velocity potential \( \phi \) satisfies the four conditions shown in equation (1). The fluid pressure changes caused by the two velocity potentials are respectively recorded as \( PW \), \( PD \), and the fluid pressure at this point is divided along the sectional area to obtain the following two kinds of fluid dynamics: incident wave interference force and diffraction force.

According to the theory of micro-amplitude waves, the incident wave velocity potential is:

\[ \phi_w = \frac{g}{w} \sin(k\zeta + wt + \varepsilon) \]  

Use coordinate transformation to get:

\[ \phi_w = \frac{g}{w} e^{kx} \sin(kx\cos\chi - kysin\chi + we t) \]  

According to the Bernoulli equation, the pressure generated by the incident wave on the hull section can be obtained.

\[ P_W = \rho \frac{\partial \phi_w}{\partial t} = \rho g e^{kx} \cos(kx\cos\chi - kysin\chi + we t) \]  

The force is divided along the cut area to obtain the main wave interference force on the cut surface:

\[ F_1 = 2 \int_0^{y_w} P_W dy \cos(kx\cos\chi + we t) \times \int_0^{y_w} e^{kx} \cos(ky\sin\chi) dy \]  

Where: \( y_w \) is the half width of the profile waterline; \( \chi \) is the wave angle.

Similarly, the wave force can be obtained.

\[ F_3 = (\frac{\omega}{\omega e} N - \bar{U} \frac{\partial m}{\partial x}) \bar{U}_x + (m + \frac{\bar{U}}{\omega e} \frac{\partial N}{\partial x}) \bar{U}_x \]  

Where: \( \bar{U}_x \) is the average equivalent acceleration, \( \bar{U}_x \) is the trajectory velocity of the fluid particle at the midline of the hull, \( m \) is the additional mass, and \( N \) is the damping coefficient.

2.2. Vessel motion model

The schematic diagram of the six-degree-of-freedom movement of the mining vessel studied in this paper is shown in Figure 2. Also assume that the hull is symmetrical about the 0yz plane. The illustrated mining vessel has the following characteristics compared to conventional vessels: (1) the speed of mining vessel is 0 during operation; (2) the mining vessel has complex subsystems under water. However, this paper studies the motion response of the mining vessel under the action of the waves, and the radial dimension of the lifting pipe near the bottom of the mining vessel is small relative to the mining vessel, as shown in Figure 1. Therefore, the quality of its subsystem (including the riser; pump; buffer; miner etc.) can be converted to the mining vessel regardless of its size effect.

The movement of the vessel under the waves is a six-degree-of-freedom rigid body motion. According to the coordinate system, its motion can be described as yawing, rolling, pitching, heaving, surging, and swaying [10]. The pose in space is represented by coordinates \( \eta = (x, y, z, \phi, \theta, \psi) \), where \( x, y, z \) represent the lateral, longitudinal, and vertical positions, respectively; \( \phi, \theta, \psi \) represent roll, pitch, and yaw angle. The vector \( \sigma = (\mu, \nu, \omega, p, q, r) \) respectively represents the translational speed and
rotational angular velocity of the hull in the corresponding direction in the ocean wave. The vector \( \mathbf{r} = (x, y, z, k, m, n) \) represents the force and moment experienced by the hull in the motion coordinate system, respectively.

\[
\tau = (x, y, z, k, m, n)
\]

\( \eta \) is the vessel motion response, and \( f \) is the wave force. \( a_{ij}, b_{ij}, c_{ij} \) (i, j = 3 or 5) represent additional mass, additional damping, and restoring force coefficient, respectively.

### 3. Implementation method

#### 3.1. Calculation model

In this paper, the technical parameters of the mining vessel in reference are taken as the research object [12], and the main geometrical dimensions of the hull are shown in Table 1.

| Parameters        | symbols | Value   |
|-------------------|---------|---------|
| Long line length  | L       | 288     |
| Boat width        | B       | 48.5    |
| Draught           | T       | 18.8    |
| Vessel weight     | G       | 354100  |

In the AQWA potential flow theory, it is required to have more than 7 units in one wavelength direction to ensure the diffraction precision[13]. In this simulation calculation, the grid size is set to 0.5m and the total number of grids is 1025648. The simulated deep sea environment has a water depth of 1000m and the sea area has a length and width of 458 m*642 m. The established AQWA hull calculation model is shown in Figure 3.

