

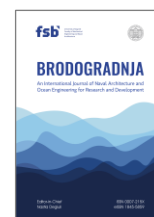


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Coupled aero-hydro-servo-mooring dynamic responses of a semi-submersible floating offshore wind turbine subjected to wind, wave and current loading



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ABSTRACT

To investigate the dynamic response of a semi-submersible floating offshore wind turbine (FOWT) under combined wind, wave, and current conditions, an integrated multi-physics time-domain dynamic model was developed based on blade element momentum (BEM) theory and potential flow theory. This study investigates aerodynamic performance, platform motions, and mooring tension characteristics under different environmental conditions, revealing the influence mechanisms of these factors on the FOWT system. Research indicates that wave loads dominate dynamic oscillations. The heave response increases to 4.35 times its original value near resonance with the natural period, while exhibiting weak coupling with aerodynamic performance. Increasing wave height induces nonlinear growth in platform responses, with peak surge displacement doubling and pitch motion increasing by 53.6 %. This intensification of second-order slow-drift excitation further raises rotor thrust fluctuations by 28.2 %. Wind loads primarily determine steady-state platform attitudes and power production, with rated wind speed producing the largest mean offsets and stronger aerodynamic load fluctuations. Ocean currents primarily induce static equilibrium shifts, increasing the mean platform offset by 12.9 %. However, the influence of current velocity on dynamic response amplitudes and aerodynamic performance is less than 1 %.

1. Introduction

Driven by dwindling conventional fossil energy reserves and the compounding threat of associated environmental degradation, the large-scale, efficient exploitation of renewable alternatives has become a paramount global imperative [1-3]. Common marine renewable energy sources include tidal current energy [4-6], wave energy [7-9], and offshore wind energy [10-12]. Among these resources, offshore wind energy

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has attracted extensive attention due to its abundant resource potential, economic competitiveness, and technological maturity, making it one of the most promising commercially developed renewable energy sectors with significant electricity generation potential [13-15].

As the primary devices for exploiting offshore wind resources, offshore wind turbines are generally classified into fixed-bottom and floating configurations based on their substructure types. Research on fixed-bottom turbines is relatively mature, focusing primarily on the wave load characteristics of foundation forms such as monopiles and jackets, pile-soil interaction, and dynamic responses in harsh marine environments [16, 17]. Paulsen et al. [18] investigated the impact of wave slamming on monopile foundations, establishing a closed-form expression for wave slamming probability and a simplified formula for slamming loads, and further analyzed the effects of slamming loads on the global wind turbine structure through time-domain simulations. Padrón et al. [19] utilized a comprehensive aero-hydro-servo-elastic framework incorporating dynamic pile-soil interaction to assess the structural behaviors of offshore wind systems under wind, wave, and seismic loadings.

As offshore wind deployment expands into deeper waters, floating offshore wind turbines (FOWTs) are emerging as a promising alternative to traditional fixed-bottom turbines due to their technical viability and potential economic advantages [20, 21]. However, this transition introduces a fundamental shift in the system's dynamic characteristics. Unlike fixed-bottom structures, which benefit from stiff foundations that effectively constrain global motions, floating installations are highly compliant and subject to pronounced six-degree-of-freedom rigid-body motions under complex marine environments [22, 23]. Despite the strong interaction between aerodynamic loads and platform motions, early-stage studies predominantly adopted one-way coupled approaches to reduce computational costs. Cai et al. [24] employed a computational fluid dynamics (CFD)-based framework to investigate the dynamic aerodynamic responses of floating wind turbines subjected to simultaneous surge and pitch motions. Fang et al. [25] investigated the aerodynamic responses of the NREL 5MW wind turbine under platform motions using high-fidelity unsteady CFD simulations. By imposing prescribed single-degree-of-freedom (DOF) harmonic motions, they analyzed the unsteady aerodynamic characteristics of the turbine under various motion frequencies and amplitudes.

