

AQWA-Based Motion Response Analysis of a Suezmax FPSO

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Abstract

To investigate the motion response characteristics of a long-term moored floating production, storage and offloading unit (FPSO) under wave action, a Suezmax FPSO was selected as the research object. Based on three-dimensional linear potential-flow theory and wave radiation/diffraction theory, numerical simulations of the motion responses under wave loading were conducted using AQWA. The six-degree-of-freedom response amplitude operators (RAOs), first-order wave excitation forces, and time-domain motion response characteristics of the platform under different wave directions were systematically analysed. The effects of wave frequency and wave direction on the seakeeping performance of the FPSO were also discussed. The results show that the six-degree-of-freedom motion responses of the FPSO exhibit significant directional dependence. The RAO peaks are mainly concentrated in the low-frequency range, and the motion responses are significantly amplified when the wave frequency approaches the natural frequency of the platform. Moreover, the RAO peaks are not determined solely by the maximum value of any single type of excitation force, but result from the combined effects of the Froude–Krylov force, diffraction force, and other hydrodynamic forces. The time-domain analysis further verifies the frequency-domain results, indicating that the pitch and roll responses increase most significantly under severe sea conditions.

Keywords

FPSO; AQWA; Motion Response Analysis.

1. Introduction

With the continuous growth of global energy demand and the gradual depletion of onshore oil and gas resources, the development of offshore oil and gas resources has become an important direction in the energy sector. Floating production platforms are currently widely used worldwide. Among them, floating production, storage and offloading units (FPSOs) have been extensively applied in deepwater oil and gas field development because of their broad environmental adaptability, large oil storage capacity, operational flexibility, reusability, and favorable economic performance^[1]. Among the available FPSO construction schemes, converting an existing large oil tanker offers the advantages of a relatively short conversion period and good economic efficiency. Suezmax tankers, characterized by their large deadweight capacity, moderate principal dimensions, and mature hull forms, represent a typical and suitable base vessel for FPSO conversion. Unlike conventional seagoing vessels, FPSOs are generally stationed in a specific sea area for extended periods and are subjected to the combined effects of wind, waves, currents, and mooring constraints. Their motion responses not only affect topside operations, personnel comfort, and offloading safety, but also

influence the cyclic load levels of the hull structure and associated systems. Therefore, considerable research has been conducted on the hydrodynamic motion responses of offshore platforms under marine environmental conditions.

Current studies are primarily based on three-dimensional potential-flow theory, with frequency-domain and time-domain hydrodynamic analyses conducted using software packages such as SESAM and AQWA, which have become the mainstream approaches in offshore engineering. Wang et al.^[2] investigated the hydrodynamic performance and motion response characteristics of a novel semi-submersible platform under conventional sea conditions. Their results revealed significant coupling among heave, roll, and pitch motions, indicating that particular attention should be paid to the platform motion responses when the wave period approaches its natural heave period. Fang Shixiang et al.^[3] used AQWA to compare the effects of heave plates with different geometries on the heave performance of a cylindrical FPSO. Time-domain simulations were performed under various operating conditions to compare the corresponding heave responses, and the safety of the designed mooring system was also evaluated. Ji Linshuai et al.^[4] employed AQWA to investigate the hydrodynamic performance of an FPSO under different loading conditions and wave incident angles. Ibinab et al.^[5] analysed the motion responses of an FPSO and calculated its six-degree-of-freedom (6-DOF) response amplitude operators (RAOs) using ANSYS AQWA. A MATLAB-based program was also developed to validate the calculated heave responses under head-sea conditions.

The above studies demonstrate that motion response analysis of FPSOs provides an important basis for evaluating overall arrangement, operational adaptability, and structural safety. Therefore, this study takes a Suezmax FPSO as the research object. Based on potential-flow theory and wave radiation/diffraction theory, numerical simulations of the frequency-domain and time-domain motion responses of the vessel under wave loading are conducted using the hydrodynamic analysis software AQWA.

2. Theoretical Foundations and Hydrodynamic Model

2.1 Three-Dimensional Potential Flow Theory

For large-scale floating structures such as FPSOs, the characteristic dimensions of the hull may be comparable to the incident wavelength. Consequently, the incident wave field is significantly disturbed by the wetted surface of the hull, and wave diffraction effects should be considered when calculating first-order wave loads and motion responses. Therefore, three-dimensional radiation/diffraction theory is adopted as the basis for the frequency-domain hydrodynamic analysis in this study. The fluid is assumed to be incompressible, inviscid, and irrotational, while the hull is assumed to undergo small-amplitude rigid-body motions in six degrees of freedom^[6,7].

Within the frequency-domain potential-flow framework, the total velocity potential can be decomposed into the incident-wave potential, diffraction potential, and radiation potential:

$$\phi = \phi_i + \phi_d + \phi_r \quad (1)$$

Where:

ϕ_i is the incident-wave potential, ϕ_d is the diffraction-wave potential, ϕ_r is the radiation-wave potential.

The incident-wave velocity potential is determined by the prescribed regular incident wave; the diffraction-wave velocity potential represents the disturbance of wave propagation caused by the hull; and the radiation-wave velocity potential is induced by the six-degree-of-freedom motions of the platform.

Compared with conventional methods developed for slender hulls, three-dimensional potential-flow theory can more accurately account for the influence of hull geometry on the surrounding flow field.

It has therefore become the theoretical basis of mainstream hydrodynamic software packages such as AQWA and SESAM and is capable of meeting the requirements of frequency-domain seakeeping analysis for FPSOs.

