

Article

Dynamic Response Analysis of Floating Offshore Wind Turbines During Towing Operations

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Abstract

Floating offshore wind turbines (FOWTs) have become an important structural configuration for deep-water offshore wind energy development. However, existing studies have mainly focused on towing experience for conventional offshore structures and static stability assessment, while a systematic understanding of the multi-body coupled dynamic response characteristics and hazardous response factors of large-scale FOWTs under combined wind, wave, and current loads remains limited. To address the insufficient understanding of critical hazardous response indicators in existing studies, a 10 MW semi-submersible floating wind turbine was investigated in this study. Variations in environmental loads, towline constraints, and FOWT responses during towing were incorporated into a multi-body coupled analysis framework, and the key hazardous response indicators governed by different dominant environmental factors were identified. The results indicate that increasing wind speed significantly amplifies the pitch response, with the extreme pitch angle reaching approximately -7.17° under the 24 m/s wind condition. Variations in current velocity have limited influence on response amplitudes. Wave height has the most pronounced effect on heave motion and nacelle acceleration. Under the 6.5 m wave height condition, their extreme values reach approximately -1.37 m and 1.15 m/s², respectively. Under the single-tug towing configuration, the 45° and 90° environmental directions induce pronounced lateral and yaw offsets, indicating insufficient path-keeping capability under unfavorable environmental directions. Comprehensive analysis demonstrates that pitch motion should be regarded as the primary hazardous response indicator under high wind speed conditions, while nacelle acceleration and heave motion require particular attention under high wave height conditions.

Keywords: floating offshore wind turbine; integrated towing; motion response; performance analysis; numerical simulation



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1. Introduction

With the gradual depletion of global fossil energy and the severe challenges posed by climate change, transitioning the energy structure has become urgent. Wind energy occupies a crucial position in the development of renewable energy, and offshore wind power possesses abundant wind resources with substantial development potential. Currently, offshore wind power is trending toward larger-scale, deep-water, and high-capacity deployment, and floating offshore wind turbines have emerged as the optimal choice for deep-water wind energy development.

Within the entire lifecycle of offshore structures, towing constitutes a critical operation encompassing construction, deployment, operation, maintenance, and decommissioning. Unlike fixed-bottom wind turbines, which require complex offshore installation using large floating cranes, floating offshore wind turbines are typically assembled onshore and transported as a whole via wet towing. Existing towing studies have primarily focused on conventional marine structures, such as oil and gas platforms and caissons [1–5], which provide important references for the development of towing technologies. However, floating offshore wind turbines exhibit significant differences from these traditional offshore structures in terms of structural configuration, mass distribution, and load characteristics. Consequently, their dynamic response during towing is more complex, and current research findings cannot be directly applied to the towing of floating wind turbines.

Floating offshore wind turbines are characterized by a high center of gravity, large scale, and sensitivity of the superstructure to dynamic loads, which lead to higher uncertainties and more complex environmental adaptability during towing. Consequently, many researchers have investigated the static stability of these structures during towing. Han et al. [6] assessed the stability of a tension-leg platform during transport using static stability curves, without considering mooring lines. Cai et al. [7] proposed a novel semi-submersible spar-type floating foundation and analyzed its hydrostatic stability during wet towing. Crowle et al. [8] presented the design requirements for the installation and towing of floating wind turbines and provided criteria for comprehensive stability verification. These studies primarily evaluate safety during the towing stage from a static stability perspective, offering guidance on structural stability; however, they remain insufficient for capturing the dynamic response characteristics under the combined action of wind, waves, and currents.

In studies of the offshore towing of floating wind turbines, the multibody coupling relationship is crucial for revealing the interaction mechanisms and overall dynamic characteristics among the tug, mooring lines, and the floating wind turbine. Wang [9] established a numerical model for the aero-hydro-elastic-mooring multibody coupled analysis of a semi-submersible wind-wave hybrid system, and validated it through model experiments. Cao et al. [10] developed and validated a towing numerical model for multi-float systems based on potential flow theory and multibody hydrodynamic interactions. Ding et al. [11] constructed a numerical towing system model including the tug, towlines, and turbine, and studied the wet towing of a tension-leg floating wind turbine using multibody dynamics. Moreno et al. [12] performed dynamic modeling of the ship-floating wind turbine platform and computed the turbine's hydrodynamic characteristics by solving multibody radiation-diffraction problems. Hallak et al. [13] proposed a generalized-degree-of-freedom model for simulating multibody systems and provided a detailed account of the multidegree-of-freedom coupled dynamics of floating platforms. Li et al. [14] analyzed multibody interactions among different floating platforms using a composite hydrodynamics approach. Kim and Bae [15] formulated a time-domain multibody motion equation to demonstrate the effects of platform-hydrodynamic interactions on rotor performance. Methods based on multibody dynamics can describe the complex coupled interactions among the tug, towlines, and turbine, providing an effective approach for analyzing motion responses under complex environmental conditions. On this basis, it is necessary to further analyze and identify key response characteristics and critical response indices.

Due to the complex issues involved in the towing of floating wind turbines, including multibody interactions, environmental load coupling, and dynamic responses, many researchers have analyzed the key influencing factors and risk constraints of the towing process. T. Büttner et al. [16] conducted physical model tests on the OrthoSpar platform under various wave conditions, investigating responses such as roll, pitch, and towline

forces. They highlighted the need to avoid resonant wave frequencies during towing and installation, emphasized the effect of wave direction on stability, and recommended avoiding incident wave directions of 30° and 90° . Le et al. [17] performed numerical simulations of three- and four-column floating wind turbines, indicating that towing performance remains acceptable at a wave height of 5 m, which represents the maximum allowable wave height for towing. Yin et al. [18] studied vortex-induced motions of floating platforms at different towing speeds through model tests, with particular focus on roll and pitch motions. Chen et al. [19] identified the maximum towing speed as 4 knots, noting that speed has a more pronounced effect on roll and pitch, and that towing against the waves is optimal. Ramachandran et al. [20] analyzed accelerations at the nacelle as the most critical control factor and proposed using the significant wave height as a limiting criterion for safe towing. Davis et al. [21] investigated the towing of a cruciform-shaped barge-type FOWT, finding that the cross configuration exhibited larger mean pitch angles, which is an important parameter for towing. Gao et al. [22] developed a numerical model for towing floating wind turbines, recommending towing speeds below 4 knots with multiple assisting tugs. Feng et al. [23] conducted a time-domain simulation of the wet towing process of the “Sanxia Yinling” semi-submersible wind turbine, indicating that operational sea conditions should be limited to Beaufort scale 4 or lower.

In summary, existing studies have laid an important foundation for the towing analysis of floating offshore wind turbines. Research on the towing of conventional offshore structures provides valuable references for the safety assessment of towing systems, while studies on the static stability of FOWTs highlight the importance of safety analysis during towing operations. Multi-body dynamics-based approaches offer an effective tool for describing the coupled interactions among the tug, towline, and FOWT, and investigations of different environmental factors and towing constraints have revealed the significant effects of wind, waves, and other factors on towing safety. However, several limitations remain in the existing literature. On the one hand, some studies have mainly focused on static stability or a single response indicator, and systematic comparative analyses of six-degree-of-freedom dynamic responses under combined wind, wave, and current loads are still lacking. On the other hand, existing studies have often emphasized the validation of specific platforms or the analysis of individual operating conditions, leaving the hazardous response factors governed by different dominant environmental factors insufficiently understood. Therefore, from the perspectives of coupled multi-environmental effects and engineering safety assessment, it is necessary to further clarify which responses are primarily governed by different environmental factors during the towing of large-scale semi-submersible FOWTs and which key response indicators should be prioritized for towing safety monitoring.

Based on the above research background, the present study carries out the following work: (1) a multi-body dynamic model including the tug, towline, and 10 MW semi-submersible FOWT is established to simulate the coupled effects among towline constraints, environmental loads, and platform motions during wet towing; (2) based on typical environmental conditions in the South China Sea, the effects of different wind, wave, current, and relative direction conditions on the motion responses and nacelle acceleration of the FOWT are systematically analyzed; and (3) from the perspective of towing safety assessment, the response sensitivity under different dominant environmental factors is examined, and hazardous response indicators under conditions such as high wind speed and high wave height are identified. The results can provide a reference for determining environmental windows and monitoring hazardous responses during the wet towing of large-scale FOWTs.

2. Towing Calculation Method

2.1. Hydrodynamic Loads

During towing, the offshore semi-submersible wind turbine is primarily subjected to three types of loads: the self-weight of the turbine, environmental loads such as wind, waves, and currents, and the towline forces.

Due to the tall and complex structure of the floating wind turbine, wind loads can generate significant overturning moments on the turbine, which can be calculated using Equation (1):

$$F_w = \frac{1}{2} \rho_0 U_{10}^2 C_h C_s A \quad (1)$$

In Equation (1), ρ_0 is the air density; C_h is the wind height coefficient, which can be determined according to the API RP 2SK [24]; C_s is the shape factor; A is the windward area of the structure; U_{10} is the mean wind speed at a height of 10 m.