Fully integrated aero-hydro-servo-mooring numerical frameworks have been widely developed to improve the accuracy of predicting FOWT dynamic responses under combined wind, wave, and current loads [26-28]. Based on the different hydrodynamic solution methods, these methods are primarily categorized into two approaches: potential flow theory and viscous flow theory. Potential flow theory is based on the assumptions of inviscid and irrotational flow, offering high computational efficiency that is well-suited for long-term, multi-condition time-domain coupled analysis. Moreover, it can effectively handle first-order wave-frequency loads and second-order difference-frequency loads, facilitating frequency-domain natural period estimation and resonance analysis. Jonkman et al. [29] developed a comprehensive aero-hydro-servo-elastic simulation framework by merging the fundamental capabilities of the FAST, AeroDyn, and HydroDyn codes. Coulling et al. [30] validated this FAST simulation framework against DeepCwind experimental data, demonstrating its accuracy for semi-submersible platforms. Yang et al. [31, 32] developed the F2A coupling interface and its open-source extension OpenF2A, which integrates ANSYS AQWA hydrodynamic capabilities into the FAST/OpenFAST aero-servo-elastic platform, enabling multi-physics time-domain simulations of floating offshore wind turbines. The viscous flow method solves governing equations based on the Navier–Stokes equations and can capture strongly nonlinear phenomena such as flow separation, vortex shedding, and wave breaking, providing more accurate simulations of the flow details around complex structures [33-37]. Tran et al. [38] implemented a multiphase flow approach within a CFD framework to investigate the coupled aerodynamic and hydrodynamic effects on the stability and rotor aerodynamics of a semi-submersible turbine. Cheng et al. [39] constructed an integrated hydro-aero-mooring numerical tool (FOWT-UALM-SJTU) using OpenFOAM, performing comprehensive evaluations on the interactive dynamics of FOWT configurations.

While the previous studies have conducted extensive investigations into floating wind turbines, most of them have focused on the dynamic responses under specific combinations of environmental parameters or typical operating scenarios. Consequently, a clear understanding of how variations in environmental

parameters, including wind speed, wave conditions, and current velocity, affect the overall dynamic responses of FOWTs remains limited [40, 41]. To bridge this gap and provide a comprehensive reference for robust system design, this study systematically evaluates the impact of continuous ambient fluctuations on floating wind systems. For this purpose, the NREL 5MW turbine mounted on the OC4-DeepCwind semi-submersible foundation is adopted as the baseline model. This platform was selected due to its widespread adoption as a benchmark case and extensive experimental validation, making it a representative model for FOWT research [42, 43]. Specifically, the system dynamic responses are evaluated under a range of wind speeds, wave conditions (including wave height and period), and current velocities. By systematically analyzing these multi-dimensional parameter variations, this work reveals the coupling mechanisms and sensitivity characteristics of the system, providing valuable insights for structural optimization and safety assessment of future floating offshore wind projects. The overall floating wind turbine is shown in Figure 1.

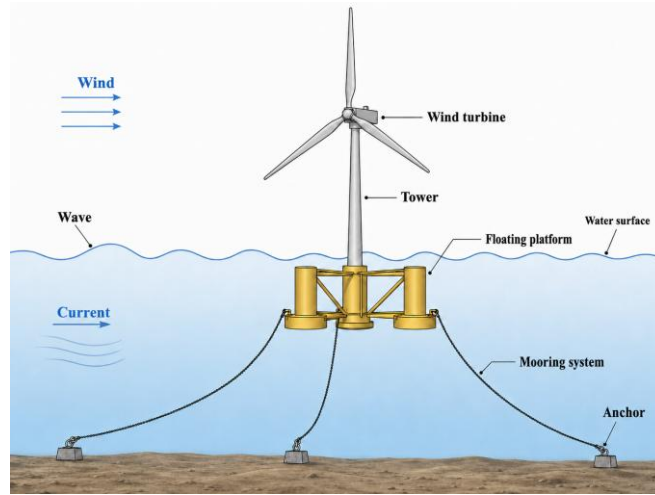


Fig. 1 Geometric model of floating wind turbine system

2. Numerical methodology

2.1 Aerodynamic model

To resolve blade aerodynamics via blade element theory, each blade is idealized as an assembly of multiple isolated cross-sections. [44]. By performing a spanwise integration of these localized aerodynamic inputs, the macroscopic thrust and driving torque of the entire blade are obtained. The governing formulations for the specific thrust and torque are defined as follows:

$$dT = \frac{1}{2} \rho_a V_{rel}^2 N c (C_L \cos \theta - C_D \sin \theta) dr \quad (1)$$

$$dM = \frac{1}{2} \rho_a V_{rel}^2 N c (C_L \sin \theta + C_D \cos \theta) r dr \quad (2)$$

where V_{rel} denotes the blade velocity relative to the ambient airflow, c represents the local chord length of the respective blade element profile, N signifies the number of blades, C_L and C_D denote the respective coefficients for lift and drag. θ represents the aerodynamic inflow angle, and r signifies the blade radius. The computational framework directly incorporates the aerodynamic penalties stemming from tip and hub losses, as well as skewed wake inductions. Furthermore, to accurately correct the aerodynamic coefficients amidst severely transient states, the framework further incorporates the dynamic stall model proposed by Beddoes-Leishman.

2.2 Hydrodynamic model

2.2.1 Wave load

The OC4-DeepCwind semi-submersible platform is classified as a large-scale structure, as the ratio of its characteristic diameter to wavelength (D/L) exceeds 0.2. Consequently, wave diffraction effects become significant, thereby necessitating the implementation of a potential flow theory approach within the numerical framework to resolve the wave-induced loadings. The core of potential flow theory lies in the assumption that the flow field is irrotational and potential, which allows for the definition of a velocity potential function $\Phi(x, y, z, t)$. This velocity potential can be expressed as:

$$\Phi(x, y, z, t) = \Phi_I + \Phi_D + \Phi_R \quad (3)$$

where Φ_I represents the velocity potential of the unperturbed incoming wave field, Φ_D denotes the diffraction potential resulting from the interference of waves by the structure, and Φ_R represents the radiation potential emerging from the hydrodynamic disturbances generated by the rigid-body motions of the structure.

Throughout the fluid domain, the velocity potential characterizing the flow field is required to conform to the following governing criteria.

The Laplace equation in the fluid domain:

$$\frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2} + \frac{\partial^2 \Phi}{\partial z^2} = 0 \quad (4)$$

The bottom boundary condition:

$$\frac{\partial \Phi}{\partial z} = 0 \quad (5)$$

The free surface condition:

$$-\omega^2 \Phi + g \frac{\partial \Phi}{\partial z} = 0 \quad (6)$$

The body boundary condition:

$$\frac{\partial \Phi}{\partial \mathbf{n}} = \mathbf{v}_n \quad (7)$$

Within the theoretical framework of potential flow, the total wave-induced loading F_w experienced by the floating body is mathematically decoupled into two distinct parts: the first-order wave-frequency components alongside the second-order difference-frequency excitations.

$$\mathbf{F}_w = \mathbf{F}_{ex(1)} + \mathbf{F}_{ex(2)} \quad (8)$$

where $\mathbf{F}_{ex(1)}$ is generated based on the JONSWAP spectrum using the principle of linear superposition [45]:

$$\mathbf{F}_{ex(1)} = \text{Re} \left[\sum_{k=1}^N A_k \mathbf{X}(\omega_k) e^{j\omega_k t} \right] \quad (9)$$

where A_k represents the complex-valued spectral amplitude associated with the k wave constituent, and $\mathbf{X}(\omega_k)$ represents the first-order wave excitation force transfer function.