2.2 Wave Load Calculation Theory

According to the linearized Bernoulli equation, the first-order hydrodynamic pressure can be expressed as:

$$p = -\rho \frac{\partial \phi}{\partial t} \quad (2)$$

Where:

p -first-Order Wave-Induced Dynamic Pressure(Pa); ρ -seawater Density($\text{kg}\cdot\text{m}^{-3}$); ϕ -velocity Potential Function; t -time(s).

By integrating the hydrodynamic pressure over the wetted surface of the hull, the wave-induced forces and moments can be obtained:

$$F_w = \iint_{S_B} -p \mathbf{n} ds \quad (3)$$

$$M_w = \iint_{S_B} -p(\mathbf{r} \times \mathbf{n}) ds \quad (4)$$

Where:

S_B is the Hull Wetted Surface Area; $\mathbf{n}$ is the Unit Outward Normal Vector to the Wetted Surface; $\mathbf{r}$ is the Position Vector of the Integration Point Relative to the Platform's Centre of Gravity.

AQWA discretizes the wetted surface of the hull using the boundary element method. By solving the boundary integral equation for the velocity potential, the wave excitation forces, added-mass coefficients, and radiation-damping coefficients of the platform at different wave frequencies are obtained.

Within linear potential-flow theory, the first-order wave excitation force consists of the Froude–Krylov force and the diffraction force.

$$F^{(1)}(\omega, \beta) = F_{FK}(\omega, \beta) + F_D(\omega, \beta) \quad (5)$$

Where;

$F^{(1)}$ is the First-Order Wave Excitation Force, F_{FK} is the F–K Forces, F_D is the Diffraction Forces.

The Froude–Krylov force is obtained by integrating the undisturbed incident-wave pressure field over the wetted surface of the hull, whereas the diffraction force arises from the scattering of the incident waves by the hull.

2.3 Hydrodynamic Model

The research object is a Suezmax FPSO operating under the half-load condition. The principal dimensions of the FPSO model are listed in Table 1.

Table 1. Main geometric and inertial parameters of the Suezmax FPSO

Parameter	Value
Length Overall /m	278.9
Breadth Moulded /m	47.0
Depth Moulded /m	25.9
Draft /m	12.2
Roll Mass Moment of Inertia /kg·m ²	2.28×10 ⁹
Pitch Mass Moment of Inertia /kg·m ²	3.14×10 ¹⁰
Yaw Mass Moment of Inertia /kg·m ²	3.25×10 ¹⁰

Based on the design drawings, a numerical model of the Suezmax FPSO was established and its wetted surface was discretized into a hydrodynamic mesh, as shown in Fig. 1.

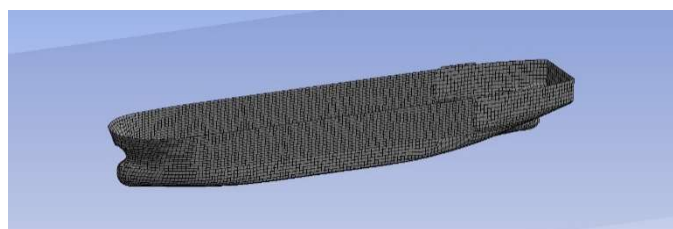


Fig. 1 Mesh Model of the Suezmax FPSO

2.4 Wave Heading

The wave heading angle is defined as the angle between the incident-wave propagation direction and the vessel-fixed coordinate system, as illustrated in Fig. 2. Owing to the pronounced length-to-beam ratio of the FPSO hull, head-sea and beam-sea conditions are generally associated with different dominant degrees of freedom. To highlight the differences in motion responses under representative wave headings, four typical wave directions, namely 45°, 90°, 135°, and 180°, are examined in the frequency-domain motion analysis. The results comprehensively reveal the motion response characteristics of the hull under different wave headings and can provide a basis for mooring-system design and operational-window assessment.

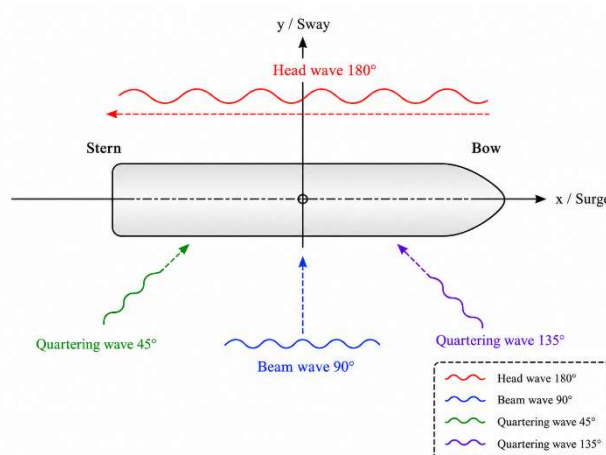


Fig. 2 Schematic illustration of wave directions for the FPSO

3. Numerical Simulation Results and Analysis

Based on the hydrodynamic numerical simulations, the frequency-domain results are used to establish the fundamental relationship between wave headings and the corresponding sensitive degrees of freedom. The Froude–Krylov and diffraction-force components are examined to identify the composition of wave excitation at different frequencies. The time-domain results are used to evaluate the fluctuation ranges of the motion responses under the combined effects of the actual spectral bandwidth and random wave phases.