Ocean currents are typically considered as steady flows and can be calculated using Equation (2):

$$F_{current} = C_d \frac{\rho_w}{2} D u_z |u_z| \quad (2)$$

In Equation (2), C_d is the water drag coefficient; ρ_w is the water density; D is the flow-facing area of the floating structure; u_z is the current velocity at depth z .

Waves represent the primary operational environmental condition for offshore structures. In this study, the JONSWAP wave spectrum was selected for wave response analysis, as expressed in Equation (3).

$$S(\omega) = \alpha H_s^2 \omega_p^4 e^{-\frac{5}{4}(\frac{\omega}{\omega_p})^{-4}} \gamma^r \quad (3)$$

In the equation, $S(\omega)$ is the wave spectral density; ω is the wave angular frequency; ω_p is the peak angular frequency corresponding to the spectral peak; H_s is the significant wave height; α is the spectral energy scale coefficient; γ is the peak enhancement factor; r is the exponent of the peak enhancement factor, $r = e^{-\frac{(w-\omega_p)^2}{2\sigma^2\omega_p^2}}$; and σ is the spectral width parameter; when $\omega - \omega_p < 0$, $\sigma = 0.07$; when $\omega - \omega_p > 0$, $\sigma = 0.09$. The parameter γ controls the sharpness of the JONSWAP spectrum peak, with larger values producing a more pronounced peak.

2.2. Multibody Dynamics of the Towing System

The towing system consists of the tug-towline-floating wind turbine, forming a typical multibody coupled system that exhibits complex dynamic interactions. The motion of the tug under waves, wind, and currents is transmitted to the floating turbine through the towline, while the large-scale response of the floating body in turn influences the towline tension and tug maneuvering, resulting in significant nonlinear feedback. Based on multibody dynamics theory, a dynamic model of the towing system can be established, enabling the analysis of tug and towline dynamic responses as well as floating body motions, and providing a theoretical basis for the identification of hazardous factors.

The generalized coordinates of the floating wind turbine towing system are defined as:

$$q = \begin{bmatrix} q_B^T & q_{T1}^T \end{bmatrix} \quad (4)$$

In the equation, q_B^T represents the generalized coordinates of the floating wind turbine; q_{T1}^T represents the generalized coordinates of a single tug.

For any rigid body, motion is described using six degrees of freedom, i.e.,:

$$q_i = [x_i \ y_i \ z_i \ \phi_i \ \theta_i \ \psi_i] \quad (5)$$

The equations of motion of the towing system are expressed as follows:

$$[M + A]\ddot{q} + C\dot{q} + Kq = F = F_{wave} + F_{current} + F_{wind} + F_{tow} \quad (6)$$

$$\left(\begin{bmatrix} M_B & 0 \\ 0 & M_{T1} \end{bmatrix} + \begin{bmatrix} A_B & A_{BT1} \\ A_{T1B} & A_{T1} \end{bmatrix} \right) \begin{bmatrix} \ddot{q}_B \\ \ddot{q}_{T1} \end{bmatrix} + \begin{bmatrix} C_B & 0 \\ 0 & C_{T1} \end{bmatrix} \begin{bmatrix} \dot{q}_B \\ \dot{q}_{T1} \end{bmatrix} + \begin{bmatrix} K_B & K_{BT1} \\ K_{T1B} & K_{T1} \end{bmatrix} \begin{bmatrix} q_B \\ q_{T1} \end{bmatrix} = \begin{bmatrix} F_B \\ F_{T1} \end{bmatrix} \quad (7)$$

In the equation, $[M + A]$ represents the mass and added mass matrices; C represents the radiation damping matrix; K represents the restoring force coefficient matrix; q represents the displacement vector; $\dot{q}$ and $\ddot{q}$ denote the first and second derivatives of displacement, i.e., velocity and acceleration, respectively. The right-hand side represents the external forces F acting on the system, where F_{wave} is the wave force, calculated via potential flow theory; $F_{current}$ and F_{wind} denote the current and wind forces, calculated using the relevant formulas in Section 2.1; F_{tow} represents the towing force.

3. Towing Simulation Analysis

3.1. Towing System Model

For the towing of high-capacity semi-submersible wind turbines, a systematic modeling and numerical analysis approach was adopted. First, a three-dimensional model of the 10 MW OO-Star foundation and DTU blades was created using SolidWorks (version 2023). The coordinate origin was defined at the still water level of the floating platform, with the x -axis aligned with the towing direction, the y -axis defined as the transverse direction, and the positive z -axis directed vertically upward. Therefore, when the center of gravity or center of buoyancy is located below the still water level, its vertical coordinate is expressed as a negative value. Tables 1 and 2 summarize the structural parameters of the OO-Star platform [25] and the DTU blades [26], respectively. The towline parameters are listed in Table 3. The three-dimensional model and a schematic of the towing setup are shown in Figures 1 and 2.

Table 1. OO-Star Platform Parameters [25].

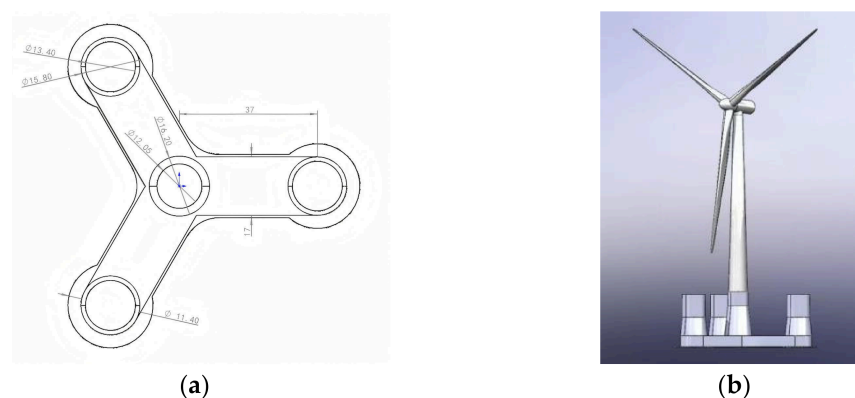
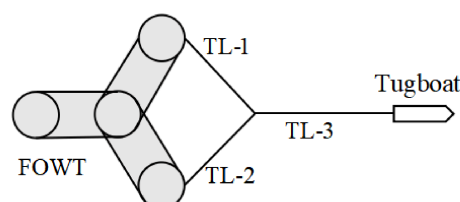
Parameter Type	Value
Floater Angle	120°
Floater Length	21.1 m
Floater Diameter	7 m
Central Column Height	33 m
Side Column Height	32 m
Lower Radius of Central Column	8.1 m
Lower Radius of Side Column	7.9 m
Mass	21,709 t
Height of Center of Gravity	−15.23 m
Height of Center of Buoyancy	−14.24 m
Draft	22 m
Freeboard Height	11 m
Design Water Depth	130 m

Table 2. DTU Blade Parameters [26].

Parameter Type	Value
Number of Blades	3
Rated Power	10 MW
Hub Height	119 m
Hub Diameter	5.6 m
Rotor Diameter	178.3 m
Rotor Mass	227 t
Nacelle Mass	446 t
Tower Mass	1257 t
Shaft Tilt Angle	5°
Tower Base Outer Diameter	11.385 m
Tower Top Outer Diameter	5.2 m

Table 3. Main Parameters of the Towline.

Parameter Type	Value
Towline type	Nonlinear catenary
Material	High-modulus polyethylene (HMPE)
Mass of unit length (kg/m)	47.89
Equivalent diameter (m)	0.088
Stiffness of towing cable (catenary) (kN)	3.13×10^5
Breaking force (kN)	4.9×10^3
TL-1 length (m)	100.5
TL-2 length (m)	100.5
TL-3 length (m)	150.5

**Figure 1.** Schematic of the Semi-submersible Wind Turbine Model. (a) Schematic of OO-Star Semi-submersible Floating Foundation Dimensions; (b) 3D Model of the Full Semi-submersible Wind Turbine.**Figure 2.** Schematic of the Semi-submersible Wind Turbine Towing Setup.

3.2. Environmental Conditions

To define the range of environmental parameters for the towing scenarios, actual sea condition data from the South China Sea were referenced. Wet towing is typically designed based on extreme conditions with a 10-year return period [27]. Table 4 presents the main environmental parameters corresponding to a 10-year return period in the South China Sea.

Table 4. Environmental Parameters for 10-Year Return Period in the South China Sea [27].