Figure 2. Schematic diagram of the hull six degrees of freedom motion

According to the STF slicing method [11], considering the coupling motion of the two degrees of freedom of heave and pitch and the coupling equation of roll, pitch and yaw, the following equations can be obtained:

\[
\begin{align*}
(m + a_{33})\ddot{\eta}_3 + b_{33}\dot{\eta}_3 + c_{33}\eta_3 + a_{35}\ddot{\eta}_5 + b_{35}\dot{\eta}_5 + c_{35}\eta_5 &= f_3 e^{-iw_0 t} \\
(a_{35}\ddot{\eta}_3 + b_{53}\dot{\eta}_3 + c_{53}\eta_3 + (I_{55} + a_{35})\ddot{\eta}_5 + b_{55}\dot{\eta}_5 + c_{55}\eta_5 &= f_5 e^{-iw_0 t}
\end{align*}
\]

Where: \( m \) is the displacement of the vessel, \( I_{55} \) is the moment of inertia of the vessel relative to the y-axis, \( I_{55} = mG L^2 \), \( \eta \) is the vessel motion response, and \( f \) is the wave force. \( a_{ij}, b_{ij}, c_{ij} \) (i, j = 3 or 5) represent additional mass, additional damping, and restoring force coefficient, respectively.
3.2. Simulated environmental conditions

In this simulation analysis, the wind spectrum selects the NPD spectrum and the average wind speed is 20 m/s. Considering the actual sea conditions, the current is defined by an externally input CSV table, defining the sea current velocity of 1.2 m/s at the surface (z = 0), the sea current velocity of 0 m/s at -100 m, a sea current direction of 0°, and a wave spectrum of JONSWAP spectrum. The specific parameters are shown in Table 2:

| Parameter          | Symbol | Value          |
|--------------------|--------|----------------|
| significant wave height | Hs     | 2.5            |
| peak period        | Tp     | 7.1            |
| spectral wind factor | Gamma  | 1.0            |
| direction          | /      | 0°, 30°, 60°, 90° |
| wave seed          | /      | 100            |

In the simulation, the mass of the hull is represented by adding mass points, and the position of the mass point is coincident with the centre of the float, and the moment of inertia of the geometry float is defined. The calculated wave direction is 0° ~180°, and the lowest calculation frequency is set to 0.2 Hz (31.42 s). The highest calculation frequency is determined by the grid size. It is automatically set by the program according to the calculation model in Ansys. After preliminary setting, a wave surface cloud image is obtained as shown in Fig. 4.

4. Simulation results analysis

4.1. Response Amplitude Operator (Rao)

The response amplitude operator characterize the hydrodynamic performance of the mining vessel. The hydrodynamic simulation software Aqwa uses a series of regular wave simulations to obtain the Rao value of the overall motion response of the mining vessel. Figure 5 shows the mining vessel Rao in the four directions of wave angles of 0°, 30°, 60° and 90°.

Fig. 5(a)–(f) show that under different wave incident angles, Rao in the same degree of freedom has a similar trend, and the frequency corresponding to the peak of each degree Rao is not much different, which is related to the natural frequency of hull.

It can be seen from Fig. 5(a)–(c) that the Rao values of the same degree of freedom have similar trends under different wave angles, and the simulation results are in agreement with the reference [14]. The wave angle is 0°, the Rao value of the roll and yaw is close to zero. However, in the pitching degree of freedom, the Rao value of the wave angle of 0° is similar to the amplitude of the 30° wave angle. When the wave angle is 0° and 30°, the Rao value has a distinct double peak, and the second peak point corresponds to a frequency higher than the first peak point, but the Rao value at this time is lower than that of the first peak point. Comparing Fig. 5(d), when the wave angle is 0° and 30°, the Rao curve in the surging direction also shows a small peak during the descent, and its corresponding frequency is the same as that of the second peaks in Fig. 5(b). This shows that the lower wave angle has a strong coupling between the pitch and surge direction. The wave angle is 90°, that is, under the transverse wave condition, the rolling Rao value is much higher than the other wave angles. This is because the length of the mining...
vessel is relatively large. Under the transverse wave condition, the wave force acts on the length of the hull, and the moment of the hull subjected to the wave force is large.

It can be seen from Fig. 5(d)-(f) that under different wave angles, the Rao displacement amplitude value generally decreases with the increase of frequency. When the frequency is greater than 0.2 Hz, the Rao value of the surge, sway, and heave motion tends to zero. Under the action of 90° transverse waves, the Rao value of sway and heave is larger than that of other wave angles; and with the increase of the wave angle, the Rao value increases, indicating that the swaying and heaving is more significant under transverse wave state. As can be seen from Fig. 5(f), the Rao value of the four wave angles appears to be a jump phenomenon at a frequency of about 0.15 Hz, and the jump phenomenon under the action of the transverse waves is significantly higher than the other three cases. This is because the motion response of the hull in the waves is not only affected by the external load, but also the natural frequency and inertia of the hull. The heave motion is affected by inertia beyond the natural frequency.