3.1 Frequency-Domain Motion Response RAOs

A vessel has six degrees of freedom, as illustrated in Fig. 3. Under wave excitation, the hull undergoes coupled motions in six degrees of freedom, which can be classified into translational motions along the coordinate axes and rotational motions about the coordinate axes. The translational motions comprise surge along the (x)-axis, sway along the (y)-axis, and heave along the (z)-axis, with displacement measured in units of length. The rotational motions comprise roll about the (x)-axis, pitch about the (y)-axis, and yaw about the (z)-axis, with their amplitudes measured in angular units^[8].

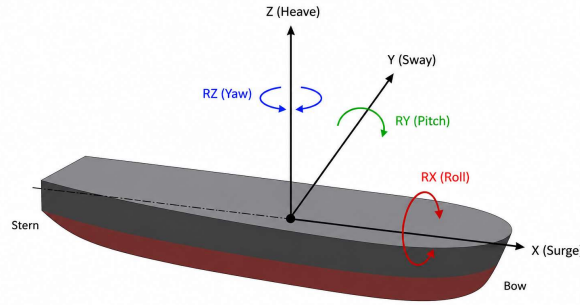


Fig. 3 Schematic Illustration of the Six Degrees of Freedom Motions of an FPSO

The frequency-domain equations of motion for the six degrees of freedom can be expressed as:

$$[-\omega^2(M + A(\omega)) + i\omega B(\omega) + C]\xi(\omega, \beta) = F(\omega, \beta) \quad (6)$$

Where:

M is the Structural Mass Matrix, $A(\omega)$ is the Added-Mass Matrix, $B(\omega)$ is the Radiation-Damping Matrix, C is the Hydrostatic Restoring Matrix, ξ is the Motion Response Vector, F is the First-Order Wave Excitation Force Vector, ω is the Wave Angular Frequency, β is the Wave Heading Angle.

To quantitatively characterize the motion response of the FPSO under wave excitation, the response amplitude operator (RAO) is introduced and defined as the ratio of the hull motion response amplitude to the incident wave amplitude:

$$RAO_{j(\omega, \beta)} = \frac{|\xi_j(\omega, \beta)|}{a} \quad (7)$$

Where:

$RAO_{j(\omega, \beta)}$ is the Response Amplitude Operator of the j th Degree of Freedom, $|\xi_j(\omega, \beta)|$ is the Motion Response Amplitude of the j th Degree of Freedom, a is the Regular-Wave Amplitude.

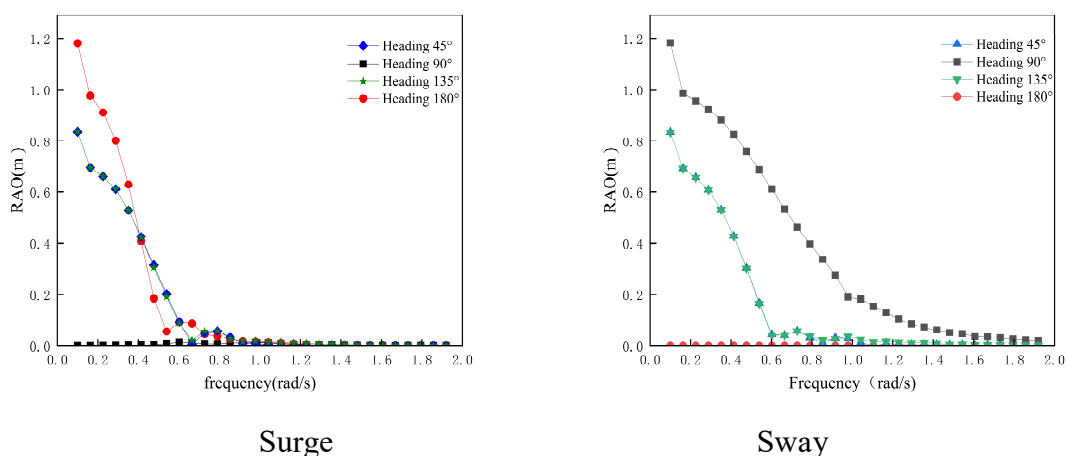
Ocean random waves can be regarded as the linear superposition of regular waves with different frequencies, amplitudes, propagation directions, and initial phases. Therefore, the motion responses of a vessel in random seas can be obtained by combining the RAOs of each degree of freedom with the wave spectrum. The RAO describes the variation in vessel motion response with wave frequency under unit wave-amplitude excitation and is an important indicator for evaluating vessel seakeeping and motion performance.

Fig.4 presents the variations in the six-degree-of-freedom RAOs with wave frequency under four wave headings. Overall, the motion responses in all degrees of freedom exhibit pronounced frequency selectivity and directional dependence, with the main responses concentrated in the low- and medium-low-frequency ranges. When the wave frequency exceeds approximately 1.2–1.4 rad/s, the RAOs of most degrees of freedom decrease to relatively low levels, indicating that the FPSO is more sensitive to long-period waves.

For surge, the largest RAO occurs under the 180° head-sea condition, followed by the responses under the 45° and 135° oblique-wave conditions, whereas the response under the 90° beam-sea condition is nearly zero. This indicates that surge is primarily governed by longitudinal wave excitation. Sway exhibits the opposite trend: the strongest response occurs under the 90° beam-sea condition, intermediate responses are observed at 45° and 135°, and the response under the 180° head-sea condition is almost negligible. Heave responses are observed under all wave headings. In particular, a distinct peak appears at approximately 0.60 rad/s under the 90° beam-sea condition, indicating strong coupling between the beam-sea excitation and the heave dynamic characteristics of the platform near this frequency.