Environmental Parameter	South China Sea
Wave Spectrum	Jonswap
Wave Direction	Omnidirectional
Significant Wave Height (m)	6.50
1 h Wind Speed ($\text{m}\cdot\text{s}^{-1}$)	19.3
Wind Direction	Omnidirectional

During the towing of a semi-submersible floating wind turbine, the primary environmental load factors include wind, waves, and ocean currents. When selecting towing scenarios, the coupled effects of wind speed, wave height, and current velocity are fully considered to cover the main operational conditions encountered during actual towing. Considering the characteristics of the South China Sea, waves are modeled using the JONSWAP spectrum, and the peak enhancement factor is set to 2.49 based on the wave spectrum model for the South China Sea reported by Liu et al. [28]. The spectral peak period can be determined according to the significant wave height. Huang et al. [29] analyzed the empirical relationship between significant wave height and spectral peak period along navigational routes in the South China Sea, resulting in the following empirical relation:

When the significant wave height $h_s < 8$ m:

$$t_p = 6.704 \cdot h_s^{0.259} \quad (8)$$

When the significant wave height $h_s \geq 8$ m:

$$t_p = 7.975 \cdot h_s^{0.365} \quad (9)$$

Based on the range of environmental parameters corresponding to a 10-year return period in the South China Sea, the environmental conditions were reasonably extended and representative parameter combinations were selected. Ensuring that the constructed scenarios cover the characteristics of the 10-year return period while also reflecting the influence of different environmental factors on towing responses, a total of 17 calculation cases were defined. The corresponding environmental parameters for these design scenarios are listed in Table 5. To evaluate the main towing responses under conditions close to the upper limit of engineering towing speed, the towing speed in this study was set to 4 kn with reference to the commonly used speed limits in wet towing operations of large-scale FOWTs [19,22].

3.3. Model Validation

To validate the model and ensure the reliability of the numerical results, the hydrodynamic model of the FOWT was examined. First, the natural periods of the platform were validated through free-decay time-domain simulations of the FOWT model. Specifically, when the model was subjected to initial excitation under windless and waveless conditions, the motion response time histories in the corresponding degrees of freedom were obtained, and the natural periods were identified through Fourier analysis. The results were then compared with the natural periods reported in the public reference data of the LIFES50+ project [25]. The mooring parameters were set consistently with those in the reference. The results are shown in Table 6.

The relative errors of the calculated natural periods were all within 10%, with a mean relative error of 4.65%. In addition, the root mean square error (RMSE) of the natural periods was 2.78 s, corresponding to a normalized root mean square error (NRMSE) of 3.26%. Overall, the natural periods predicted by the numerical model agreed well with the reference results, demonstrating the satisfactory accuracy of the established model.

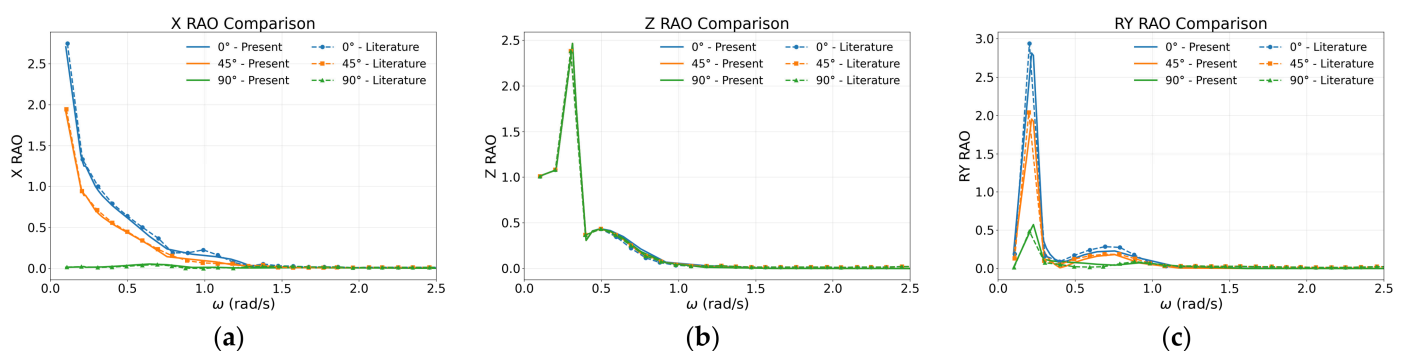
Table 5. Environmental Parameters under Different Design Scenarios.

Case	Significant Wave Height (m)	Spectral Peak Period (s)	Mean Wind Speed (m/s)	Current Speed (m/s)	Relative Wind-Wave-Current Direction (°)
LC0	3.5	9.27	16	0.8	180
LC1	3.5	9.27	8	0.8	180
LC2	3.5	9.27	12	0.8	180
LC3	3.5	9.27	20	0.8	180
LC4	3.5	9.27	24	0.8	180
LC5	3.5	9.27	16	0.4	180
LC6	3.5	9.27	16	0.6	180
LC7	3.5	9.27	16	1.0	180
LC8	3.5	9.27	16	1.2	180
LC9	0.5	5.60	16	0.8	180
LC10	2	8.02	16	0.8	180
LC11	5	10.17	16	0.8	180
LC12	6.5	12.3	16	0.8	180
LC13	3.5	9.27	16	0.8	0
LC14	3.5	9.27	16	0.8	45
LC15	3.5	9.27	16	0.8	90
LC16	3.5	9.27	16	0.8	135

Table 6. Validation of Natural Periods of the Model.

Degree of Freedom	Natural Period from Public Reference (s)	Natural Period from Numerical Simulation (s)	Relative Error
Surge	185.2	181.83	1.8%
Heave	20.9	20.01	4.3%
Pitch	31.6	28.59	9.5%
Yaw	103.1	100	3.0%

To further validate the hydrodynamic response characteristics of the model, the response amplitude operators (RAOs) of the FOWT were calculated and compared with the RAO results reported in the existing literature for the same model [30], as shown in Figure 3. The RAO curves of the model established in this study show generally consistent trends with the reference results over the main frequency range, and the response peak positions correspond well to the natural frequencies of the platform. This indicates that the present model can accurately capture the main hydrodynamic response characteristics of the platform and provides a reliable basis for the subsequent time-domain towing analysis.

**Figure 3.** RAO comparison: (a) surge; (b) heave; (c) pitch.

3.4. Analysis of Second-Order Wave-Load Effects

To further analyze the effects of second-order wave forces on the towing responses, three representative cases, J1, J2, and J3, corresponding to low, moderate, and high towing environmental intensities, were selected, as listed in Table 7. Comparative calculations were

conducted under different wave-load settings, including four configurations: first-order wave forces only, first-order wave forces with mean drift force, further inclusion of the difference-frequency QTF, and simultaneous consideration of both difference-frequency and sum-frequency QTFs. Figure 4 presents the statistical results for the FOWT motion responses that show relatively pronounced variations under different wave-load settings, namely heave and pitch.

Table 7. Cases for the Analysis of Second-Order Wave-Load Effects.

Case	Significant Wave Height, H_s (m)	Spectral Peak Period, T_p (s)	Mean Wind Speed (m/s)	Current Velocity (m/s)	Wind-Wave-Current Direction ($^{\circ}$)
J1	0.5	5.60	8	0.4	180
J2	3.5	9.27	16	0.8	180
J3	6.5	12.30	24	1.2	180

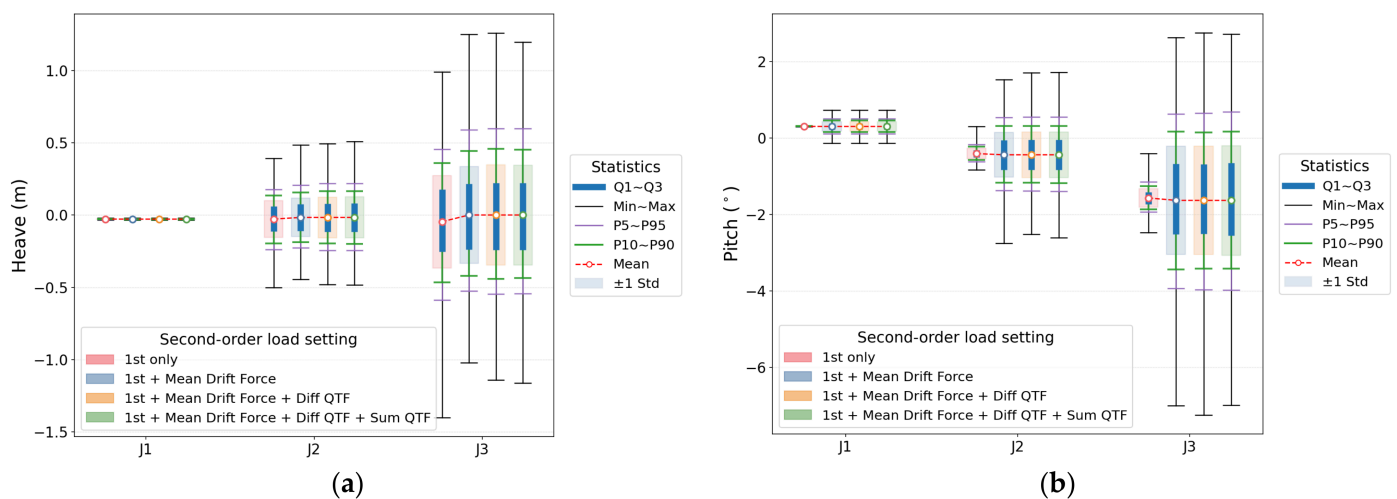


Figure 4. Motion Responses under Different Wave-Load Settings: (a) Heave; (b) Pitch.