$\mathbf{F}_{ex(2)}$ is employed to capture the low-frequency response of the platform under high sea states, and its theoretical expression is given as [45]:

$$\mathbf{F}_{ex(2)} = \text{Re} \left[\sum_{k=1}^N \sum_{l=1}^N A_k A_l^* \mathbf{X}^-(\omega_k, \omega_l) e^{j(\omega_k - \omega_l)t} \right] \quad (10)$$

where $\mathbf{X}^-(\omega_k, \omega_l)$ represents the second-order difference-frequency quadratic transfer function.

2.2.2 Wind load

The Kaimal wind spectrum is commonly employed in engineering practice to simulate turbulent winds. The aerodynamic force sustained by the floating offshore wind turbine (FOWT), designated as $\mathbf{F}_a$, can be quantified via the following expression [46]:

$$\mathbf{F}_a = C_h C_s A_a \mathbf{p}_a \quad (11)$$

where C_h represents the height coefficient, C_s is the shape coefficient, A_a represents the equivalent area of the wind turbine components exposed to wind, and $\mathbf{p}_a$ is the wind pressure, which is defined as:

$$\mathbf{p}_a = \frac{1}{2} \rho_a V_a^2 \quad (12)$$

where ρ_a is the air density, and V_a represents the design wind speed.

2.2.3 Current load

The velocity and period of ocean current particle motion exhibit slow temporal variations. The current load $\mathbf{F}_c$ acting below the water surface is expressed as:

$$\mathbf{F}_c = \frac{1}{2} A_c C_D \rho_w V_c^2 \quad (13)$$

where A_c represents the effective area of the platform's underwater geometry subjected to the incident current, C_D denotes the drag coefficient, ρ_w denotes the seawater density, and V_c represents the current velocity.

2.2.4 Equations of motion

The dynamic equation dictating the platform's motions is mathematically formulated as [47]:

$$\mathbf{K}\mathbf{X}(t) + \mathbf{C}\dot{\mathbf{X}}(t) + (\mathbf{m} + \mathbf{A}_\infty)\ddot{\mathbf{X}}(t) + \int_0^t h(t-\tau)\ddot{\mathbf{X}}(\tau)d\tau = \mathbf{F}_t(t) + \mathbf{F}_h(t) + \mathbf{F}_e(t) \quad (14)$$

where $\mathbf{K}$ represents the total rigidity matrix, $\mathbf{C}$ denotes the total damping matrix, $\mathbf{m}$ represents the structural mass matrix, $\mathbf{A}_\infty$ is the instantaneous added mass matrix, $\mathbf{X}(t)$, $\dot{\mathbf{X}}(t)$, and $\ddot{\mathbf{X}}(t)$ signify the respective vectors for the displacement, velocity, and acceleration of the floating system, $h(t-\tau)$ represents the retardation function, $\mathbf{F}_t(t)$ denotes the tension exerted by the mooring system on the platform, $\mathbf{F}_h(t)$ denotes the aggregate hydrodynamic load on the floating platform, $\mathbf{F}_e(t)$ denotes the external excitation vector calculated via an external Dynamic Link Library.

2.3 Mooring load

A dynamic modeling method is employed in the calculation of mooring tension to accurately predict the dynamic response of mooring cables. It is assumed that the mooring line consists of N uniformly sized Morison elements, with each segment possessing identical density and geometric characteristics.

The governing equations of motion for an arbitrary mooring line element are expressed as [48]:

$$\frac{\partial \mathbf{T}_a}{\partial S_e} + \frac{\partial \mathbf{V}}{\partial S_e} + w + \mathbf{F}_h = m_e \frac{\partial^2 \mathbf{R}}{\partial t^2} \quad (15)$$

$$\frac{\partial \mathbf{M}_a}{\partial S_e} + \frac{\partial \mathbf{R}}{\partial S_e} \mathbf{V} = -\mathbf{q} \quad (16)$$

where $\mathbf{T}_a$ represents the tension vector at the mooring element nodes, $\mathbf{V}$ represents the shear force vector, w is the linear weight density of the respective mooring segment, $\mathbf{F}_h$ represents the hydrodynamic forcing vector per unit length, m_e is the mass per unit length, $\mathbf{R}$ is the spatial coordinate vector, S_e denotes the unstretched length of the mooring element, $\mathbf{q}$ denotes the distributed moment load per unit length, $\mathbf{M}_a$ represents the bending moment vector.