Roll is the most sensitive motion mode to wave heading. A pronounced peak occurs near 0.90 rad/s under the 90° beam-sea condition. Relatively evident roll responses are also observed under the 45° and 135° oblique-wave conditions, whereas the response under the 180° head-sea condition is nearly zero. Pitch is mainly excited by head seas and oblique waves, with peak responses occurring within the frequency range of approximately 0.40–0.50 rad/s. Yaw responses occur primarily under the 45° and 135° oblique-wave conditions, indicating that the asymmetric longitudinal and transverse excitation induced by oblique waves can readily cause horizontal-plane rotational motion of the platform.

In summary, under the 180° head-sea condition, particular attention should be paid to surge, heave, and pitch. Under the 90° beam-sea condition, sway, heave, and roll are the primary motions of concern. Under the 45° and 135° oblique-wave conditions, the coupled responses of roll, pitch, and yaw should be carefully considered. Among these responses, the roll peak under the 90° beam-sea condition is the most pronounced and represents the critical response governing the operational adaptability and motion safety of the Suezmax FPSO.



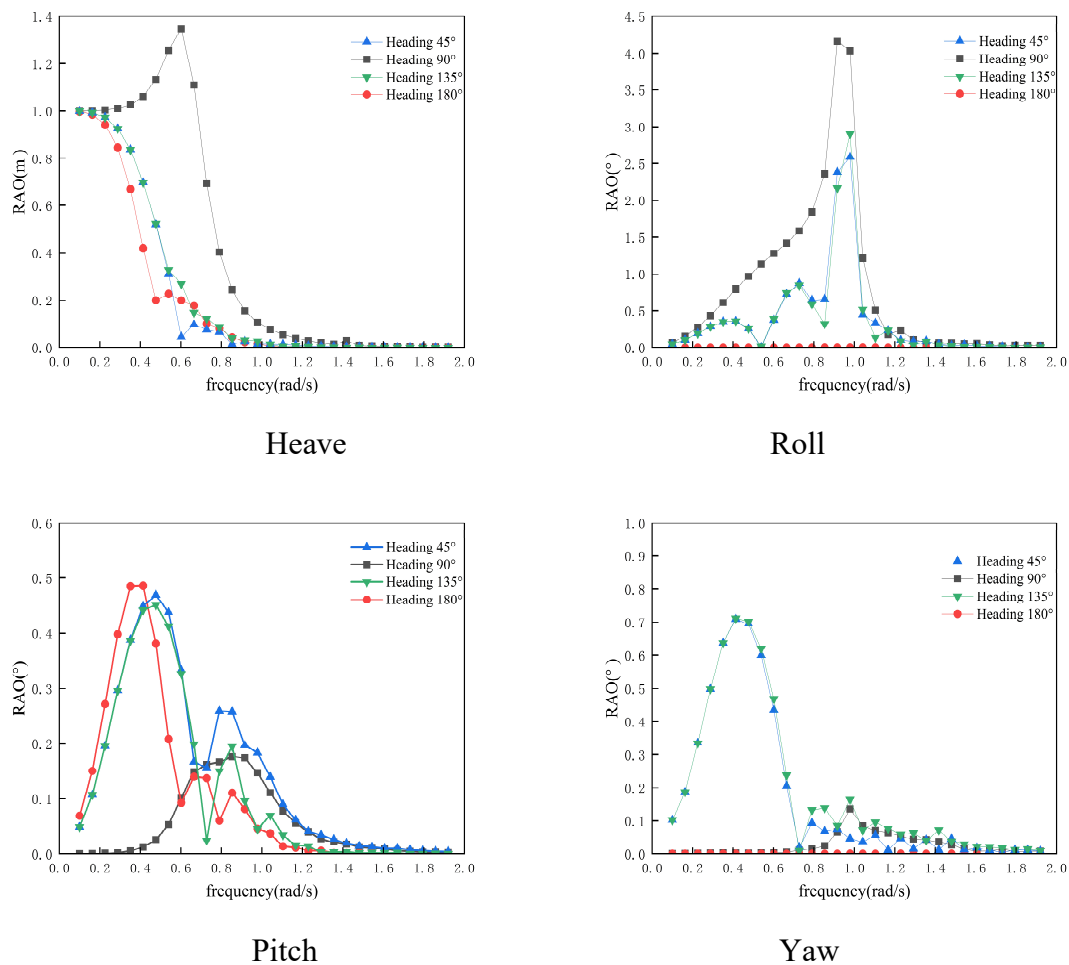


Fig.4 Frequency-Domain RAOs of the FPSO

3.2 Wave Excitation Forces

The external wave excitation acting on the FPSO mainly consists of the Froude–Krylov force and the diffraction force. Together, these components constitute the first-order wave excitation force in the frequency-domain equations of motion of the FPSO and play an important role in determining the hull motion responses. Figs 5 and 6 show the frequency-domain distributions of the Froude–Krylov and diffraction forces, respectively, in the six degrees of freedom of the FPSO. Their peak frequency ranges and relative contributions vary with the degree of freedom and wave heading.

For surge, the excitation forces are relatively significant under the 180° head-sea condition and the 45° and 135° oblique-wave conditions, whereas they are nearly zero under the 90° beam-sea condition. This indicates that the surge excitation is primarily governed by the longitudinal component of the incident waves. For sway and roll, the largest excitation occurs under the 90° beam-sea condition, with distinct peaks appearing in the low- to medium-frequency range, whereas both components are almost negligible under the 180° head-sea condition. Heave is subjected to considerable low-frequency excitation under all wave headings, with a relatively slower decay under the 90° beam-sea condition. Pitch excitation is most pronounced under head seas and oblique waves, with its peaks concentrated within the frequency range of approximately 0.4–0.5 rad/s. Yaw is mainly excited under the 45° and 135° oblique-wave conditions, indicating that the asymmetric longitudinal and transverse pressure distributions induced by oblique incident waves are important contributors to the yaw moment.