It can be observed that, under the low-environmental-intensity case J1, the response differences among the different wave-load settings are relatively small, indicating that second-order wave forces have a limited influence on the towing responses under mild sea conditions. As the environmental intensity increases, the influence of second-order loads on the response extreme-value range gradually becomes more pronounced, particularly for the pitch response. After the inclusion of the mean drift force, difference-frequency QTF, and sum-frequency QTF, the response amplitude range increases noticeably. This indicates that second-order wave forces can affect the motion responses of FOWTs during towing and therefore should not be completely neglected.

From the comparison of different second-order load components, the mean drift force has a certain influence on both the response mean values and the extreme-value ranges. After the difference-frequency and sum-frequency QTFs are included, the changes relative to the cases considering only first-order wave forces and mean drift force are relatively limited. This suggests that, for the towing conditions and global platform motion responses considered in this study, the difference-frequency and sum-frequency forces do not act as dominant factors. Considering both computational accuracy and efficiency, the subsequent calculations in this study adopt the setting that includes first-order wave forces and mean drift force.

4. Analysis of the Influence of Environmental Factors on Towing Motion Characteristics

4.1. Towing Characteristics Under Different Wind Speeds

The semi-submersible wind turbine towing process was simulated using the hydrodynamic software AQWA (version 2025R1). A total simulation time of 5000 s was used. To eliminate initial transient start-up effects and ensure the stationarity required for statistical analysis, the first 1000 s were excluded, resulting in an effective calculation period of 4000 s. Table 8 summarizes the towing motion responses of the wind turbine under LC0 to LC4 for varying wind speed conditions.

Table 8. Statistical Analysis of Wind Turbine Motion Responses under Different Wind Speeds.

Response	Statistic	LC1	LC2	LC0	LC3	LC4
Sway (m)	Maximum	−0.0333	−0.0322	−0.0306	−0.0289	−0.0274
	Minimum	−0.0400	−0.0392	−0.0379	−0.0367	−0.0353
	Mean	−0.0369	−0.0359	−0.0347	−0.0332	−0.0315
Heave (m)	Maximum	0.4913	0.4891	0.4841	0.5238	0.4796
	Minimum	−0.4421	−0.4436	−0.4455	−0.4504	−0.4558
	Mean	−0.0147	−0.0153	−0.0161	−0.0173	−0.0188
Roll (°)	Maximum	0.0216	0.0216	0.0217	0.0222	0.0230
	Minimum	0.0194	0.0193	0.0191	0.0184	0.0173
	Mean	0.0205	0.0204	0.0204	0.0203	0.0202
Pitch (°)	Maximum	1.2693	1.3292	1.5244	2.1105	2.8476
	Minimum	−0.4002	−1.2345	−2.7555	−4.7192	−7.1746
	Mean	0.5173	0.1059	−0.4406	−1.1203	−1.9305
Yaw (°)	Maximum	0.0162	0.0166	0.0168	0.0172	0.0172
	Minimum	−0.0013	−0.0027	−0.0038	−0.0037	−0.0042
	Mean	0.0082	0.0079	0.0074	0.0069	0.0063
Nacelle Acceleration (m/s ²)	Maximum	0.6089	0.6310	0.6874	0.8304	1.0122
	Minimum	0.0008	0.0009	0.0003	0.0002	0.0011
	Mean	0.1508	0.1536	0.1607	0.1779	0.2078

As shown in Table 8, the sensitivity of various motion responses of the semi-submersible wind turbine to wind speed exhibits clear differences. Among these, pitch and nacelle accelerations show the most significant variations, with the pitch response exhibiting a noticeable increasing trend with wind speed. The heave response remains relatively stable overall, while the sway, roll, and yaw responses are small in magnitude and can be neglected.

To more intuitively illustrate the variation in key responses with wind speed and considering space limitations, Figure 5 presents the statistical analysis of pitch and nacelle acceleration, which exhibit more pronounced changes. In the figure, the blue shaded area represents the 25% to 75% range of the time-series data, the black I-shaped bars indicate the minimum and maximum values, the purple and green ranges represent the P5-P95 and P10-P90 intervals, respectively, red hollow circles denote the mean values, and yellow squares represent the standard deviations.

As shown in Figure 5, the pitch response exhibits a pronounced amplification trend with increasing wind speed, and the range of extreme values continues to expand, reaching -7.17° to 2.84° under LC4. In addition, both the mean and extreme values of nacelle acceleration increase with wind speed, with a peak of 1.01 m/s^2 , indicating strong sensitivity to changes in wind speed. In contrast, sway, heave, roll, and yaw responses show relatively small variations across different wind speeds and remain generally stable. Heave and

yaw fluctuate stably around their mean values with increasing wind speed, indicating low sensitivity to wind speed changes. Although sway and roll show an increasing trend with higher wind speeds, their overall amplitudes remain small, suggesting that these responses are not the primary hazardous responses under high-wind conditions.

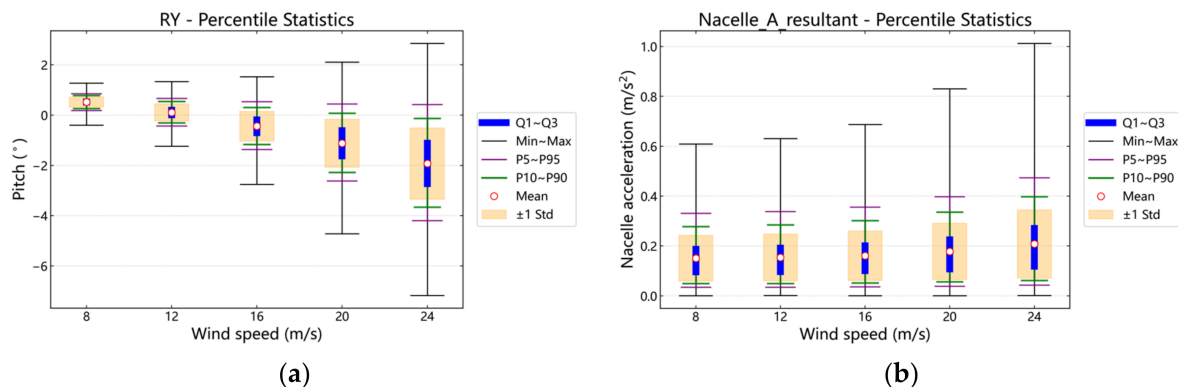


Figure 5. Statistical Analysis of Key Motion Responses of the Wind Turbine under Different Wind Speeds. (a) Statistical Analysis of Pitch; (b) Statistical Analysis of Nacelle Acceleration.

From a physical perspective, the enhancement of pitch response is mainly attributed to the tall structure of the semi-submersible wind turbine. Under wind loading, the upper structure generates significant overturning moments, causing pronounced longitudinal attitude fluctuations of the platform. Figure 6 presents the power spectral density of pitch. Under different wind speeds, a significant spectral peak appears around 0.035 Hz, indicating that the pitch response is dominated by the platform's natural pitch frequency. The wave peak frequency across the five wind speed cases is approximately 0.108 Hz. No significant response peak occurs near this frequency, suggesting that the system's response to wave-frequency excitation is weak under high wind speeds, while pronounced amplification occurs near the natural frequency. Furthermore, the spectral peak amplitude increases noticeably with wind speed, indicating that wind loading enhances the response energy at the natural frequency.

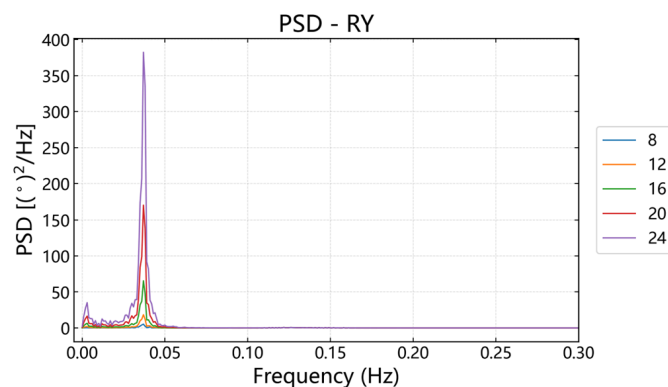


Figure 6. Power Spectral Density of Wind Turbine Pitch under Different Wind Speeds.

In summary, under LC0 to LC4, the fluctuations of sway, roll, and yaw are small and can be neglected, while heave exhibits only minor fluctuations and remains within the safe range. Pitch exhibits large fluctuations and is highly sensitive to wind speed; thus, it should be regarded as a critical hazardous response for monitoring. Nacelle acceleration also increases substantially, significantly affecting onboard equipment, and should be treated as a secondary hazardous response under high-wind conditions.

4.2. Towing Characteristics Under Different Current Speeds

Table 9 summarizes the towing motion responses of the wind turbine under LC0 and LC5–LC8, corresponding to different current speed conditions. Overall, the sensitivity of the motion responses to current speed is relatively weak. Unlike the wind speed scenarios, where response amplitudes clearly increase with environmental intensity, the range of fluctuations across all degrees of freedom under different current speeds remains small, indicating that variations in current speed have a limited influence on the system responses. As the current speed varies, the overall responses do not exhibit an obvious monotonic trend. The heave response remains mainly within ± 0.55 m and does not show an evident amplification trend with increasing current speed. The amplitudes of sway, roll, and yaw are small, and their variations are not obvious. Pitch shows relatively more noticeable variation than the other degrees of freedom, reaching approximately -2.85° under LC5. Its mean value increases to some extent with current speed, but its amplitude does not show a continuous increasing trend; instead, the negative extreme value decreases slightly. The extreme and mean values of nacelle acceleration show no obvious changes, with the maximum value remaining in the range of 0.63 – 0.73 m/s², indicating that nacelle acceleration is essentially unaffected by current speed.