Figure 5. Amplitude response operator under different wave angles
4.2. Time domain results analysis
The Rao value can be regarded as the steady-state analysis of the mining vessel under the action of waves. In complex sea conditions, the transient response situation plays a decisive role in the safety and stability of the mining vessel. Therefore, under the condition of time domain analysis, the motion response in the three degrees of freedom of roll, pitch and heave is emphasized. In Fig. 6(a), the direction of incidence of wind, wave and current is 90°; in Fig. 6(b), the direction of incidence of wind, wave and current is 0°; in Fig. 6(c), the angle of incidence of wind, wave and current are both 0°.

\[ \text{Figure 6. Time domain analysis curve} \]

It can be seen from the motion response time history graphs in Fig. 6 (a) and (b), in general, the trend of the roll and pitch motion response law is basically the same. Under time domain analysis, the rolling and pitching motions are very intense, and the maximum transient rocking angle reaches 3° in the rolling state, while in the pitching state, the maximum transient rocking angle is only 1.5°, which is about one second of the rolling state. In Fig. 6(c), heave motion is significantly different from the roll and pitch motion response. At the beginning, the heave motion responded quickly, but the response trend decreased rapidly; when t > 200 s, the heave motion response vibrated at a low amplitude near the zero line. It shows that the mining vessel has strong wave resistance in the heave direction. This is because the mining vessel is subjected to its own gravity and the gravity of the underwater mining subsystem in the vertical direction. Therefore, it has a large inertia in this direction.

4.3. Hull motion response under different currents
Under the 6-level wave, the maximum sea current velocity is as high as 1.7 m/s. In order to further study the motion response of the hull. Figure 7 shows the results of comparative analysis of hull motion response at the flow velocity 0.5 m/s, 1.2 m/s, 1.7 m/s. Among them, in the state of rolling and swaying, the direction of the sea wave is set to 90°; in the pitching and surging state, the direction of the wave is 0°, and the wind spectrum selects the NDP spectrum, and the wind speed at the reference point of 10 m is set to 10 m/s, the direction is consistent with the direction of the wave spectrum. The comparative time domain analysis results as shown in Fig. 7 are obtained, which is in agreement with the reference simulation results [15].
It can be seen from Fig. 7(d)–(f) that under different currents, the hull's motion response under the combined action of wind and wave shows a similar change. During the increase of sea current velocity from 0.5 to 1.7, the motion response in the heave direction is almost constant, indicating that the heave motion response is not affected by the current velocity. It can be seen from Fig. 7(d) and (e) that the current velocity has the greatest influence on the motion in the direction of surge and sway. The current velocity increases from 0.5 m/s to 1.7 m/s, and the stability value of the displacement increases about two time, and the greater the flow rate, the greater the response speed. The sway direction also shows obvious changes, but the steady value of displacement at different flow rates is almost constant, and the peak value of the sway response increases with increasing flow rate, increase from 0.26 at 0.5m/s to 0.36 at 1.7m/s; the magnitude of the increase is much smaller than the direction of the surging.

In Fig. 7(a)–(c), the motion response of the three rotational degrees of freedom is similar at different currents. As the current velocity increases, the amplitude of the motion response vibration in the roll direction decreases. And the duration of low amplitude vibration increase. The direction of the yaw is similar to the change of the roll direction It shows that the increase of the current velocity can increase
the stability of motion in the direction of roll and yaw. However, observing Fig. 7(b), it can be found that the magnitude of the motion response in the pitch direction increases as the velocity of current increases.

### 4.4. Statistical analysis of wave forces at different wave angles

In order to further analyze the variation law of wave force with wave angle. In this paper, through the AQWA post-processing module, the wave forces in three moving directions are obtained, and the absolute values are taken for all the data, and then the average value is obtained. After processing, the three different moving directions are obtained under different wave angles as shown in Fig.8. Among them, the wave force direction changes to 0°, 30°, 60°, 90°, and the current velocity is 1.7 m/s.

It can be seen from Fig. 8 that the average size of the wave force differs greatly under different wave angles. The wave force decreases with the increase of the wave angle in the X and Z direction, while the wave force in the Y direction increases with the increase of the wave angle which is different from the previous two. It can be seen that the heave motion response is more affected by the wave angle than the surging direction. The maximum angles of the wave forces in the three directions of X, Y, and Z are close at different wave angles, but the minimum value in the Y direction is much smaller than the X and Z directions.

![Figure 8. Average of wave forces at different wave angles](image)

### 5. Conclusion

The motion response of the mining vessel under the external load in the deep sea mining system is the key basis for the design and analysis of the mining system. In this paper, the ANSYS/AQWA hydrodynamic simulation software is used to analyze the hull motion response under complex sea conditions, and the following conclusions are drawn:

1. The Rao is sensitive to the wave angle. With the increase of the wave angle, the Rao has different trends in different degrees of freedom; however, the frequencies corresponding to the Rao peak are same.

2. Under the time domain analysis, the maximum angle of the sway direction is as high as 4°, which is much larger than the surge direction, the ability to stabilize in the direction of the heave is higher than in other directions.

3. The current velocity has a great influence on the sway and the surge, and the direction of the heave is almost unaffected by the current velocity.

4. The wave angle has a greater influence on the statistical average of the wave force, but the sensitivity of the heave direction is greater than the swaying and surging direction.

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