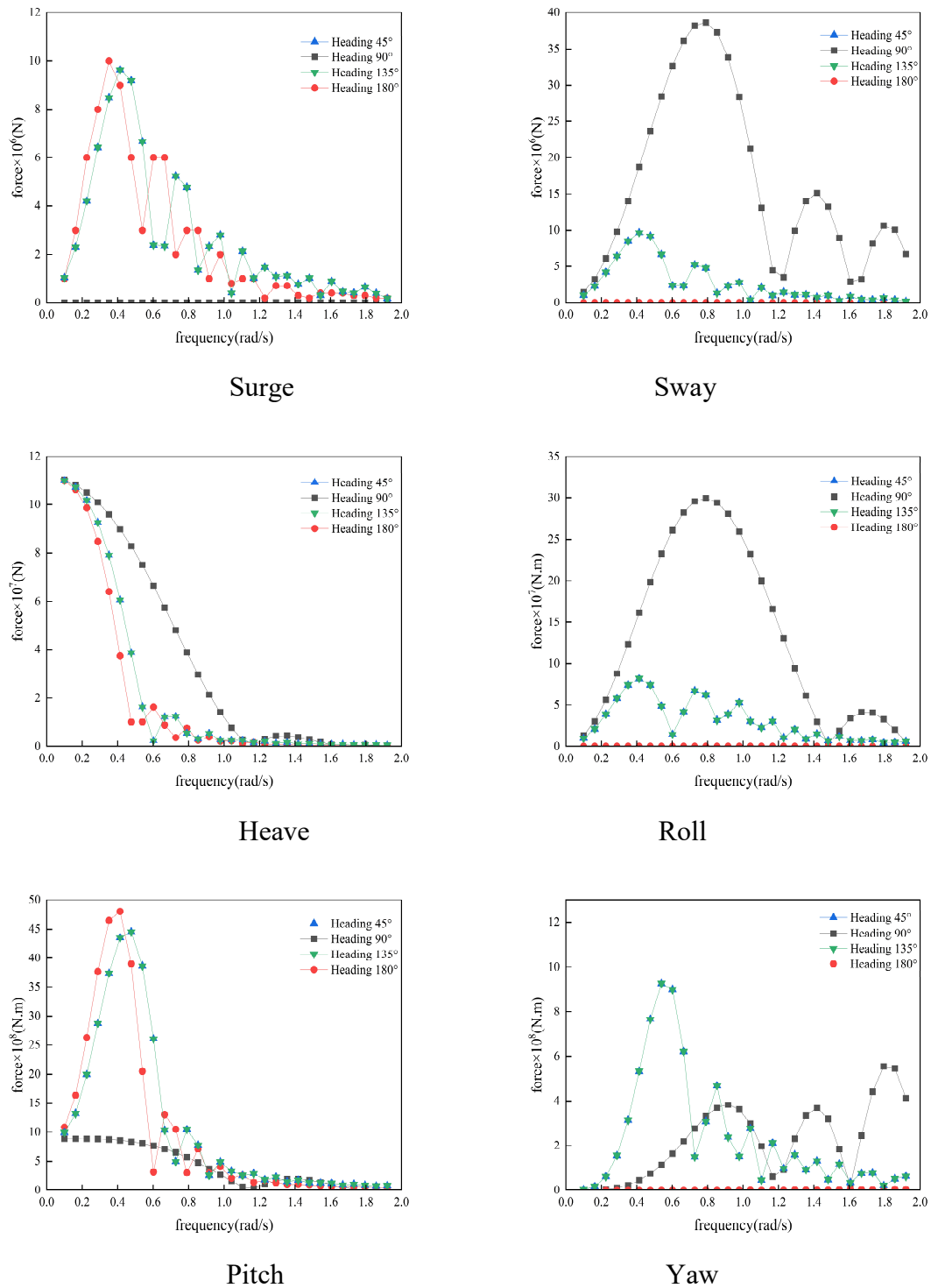


Fig.5 Froude-Krylov Forces RAO of the FPSO

Compared with the Froude-Krylov force, the diffraction force exhibits stronger fluctuations and acts over a broader frequency range. For sway and roll, the diffraction excitation under the 90° beam-sea condition is significantly greater than that under the other wave headings, with several local peaks occurring at different frequencies. This indicates that the transverse geometry of the hull has a pronounced scattering effect on the incident wave field. The diffraction force in heave is also evident under all wave headings, with a relatively large peak appearing near 0.6 rad/s under the 90° beam-sea condition.

The diffraction forces associated with pitch and yaw also exhibit clear directional dependence. In particular, relatively large diffraction excitation occurs in the intermediate-frequency range under the 90° beam-sea condition. Although most curves under the 45° and 135° wave headings are relatively similar, differences remain in some local peaks, mainly because the bow and stern geometries of the FPSO are not completely symmetric.