Table 9. Statistical Analysis of Wind Turbine Motion Responses under Different Current Speeds.

Response	Statistic	LC5	LC6	LC0	LC7	LC8
Sway (m)	Maximum	−0.0338	−0.0323	−0.0306	−0.0297	−0.0295
	Minimum	−0.0491	−0.0390	−0.0379	−0.0365	−0.0355
	Mean	−0.0382	−0.0360	−0.0347	−0.0336	−0.0327
Heave (m)	Maximum	0.5474	0.4806	0.4841	0.4526	0.4669
	Minimum	−0.4774	−0.5359	−0.4455	−0.4014	−0.4058
	Mean	−0.0164	−0.0163	−0.0161	−0.0156	−0.0150
Roll (°)	Maximum	0.0216	0.0214	0.0217	0.0222	0.0224
	Minimum	0.0192	0.0194	0.0191	0.0186	0.0184
	Mean	0.0203	0.0203	0.0204	0.0204	0.0204
Pitch (°)	Maximum	1.3323	1.7013	1.5244	1.5647	1.6052
	Minimum	−2.8550	−2.7524	−2.7555	−2.1956	−2.2802
	Mean	−0.6906	−0.5693	−0.4406	−0.3043	−0.1622
Yaw (°)	Maximum	0.0315	0.0165	0.0168	0.0166	0.0155
	Minimum	−0.0172	−0.0010	−0.0038	−0.0040	−0.0017
	Mean	0.0082	0.0078	0.0074	0.0070	0.0067
Nacelle Acceleration (m/s ²)	Maximum	0.6845	0.7266	0.6874	0.6329	0.6598
	Minimum	0.0002	0.0007	0.0003	0.0009	0.0005
	Mean	0.1621	0.1605	0.1607	0.1625	0.1632

Figure 7 presents the power spectral density of pitch under different current speeds. The spectral peak positions and amplitudes are largely consistent across all current conditions, primarily concentrated near the natural pitch frequency, while no obvious dominant peak appears near the wave peak frequency. This indicates that, under the calculated conditions, the pitch response is mainly governed by its natural frequency. The overall energy distribution shows little difference and does not change significantly with increasing current speed, indicating that current speed does not alter the dominant frequency characteristics of the pitch response.

These features indicate that, within the analyzed range of current conditions, changes in current speed do not significantly alter the response amplitudes or dominant frequency characteristics of the system. The response amplitudes in all degrees of freedom remain

generally stable. Under LC0 and LC5–LC8, the fluctuations of sway, roll, and yaw are small and can be neglected; heave and nacelle acceleration do not show evident amplification trends; and although the mean value of pitch is relatively more sensitive, its amplitude does not increase continuously with current speed. Overall, the motion responses of the semi-submersible wind turbine therefore show low sensitivity to variations in current speed.

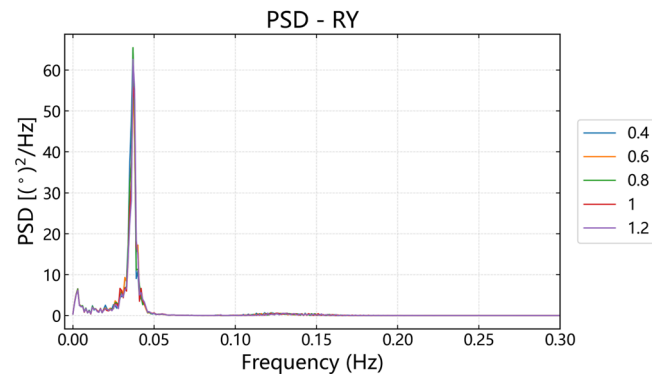


Figure 7. Power Spectral Density of Wind Turbine Pitch under Different Current Speeds.

4.3. Towing Characteristics Under Different Wave Heights

Table 10 summarizes the towing motion responses of the wind turbine under LC0 and LC9–LC12, corresponding to different wave heights. It can be observed that the heave and nacelle acceleration responses exhibit significant variations with wave height. The ranges of maximum and minimum values clearly expand as wave height increases. Figure 8 presents the statistical analysis of responses that show more pronounced changes: heave and nacelle acceleration.

Table 10. Statistical Analysis of Wind Turbine Motion Responses under Different Wave Heights.

Response	Statistic	LC9	LC10	LC0	LC11	LC12
Sway (m)	Maximum	−0.0157	−0.0242	−0.0306	−0.0268	0.0361
	Minimum	−0.0165	−0.0287	−0.0379	−0.0818	−0.1009
	Mean	−0.0161	−0.0264	−0.0347	−0.0445	−0.0448
Heave (m)	Maximum	−0.0194	0.1811	0.4841	0.8716	1.3162
	Minimum	−0.0374	−0.1817	−0.4455	−0.6924	−1.3743
	Mean	−0.0284	−0.0243	−0.0161	−0.0054	0.0008
Roll (°)	Maximum	0.0206	0.0210	0.0217	0.0261	0.0334
	Minimum	0.0202	0.0198	0.0191	0.0155	0.0094
	Mean	0.0205	0.0204	0.0204	0.0203	0.0203
Pitch (°)	Maximum	1.5005	1.3582	1.5244	1.5680	1.8909
	Minimum	−2.5104	−2.4686	−2.7555	−2.4520	−2.9560
	Mean	−0.4240	−0.4311	−0.4406	−0.4499	−0.4374
Yaw (°)	Maximum	0.0054	0.0109	0.0168	0.0801	0.1528
	Minimum	−0.0042	−0.0026	−0.0038	−0.0690	−0.1214
	Mean	0.0006	0.0042	0.0074	0.0103	0.0079
Nacelle Acceleration (m/s ²)	Maximum	0.2743	0.4728	0.6874	0.9935	1.1461
	Minimum	0.0001	0.0002	0.0003	0.0010	0.0020
	Mean	0.0575	0.1108	0.1607	0.2138	0.2596

As shown in Figure 8 and Table 10, the response characteristics of the semi-submersible wind turbine differ significantly with increasing wave height. The heave response is the most sensitive to wave height, and its fluctuation range expands markedly as wave height increases, reaching −1.37 m to 1.32 m under LC12. This indicates that increasing wave

height mainly enhances the oscillation amplitude of heave motion. Nacelle acceleration also shows a clear increasing trend with wave height, with the maximum value increasing from 0.274 m/s^2 under LC9 to 1.15 m/s^2 under LC12. This suggests that high wave height conditions further amplify the acceleration response at the nacelle and should therefore be considered as a hazardous response. In contrast, although sway, roll, and yaw vary to some extent with increasing wave height, their overall amplitudes remain small and have a limited influence on the towing motion characteristics of the FOWT. The pitch response remains within the range of -3° to 2° under different conditions. Although its amplitude shows a certain increasing trend with wave height, it does not exhibit a strictly monotonic increase, and its variation is weaker than that of heave and nacelle acceleration.

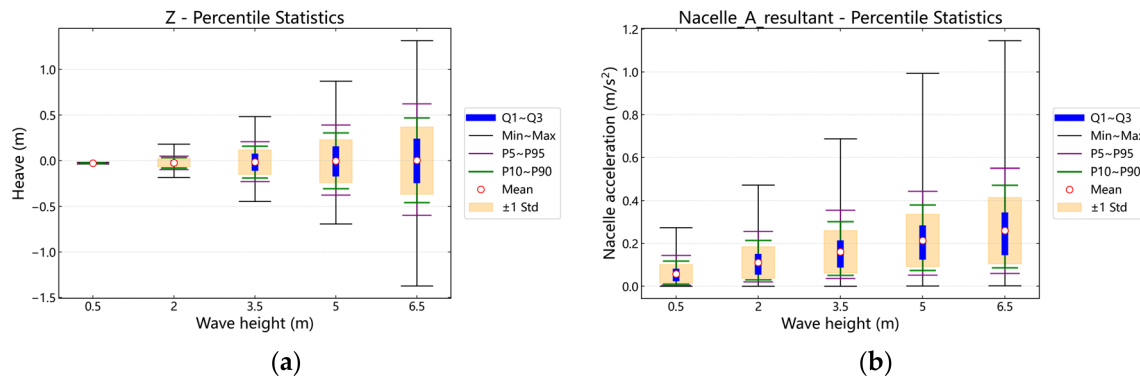


Figure 8. Statistical Analysis of Wind Turbine Motion Responses under Different Wave Heights. (a) Statistical Analysis of Heave; (b) Statistical Analysis of Nacelle Acceleration.