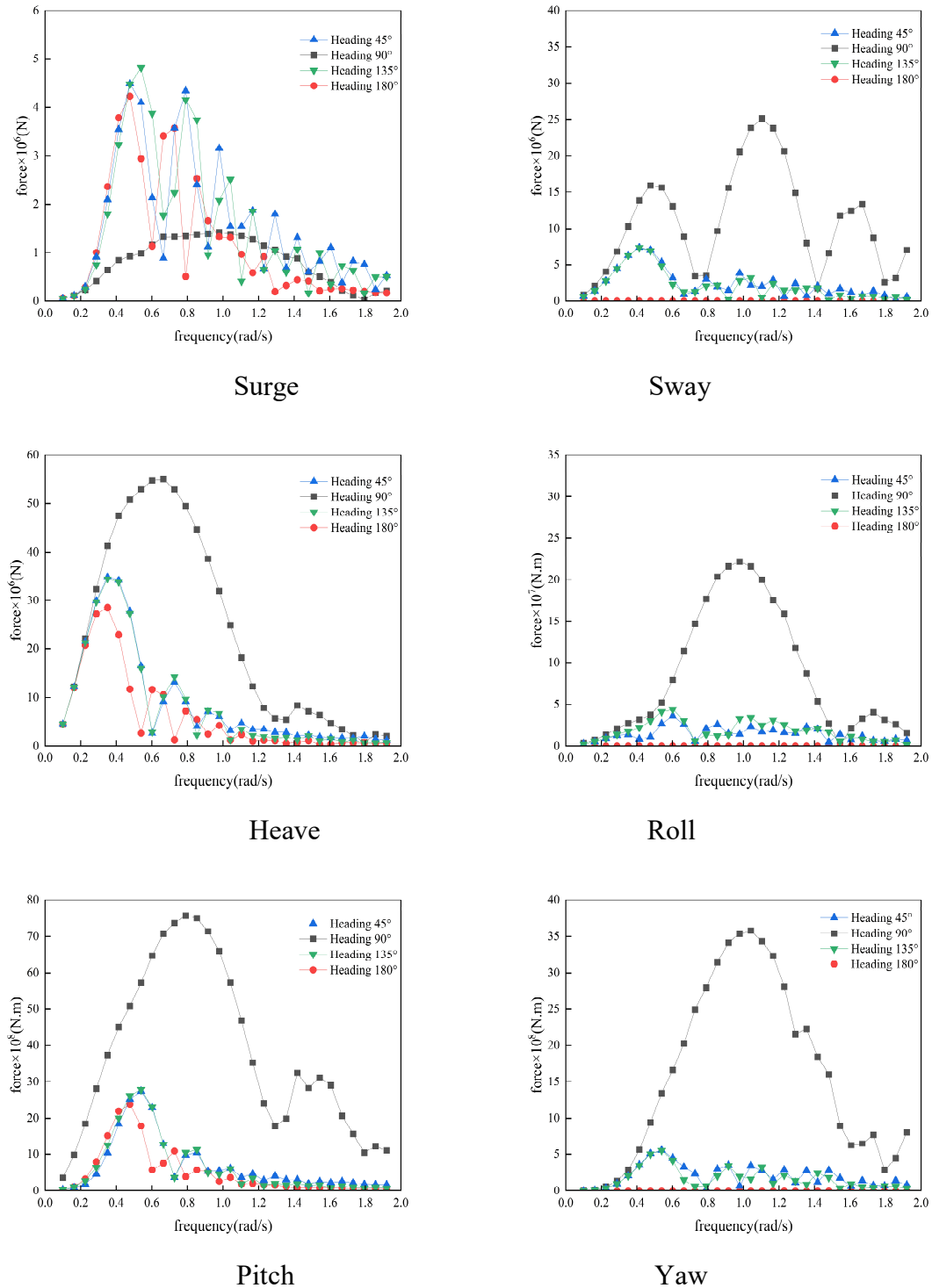


Fig. 6 Diffraction Forces RAO of the FPSO

It can therefore be concluded that the RAO peaks are not determined solely by the maximum Froude–Krylov force or diffraction force. Instead, they result from the combined effects of the first-order wave excitation force formed by these two components, together with the added mass, radiation

damping, and hydrostatic restoring force. The principal amplification regions of surge and pitch show good correspondence with the peaks of the Froude–Krylov force under head-sea conditions, whereas roll and yaw are more sensitive to diffraction effects. In subsequent optimization studies involving bilge keels, loading conditions, or mooring parameters, particular attention should be paid to these sensitive degrees of freedom and their corresponding frequency ranges.

3.3 Time-Domain Motion Response

The frequency-domain RAO describes the transfer relationship under regular-wave conditions, whereas a random sea state is formed by the superposition of wave components with different frequencies, amplitudes, and phases. To compare the response variations under relatively moderate and severe sea conditions, two sets of JONSWAP spectrum parameters, denoted as LC1 and LC2, were selected as inputs for the random-wave time-domain simulations. The frequency-domain results for the four wave headings indicate that the motion responses are particularly pronounced under head-sea and beam-sea conditions. Therefore, time-domain simulations were performed for LC1 and LC2 under both head-sea and beam-sea conditions. The significant wave height and peak period of LC2 are both greater than those of LC1, allowing the effects of increasing sea-state severity on the platform motions and instantaneous response peaks to be investigated.

Table 2. load case

Parameter	LC1	LC2
Hs/m	2.5	7.5
Tp/s	7.5	14
$\omega_p/(\text{rad/s})$	0.838	0.449
γ	1.5	3.3

3.3.1 Time-Domain Motion Response Analysis under Head-Sea Conditions

Under the head-sea condition, waves approach the FPSO from the bow at a wave heading of 180° . Fig. 7 presents the time-domain responses of surge, heave, and pitch under the two sea states. As shown in Fig. 7, under LC1, all three motion responses fluctuate slightly around their equilibrium positions, with relatively small amplitudes, indicating an overall stable operating condition. The variations in surge and heave displacement are limited, while the pitch angle remains at a low level, demonstrating that the FPSO maintains good motion stability.