Compared with wind speed and current speed scenarios, variations in wave height have a more pronounced effect on the platform heave response and nacelle acceleration, indicating that wave excitation plays a dominant role in controlling the vertical dynamic response intensity of the platform. Figure 9 presents the power spectral density of heave under different wave height conditions. As wave height increases, the spectral peak amplitude of the heave response increases significantly, indicating that increasing wave height markedly enhances the frequency-domain response energy of heave motion. Since the spectral peak period increases with wave height in the calculation cases, the corresponding wave peak frequency gradually decreases. Therefore, under high wave height conditions, the heave response energy tends to concentrate within a lower-frequency range. Overall, the main peaks are distributed within the range of 0.07–0.13 Hz, reflecting the direct influence of wave-frequency excitation on the heave response. A secondary peak appears near the natural heave frequency of the FOWT, indicating that the heave response is also affected by its natural frequency. As wave height increases, the spectral peak amplitudes corresponding to different frequency components all increase, but the dominant frequency range remains within a similar frequency band. This indicates that variations in wave height mainly increase the spectral energy of the heave response without changing its frequency-domain response characteristics.

Overall, under LC9 with low wave height, the motion responses of all degrees of freedom and the nacelle acceleration are small, and the towing system remains stable. As wave height increases to LC12, heave and nacelle acceleration increase significantly and become the most sensitive responses to wave height variation. The amplitudes of sway, roll, and yaw are small and can be regarded as non-dominant responses. Although pitch exhibits certain fluctuations, it generally remains within a moderate response range. Therefore, under high wave height conditions, particular attention should be paid to the influence of heave response and nacelle acceleration on towing safety.

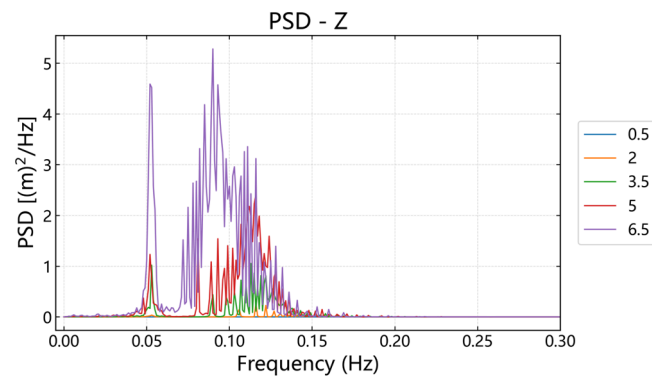


Figure 9. Power Spectral Density of Wind Turbine Heave under Different Wave Heights.

4.4. Towing Characteristics Under Different Wind-Wave-Current Directions

Table 11 summarizes the towing motion responses of the wind turbine under LC0 and LC13–LC16, corresponding to different wind-wave-current direction conditions. It should be noted that the sway response reported in Table 11 represents the lateral displacement in the global coordinate system and therefore includes the mean lateral offset of the towing trajectory. Under the oblique and transverse wind-wave-current conditions of LC14–LC16, the large sway values mainly reflect a pronounced lateral deviation of the towing trajectory, rather than a small-amplitude oscillatory sway response about an equilibrium position. It can be observed from the table that the responses exhibit significant variations under different directional conditions, with some degrees of freedom showing pronounced sensitivity to changes in direction. Figure 10 presents the statistical analysis of the responses that display more noticeable changes: sway, roll, pitch, and yaw.

Table 11. Statistical Analysis of Wind Turbine Motion Responses under Different Directions.

Response	Statistic	LC13	LC14	LC15	LC16	LC0
Sway (m)	Maximum	0.7626	167.6277	143.6403	77.8534	−0.0306
	Minimum	−0.6534	142.0545	132.3732	73.3624	−0.0379
	Mean	0.0681	157.3374	137.5804	75.4020	−0.0347
Heave (m)	Maximum	0.9071	0.8654	0.7103	0.5448	0.4841
	Minimum	−0.8871	−0.7587	−0.7624	−0.4884	−0.4455
	Mean	−0.0167	−0.0160	−0.0153	−0.0158	−0.0161
Roll (°)	Maximum	0.3004	0.7422	0.5262	0.1975	0.0217
	Minimum	−0.1375	−3.6910	−3.7800	−1.7941	0.0191
	Mean	0.0182	−1.2797	−1.3926	−0.7192	0.0204
Pitch (°)	Maximum	2.8796	1.1166	1.1684	1.5129	1.5244
	Minimum	−0.5576	−0.1995	−2.3049	−2.8610	−2.7555
	Mean	1.0722	0.4252	−0.3862	−0.5505	−0.4406
Yaw (°)	Maximum	8.2691	−28.2268	−28.8854	−15.2005	0.0168
	Minimum	−7.6017	−47.4732	−31.9845	−16.6234	−0.0038
	Mean	−0.1007	−36.0404	−30.5021	−15.9369	0.0074
Nacelle Acceleration (m/s ²)	Maximum	0.4649	0.5569	0.4775	0.5603	0.6874
	Minimum	0.0027	0.0026	0.0046	0.0013	0.0003
	Mean	0.1436	0.1560	0.1444	0.1526	0.1607

Based on the figure and table, sway and yaw are the most sensitive responses to changes in direction. Under LC13 and LC0, both sway and yaw remain at relatively low levels. The mean sway values are 0.068 m and −0.035 m, respectively, and the mean yaw values are −0.101° and 0.007°, respectively. This indicates that when the wind-wave-current

direction is approximately aligned with or opposite to the towing direction, the lateral offset and heading deviation of the platform are relatively small, and the lateral stability is favorable. In contrast, under LC14-LC16, both sway and yaw exhibit significant mean offsets, with the largest values occurring under the 45° direction, namely LC14, reaching 157.34 m and -36.04° , respectively. This indicates that, during single-tug towing, when the wind-wave-current direction is oblique or transverse to the towing direction, the lateral environmental loads increase significantly, inducing lateral offset and heading deviation of the platform and reducing the stability of the towing path.

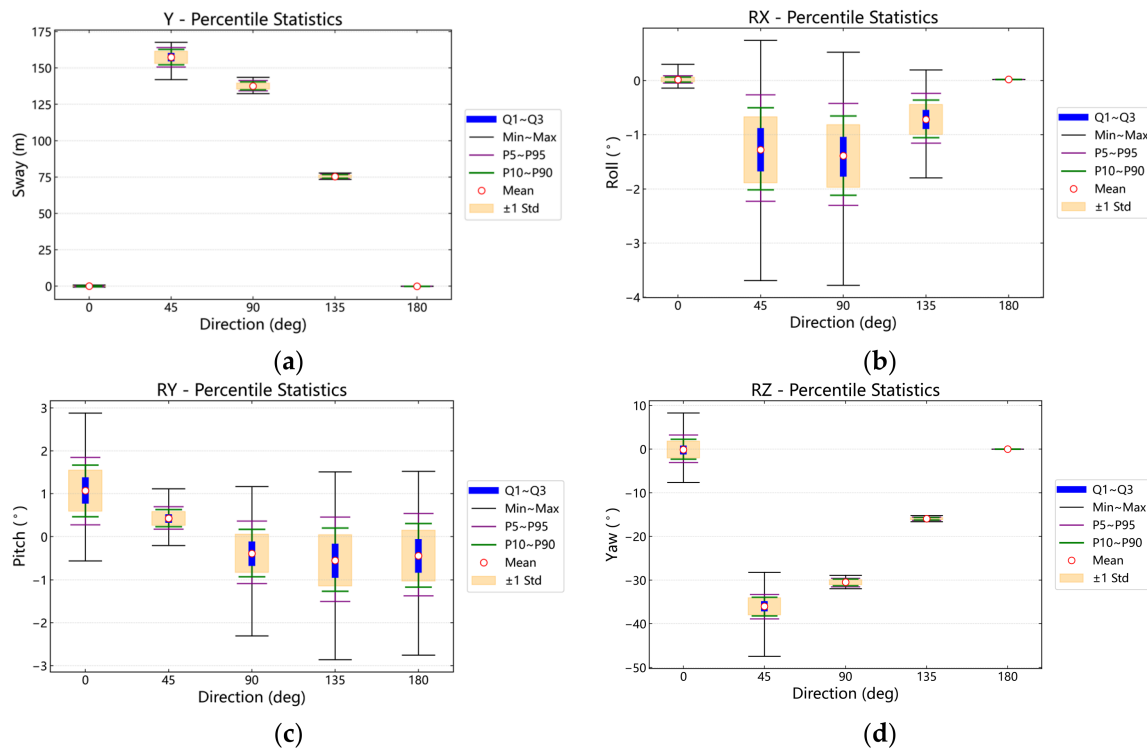


Figure 10. Statistical Analysis of Wind Turbine Motion Responses under Different Wind-Wave-Current Directions. (a) Statistical Analysis of Sway; (b) Statistical Analysis of Roll; (c) Statistical Analysis of Pitch; (d) Statistical Analysis of Yaw.

In addition to sway and yaw, the roll response also increases noticeably under LC14 and LC15, with minimum values reaching -3.691° and -3.78° , respectively. This suggests that oblique and transverse wind-wave-current loads can also induce a certain degree of roll motion. Correspondingly, the pitch response fluctuates only slightly under LC14, indicating that pitch is not the dominant control factor under this direction. The heave response shows relatively small variations with direction, with the maximum value reaching 0.907 m under LC13, suggesting that changes in wind-wave-current direction have a limited influence on vertical motion. The nacelle acceleration differs only slightly among different directions, with the maximum value of 0.687 m/s^2 occurring under LC0, which remains within the safe range.

Overall, under the calculated conditions, the wind-wave-current direction has the most pronounced influence on the lateral motions of the platform. In particular, sway and yaw increase significantly under the 45° and 90° directions. During single-tug towing, these conditions can easily lead to towing path deviation and difficulties in heading control, indicating that the lateral path-keeping capability of the single-tug towing system may be insufficient under oblique and transverse wind-wave-current conditions. Therefore, the results of LC14-LC16 primarily reflect the limitations of single-tug towing under unfavorable environmental conditions. In practical towing operations, such oblique and transverse

wind-wave-current directions should be avoided where possible, or the towing configuration should be improved through the use of auxiliary tugs. Under these conditions, sway and yaw can be used as important response indicators for identifying lateral towing-path deviation and heading-control difficulties, while variations in the roll response should also be monitored.

4.5. Analysis of Hazardous Motion Responses During Towing

To provide a more intuitive analysis of the motion performance during towing, the root mean square (RMS) values of the six-degree-of-freedom motions and nacelle acceleration of the semi-submersible wind turbine under different environmental conditions were calculated. The RMS is computed using Equation (10) and reflects the overall energy level and fluctuation intensity of the turbine responses. These results are suitable for comparative analysis across different operating conditions, as shown in Figure 11.

$$\text{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^N x_i^2} \quad (10)$$

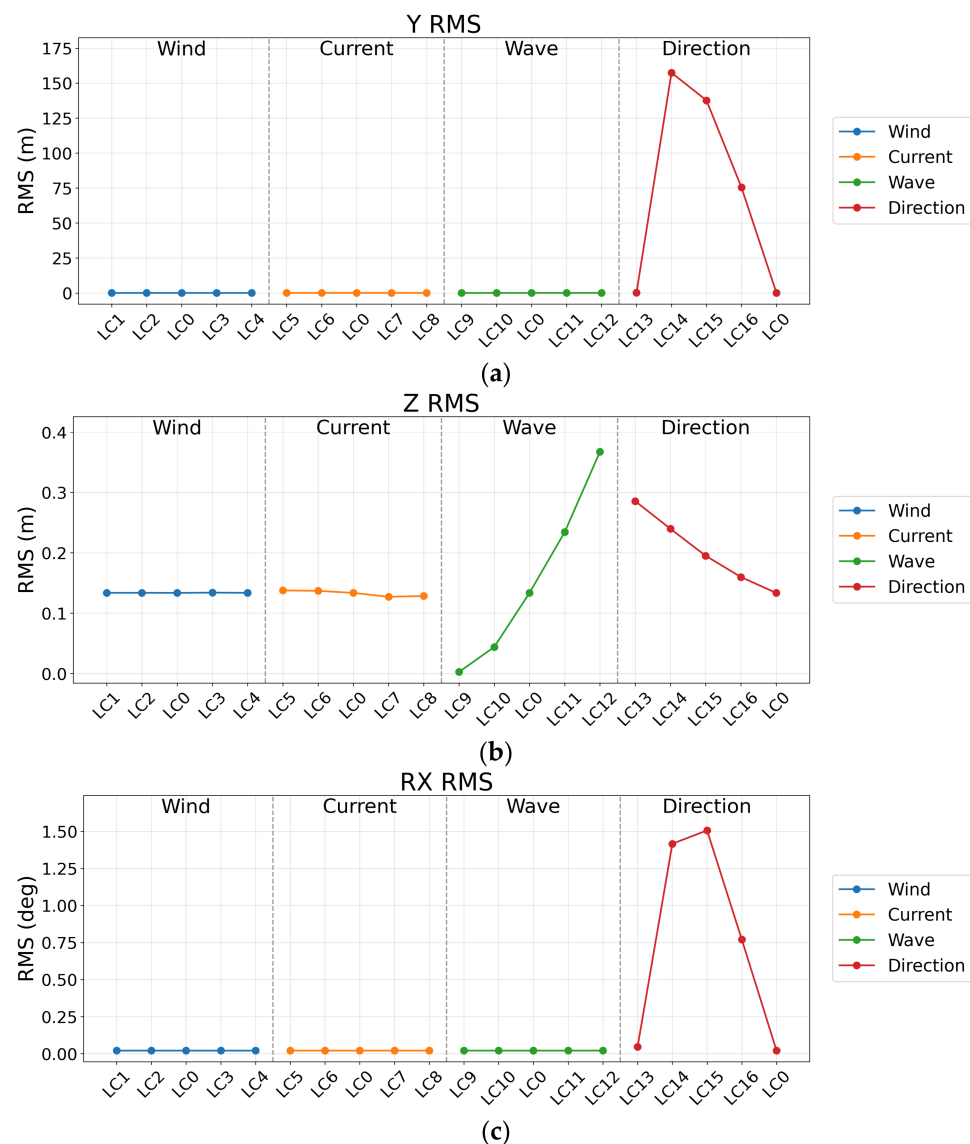


Figure 11. Cont.

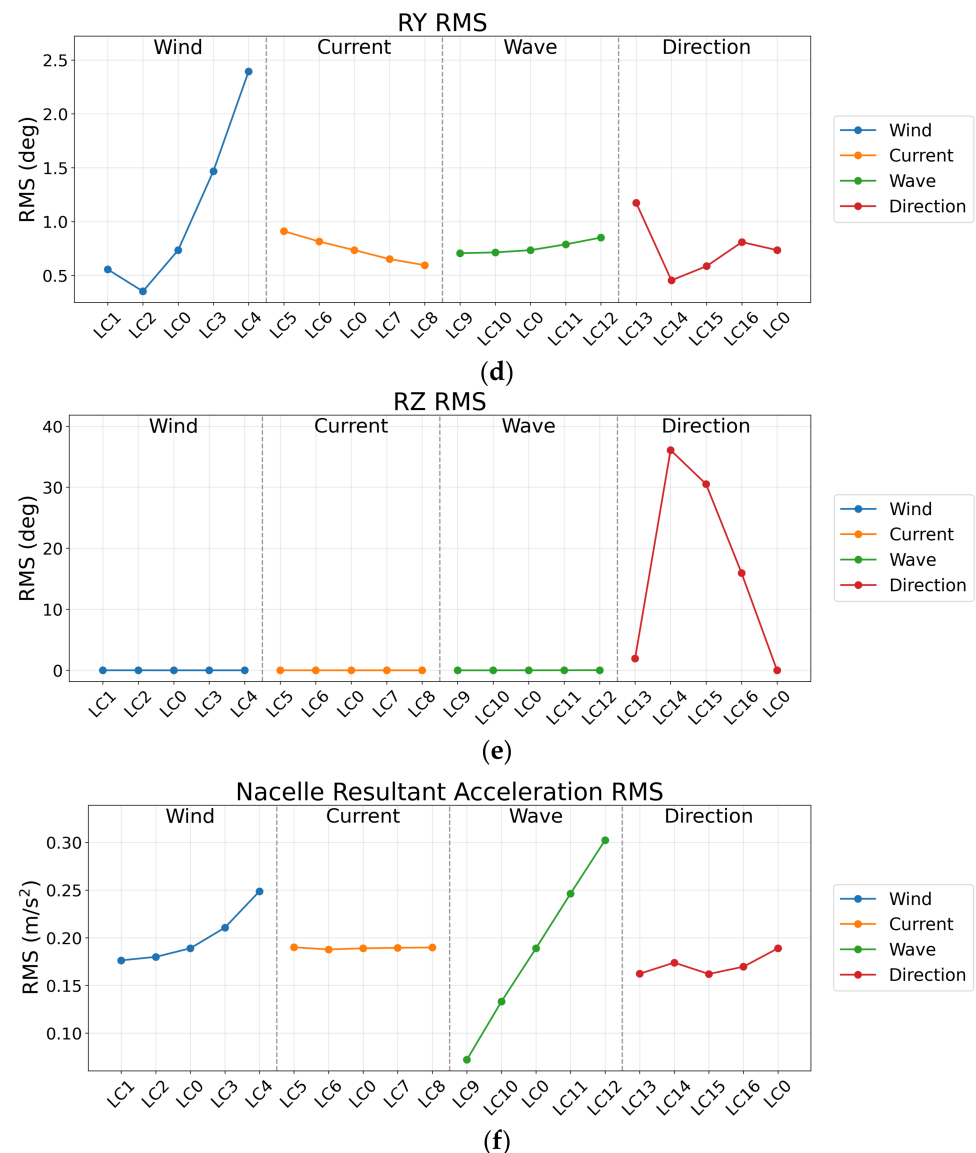


Figure 11. RMS Responses of Wind Turbine Motions and Nacelle Acceleration under Different Environmental Loads. (a) RMS of Sway; (b) RMS of Heave; (c) RMS of Roll; (d) RMS of Pitch; (e) RMS of Yaw; (f) RMS of Nacelle Acceleration.