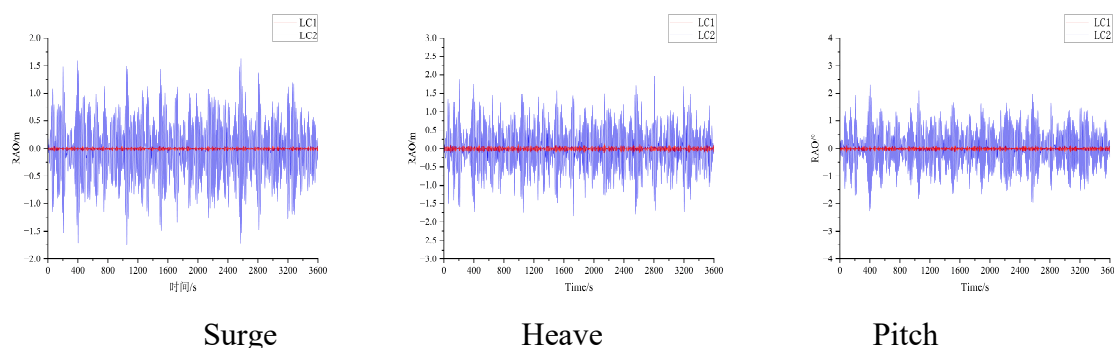


Fig. 7 Time-Domain RAO in Head Seas

As the sea state becomes more severe in LC2, the responses in all three degrees of freedom increase significantly. In particular, the surge response amplitude increases markedly, the range of heave motion expands considerably, and the pitch response exhibits the most pronounced growth. The

amplification of pitch is substantially greater than that of surge and heave, with its peak response reaching a relatively large angular range.

From an operational-management perspective, the key concern under head-sea conditions is not necessarily the maximum instantaneous displacement, but rather the effects of sustained pitch oscillations on deck equipment, cargo-handling operations, personnel access, and additional structural loads.

3.3.2 Time-Domain Motion Response Analysis under Beam-Sea Conditions

Under the beam-sea condition, waves approach the FPSO perpendicular to the vessel centerline at a wave heading of 90° . Fig. 8 presents the time-domain responses of sway, heave, and roll under the two sea states. As shown in Fig. 8, the overall motion responses of the FPSO under LC1 are relatively small, and all degrees of freedom remain in a stable state.

When the sea state becomes more severe in LC2, the sway, heave, and roll responses increase significantly. In particular, the sway displacement increases markedly, the heave response becomes increasingly pronounced, and the roll response exhibits the most substantial growth. Compared with the head-sea condition, roll is the most sensitive motion mode under beam-sea excitation. Figure 8 shows frequent large-amplitude roll oscillations, with peak values substantially exceeding those under the moderate sea condition.

This observation is consistent with the preceding frequency-domain results. The RAO analysis indicates a distinct resonance peak in roll under beam-sea conditions; therefore, large time-domain roll responses can readily occur under random-wave excitation. For an FPSO, roll is generally one of the critical factors governing operational safety. Excessive roll motion not only affects personnel safety and the operational stability of onboard equipment, but may also increase mooring-system loads and additional bending moments in the risers, thereby reducing the overall safety margin of the system.

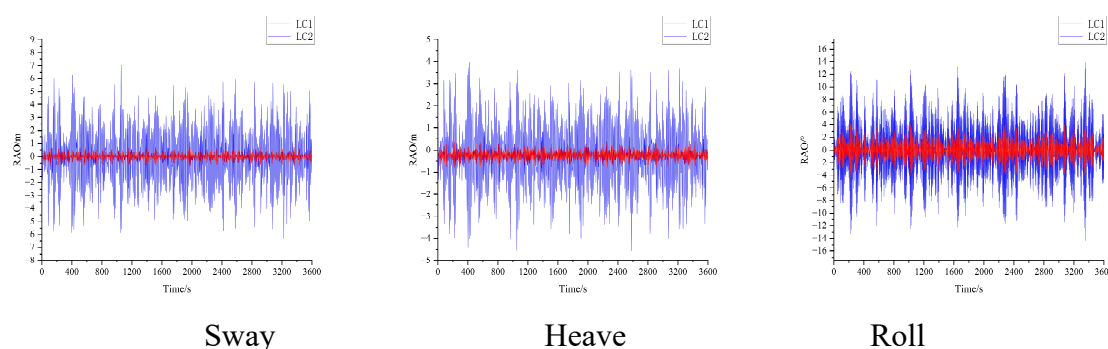


Fig. 8 Time-Domain RAO in Beam Seas

The above results show that the motion responses under LC2 are significantly greater than those under LC1 for both wave conditions, and that the FPSO is highly sensitive to low-frequency, long-period waves. Under head-sea conditions, the dominant motions are surge, heave, and pitch, whereas under beam-sea conditions, sway, heave, and roll are predominant. Pitch and roll are the two rotational degrees of freedom exhibiting the most significant increases in response.

The amplification of pitch and roll is considerably greater than that of the translational motions, indicating that the FPSO is more susceptible to rotational motions under severe sea conditions. Therefore, during the design and operation of an FPSO, particular attention should be paid to controlling the levels of pitch and roll. Measures such as appropriate mooring-system arrangement, ballast adjustment, and operational-window optimization should be adopted to reduce motion responses under severe sea conditions and thereby ensure the safety of the production system and offshore operations.