The analysis indicates that during the towing of a semi-submersible wind turbine, different environmental factors have markedly different impacts on the six-degree-of-freedom motions and nacelle acceleration. The pitch response exhibits high sensitivity to variations in wind speed, with significant increases in extreme values, fluctuation range, and dispersion. Under high wind speed conditions, large-amplitude fluctuations may occur, making pitch a primary hazardous response that requires focused monitoring. In addition, roll responses under oblique and transverse wind-wave-current directions should also be given additional attention.

Sway and yaw responses show pronounced mean offsets under oblique and transverse wind-wave-current directions. Under single-tug towing, substantial lateral offsets can occur, making it difficult to maintain the stability of the towing path and posing a potential risk. The heave response is sensitive to variations in wave height, and its fluctuation range increases noticeably under high wave height conditions, which can intensify the vertical motion of the platform. Therefore, heave should be monitored under high wave height conditions. Nacelle acceleration is sensitive to both wind speed and wave height, with particularly significant increases in fluctuation under high wave height conditions. It

should therefore be monitored as a critical hazardous response. A summary of these findings is presented in Table 12.

Table 12. Hazardous Response Indicators of the Wind Turbine under Different Environmental Factors.

Environmental Factor	Corresponding Case	Primary Hazardous Response	Secondary Hazardous Response
High Wind Speed	LC3, LC4 (LC4: not recommended as a towing window)	Pitch	Nacelle Acceleration
Different Current Speeds	LC0, LC5–LC8	negligible effect on response amplitudes	/
High Wave Height	LC11, LC12	Nacelle Acceleration	Heave
Transverse/oblique wind-wave-current directions	LC14–LC16	Insufficient single-tug path-keeping capability; sway and yaw as monitoring indicators	Roll
Combined	LC0–LC16	Pitch, Nacelle Acceleration	Sway, Yaw

Existing offshore transportation guidelines and design bases for floating offshore wind turbines usually impose limits on the roll and pitch motions of the floating body as well as the nacelle acceleration. DNVGL-ST-N001 [31] provides default motion criteria for marine transportation operations. Under restricted-weather conditions, the reference single-amplitude criteria for roll and pitch can be taken as approximately 5° . In addition, Gerwick [32], in *Construction of Marine and Offshore Structures*, gives a typical stability requirement for towed structures, stating that the maximum inclination angle should not exceed 5° under specified wind, wave, and towline loads. The COREWIND D1.2 Design Basis [33] provides a reference value for nacelle acceleration of FOWTs, which is approximately 0.3 g.

To establish engineering-based criteria for hazardous response identification, this study refers to the above standards and design documents, together with the numerical results obtained in this study. The pitch response under LC4 exceeds the 5° reference threshold and should not be regarded as a towing window with sufficient safety margin. LC4 is therefore considered an inadvisable towing condition. Although the pitch response under LC3 remains below the threshold, it is already close to this limit and should be closely monitored under high wind speed conditions. The main reason is that, as wind speed increases, the wind forces and moments acting on the elevated upper structures, such as the tower and blades, increase significantly. Under the combined effects of towline constraints and wave excitation, the platform pitch response is further amplified. Therefore, pitch should be considered as the primary hazardous response for towing safety control under high wind speed conditions. Although the nacelle acceleration does not exceed the 0.3 g limit under the investigated conditions, it shows a clear increasing trend under both high wind speed and high wave height conditions and should therefore be treated as an important monitoring indicator. Meanwhile, although sway and yaw are not directly limited by the guidelines as inclination or acceleration indicators, oblique and transverse wind-wave-current conditions can significantly affect towing-path stability and heading-control capability in a single-tug towing configuration. The results for LC14–LC16 demonstrate the limitations of single-tug towing under unfavorable environmental conditions. Therefore, sway and yaw should be monitored as indicators of towing-path deviation and difficulties in heading control during single-tug towing operations.

4.6. Limitations

Based on a coupled tug-towline-FOWT numerical model, this study analyzed the effects of different environmental factors on the wet-towing motion responses and nacelle acceleration of a floating offshore wind turbine and identified the key hazardous response indicators under different operating conditions. However, several limitations remain in this study.

First, the present simulations are based on a single-tug towing configuration and focus mainly on the effects of environmental factors, including wind speed, current speed, wave height, and the relative wind-wave-current direction, on the towing responses. The effects of tug control and multi-tug cooperative control strategies on the system motion responses are not further considered. Therefore, the large sway and yaw responses observed under oblique or transverse wind-wave-current conditions mainly reflect the reduced path-keeping and heading-control capabilities of the single-tug towing system under unfavorable environmental directions. These responses should not be interpreted as evidence that towing operations under such conditions still have sufficient controllability. In practical engineering applications, similar conditions should be further evaluated in combination with the actual towline arrangement and auxiliary tug configuration.

In addition, the towing speed directly affects towing resistance, FOWT motion responses, and related dynamic characteristics. In this study, a fixed towing speed is adopted to ensure comparability among the effects of different environmental factors, and towing speed is not analyzed as an independent variable. The investigated cases are mainly based on typical environmental conditions in the South China Sea. Therefore, the applicability of the conclusions to other sea areas or more extreme sea states requires further analysis using site-specific environmental parameters. Accordingly, this study mainly aims to reveal the response variation patterns and hazardous response indicators of a large-scale semi-submersible FOWT under different environmental factors during wet towing, and the results can provide a reference for towing safety assessment and weather-window selection. For specific engineering applications, further verification should be conducted by considering site-specific environmental conditions and the actual control strategies of the tug system.

5. Conclusions

To address the unclear hazardous response indicators and the lack of systematic understanding of environmental effects during the wet towing of large-scale semi-submersible FOWTs, this study established a coupled dynamic model of the tug-towline-semi-submersible wind turbine system based on a multibody dynamics approach. Time-domain response analyses of the semi-submersible wind turbine during towing under different environmental conditions were conducted, and key hazardous response factors were identified. The main conclusions are as follows:

1. Environmental factors significantly affect towing motion responses, and different environmental factors have distinct influences on different response quantities. Among them, wave height has the most pronounced effect on heave and nacelle acceleration. As wave height increases, the fluctuation range of the heave response expands significantly, reaching approximately -1.37 m to 1.32 m under high wave height conditions. Nacelle acceleration also shows a clear increasing trend, with the maximum value reaching approximately 1.15 m/s². This indicates that wave excitation is an important source of the enhanced vertical dynamic response of the platform during towing. Under high wave height conditions, particular attention should be paid to the influence of nacelle acceleration and heave response on towing safety;

2. Wind speed has a particularly prominent effect on pitch response. As wind speed increases, the pitch response is significantly amplified, with the extreme-value range reaching approximately -7.17° to 2.84° under the 24 m/s wind speed condition. This indicates that the wind-induced moment acting on the upper wind turbine structure can intensify the longitudinal attitude variation in the platform. Nacelle acceleration also exhibits a moderate increase with wind speed. In contrast, the influence of current speed on the responses in all degrees of freedom and nacelle acceleration is relatively weak, and the response quantities do not exhibit an obvious monotonic amplification trend;
3. Wind-wave-current direction has an important influence on towing system stability. Under a single-tug towing configuration, when the wind-wave-current direction is approximately aligned with or opposite to the towing direction, the lateral offset and heading deviation of the platform are relatively small, indicating favorable lateral stability. In contrast, under oblique and transverse wind-wave-current conditions, sway and yaw responses exhibit significant mean offsets, indicating insufficient path-keeping and heading-control capabilities of the single-tug towing system. During towing operations, transverse and oblique wind-wave-current directions should be avoided or further evaluated with the assistance of auxiliary tugs;
4. Combined with offshore transportation criteria, towing stability requirements for offshore structures, and design bases for floating offshore wind turbines, the analysis of response characteristics across all scenarios indicates that pitch under high wind speed conditions should be considered a primary hazardous response. In particular, the pitch response under LC4 exceeds the 5° reference threshold, and this condition is therefore not recommended as a towing window with sufficient safety margin, whereas LC3 should be treated as a key monitoring condition because its pitch response approaches the threshold. Nacelle acceleration and heave under high wave height conditions should be closely monitored as key hazardous responses.

The results of this study provide a theoretical reference for safety assessment and the development of optimal control strategies during the offshore towing of floating wind turbines. On this basis, future research may be further conducted in the following aspects: (1) analyzing the effects of towing speed, towline damping, tug control strategies, and multi-tug cooperation on towing responses; (2) further investigating towing safety boundaries under different sea areas, extreme sea states, and non-collinear wind-wave-current conditions; (3) optimizing wet-towing schemes for FOWTs by considering response limits and weather-window requirements, thereby providing a more comprehensive basis for towing direction selection, speed control, and hazardous response monitoring in practical engineering applications.

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Abbreviations

The following abbreviations are used in this manuscript:

FOWT	Floating Offshore Wind Turbine
RMS	Root Mean Square
LC	Load Case
JONSWAP	Joint North Sea Wave Project

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