4. Discussion

The frequency-domain and time-domain analyses indicate that the Suezmax FPSO exhibits distinctly different motion response characteristics under different wave headings. To further clarify the platform motion behavior and its engineering significance, the effects of wave frequency and wave heading on the motion responses are discussed in consideration of the long-term moored operating characteristics of the FPSO.

4.1 Effect of Wave Frequency on Platform Motion Response

The frequency-domain analysis results indicate that the six-degree-of-freedom motion responses of the Suezmax FPSO exhibit pronounced frequency selectivity, with the RAO peaks of all motion modes mainly concentrated in the low-frequency range. As the wave frequency gradually approaches the natural frequency of the platform, the motion response increases rapidly, producing a distinct resonance peak in the corresponding degree of freedom. As the wave frequency continues to increase, the influence of platform inertia becomes more significant, and the motion response gradually decreases and tends to stabilize.

This phenomenon is mainly attributed to the coupling between the wave excitation frequency and the natural frequency of the platform. When the two frequencies are close, the waves continuously transfer energy to the platform, while the restoring mechanism and damping cannot dissipate the input energy sufficiently rapidly. Resonance therefore occurs, resulting in a rapid amplification of the motion response. Owing to the large dimensions of the Suezmax FPSO, its natural periods are relatively long, making the platform more sensitive to low-frequency, long-period waves.

In addition, the added mass, radiation damping, and hydrostatic restoring force vary with wave frequency, and their combined effects determine the magnitude of the platform motion response.

4.2 Effect of Wave Heading on Platform Motion Response

The dominant degrees of freedom of the platform vary significantly with wave heading. Under head-sea conditions, the wave propagation direction is aligned with the longitudinal axis of the platform, resulting in pronounced surge, heave, and pitch responses. Both the 45° and 135° oblique-wave conditions contain longitudinal and transverse excitation components and therefore simultaneously excite surge, sway, heave, roll, pitch, and yaw motions of the FPSO, exhibiting more evident multi-degree-of-freedom coupling than that observed under head-sea or beam-sea conditions. The surge, sway, heave, and yaw RAOs under the two oblique-wave headings are generally similar, indicating that their longitudinal and transverse excitation components are comparable.

Under beam-sea conditions, waves act primarily on the side of the platform, and sway, roll, and yaw become the dominant motion modes, among which roll is the most pronounced. Conventional transport vessels can avoid hazardous wave headings by altering their course during navigation. In contrast, FPSOs generally remain stationed in a fixed sea area for extended periods using single-point or multi-point mooring systems. Their headings are constrained by the mooring system, making it difficult to actively avoid unfavorable wave directions. Therefore, the motion response characteristics under different wave headings must be fully considered during the platform design stage. The seakeeping performance of the platform should also be comprehensively evaluated in combination with long-term wave statistics for the intended operating area.

Under beam-sea conditions, roll resonance may readily occur and represents an important factor affecting the long-term operational safety of the FPSO. Therefore, during the overall design of the platform, particular attention should be paid to improving roll-restoring capability, optimizing the ballast arrangement and center-of-gravity position, and reducing transverse motion responses through appropriate mooring-system design.

5. Conclusion

This study investigates a ship-shaped FPSO converted from a Suezmax tanker. Based on three-dimensional linear potential-flow theory, a hydrodynamic analysis model of the platform was established using AQWA. The frequency-domain motion responses, wave excitation forces, and time-domain motion characteristics of the platform under different wave headings were systematically investigated. The main conclusions are as follows:

- (1) The six-degree-of-freedom motion responses of the Suezmax FPSO exhibit pronounced wave-heading dependence and frequency selectivity. The RAO peaks of the different motion modes are mainly concentrated in the low-frequency range. When the wave frequency approaches the natural frequency of the platform, the motion responses are significantly amplified and resonance occurs. As the wave frequency increases further, the motion responses in all degrees of freedom gradually decrease.
- (2) The dominant motion modes of the platform differ significantly among wave headings. Head seas primarily excite surge, heave, and pitch, whereas beam seas mainly induce sway, roll, and yaw. Among these motions, roll is the most pronounced and represents an important controlling degree of freedom for the seakeeping performance of the platform. Under the 45° and 135° oblique-wave conditions, yaw responses are relatively prominent. Pitch is more pronounced at the 45° wave heading, whereas roll is more significant at the 135° wave heading.
- (3) The wave excitation force analysis indicates that the Froude–Krylov force and diffraction force jointly determine the motion response characteristics of the platform. Surge, heave, and pitch are primarily governed by the Froude–Krylov force, whereas the contribution of diffraction effects increases significantly for roll and yaw. The motion response peaks correspond well with the peaks of the wave excitation forces, indicating that the platform motion characteristics are jointly determined by wave excitation, added mass, radiation damping, and hydrostatic restoring forces.
- (4) The time-domain analysis results are in good agreement with the frequency-domain RAO results. As the sea state changes from LC1 to LC2, the motion responses in all degrees of freedom increase significantly, with pitch and roll exhibiting the greatest amplification. Roll has considerable effects on the mooring system, flexible risers, and the operation of topside processing modules and should therefore receive particular attention during the long-term service of the platform.
- (5) The analysis results can provide a theoretical reference for assessing the suitability of ship-shaped FPSOs converted from Suezmax tankers, adjusting ballast conditions, selecting operational sea states, and developing the overall design scheme. In practical engineering projects, simulations of irregular waves at the intended operating site should also be incorporated to account for the randomness and suddenness of the marine environment and to verify the motion responses and safety of the FPSO under extreme sea conditions.

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