The expressions for the bending moment $\mathbf{M}_a$ and tension $\mathbf{T}_a$ acting on the mooring line are given as follows:

$$\mathbf{M}_a = EI \frac{\partial \mathbf{R}}{\partial S_e} \frac{\partial^2 \mathbf{R}}{\partial S_e^2} \quad (17)$$

$$\mathbf{T}_a = EA \varepsilon \quad (18)$$

where EI represents the flexural rigidity of the mooring line, EA denotes the axial stiffness, and ε is the axial strain.

3. Numerical model validation

3.1 Parameters of the FOWT

The structural configuration of the floating offshore wind turbine based on the DeepCwind platform primarily comprises three components: the wind turbine, the floating platform, and the mooring system. The NREL 5MW reference wind turbine is employed, with its main specifications summarized in Table 1. The floating platform adopts the OC4-DeepCwind semi-submersible concept, and its main characteristics are presented in Table 2. A catenary mooring system is used, with the relevant mooring parameters provided in Table 3.

Table 1 Parameters of NREL-5MW wind turbine

Wind turbine parameters	Value
Rated power (MW)	5
Number of blades	3
Rotor diameter (m)	126
Hub diameter (m)	3
Rated rotor speed (rpm)	12.1
Rated wind speed (m/s)	11.4

Table 2 Parameters of OC4-DeepCWind floating platform

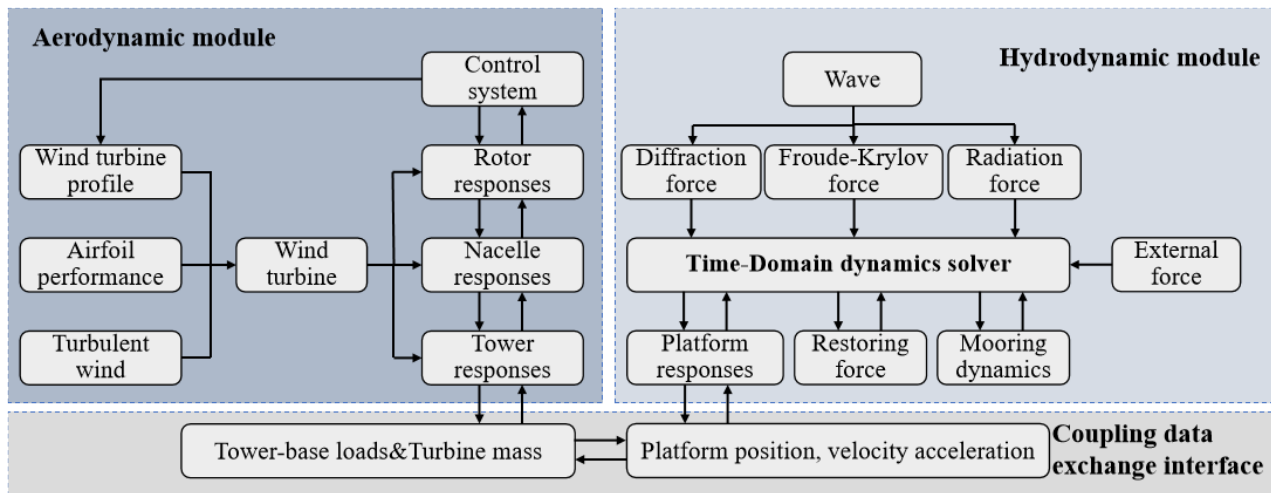
Platform parameters	Value
Platform mass (kg)	1.347×10^7
Maximum draft of the platform (m)	20
Center of gravity height (m)	-13.46
Platform roll moment of inertia (kg m^2)	6.827×10^9
Platform pitch moment of inertia (kg m^2)	6.827×10^9
Platform yaw moment of inertia (kg m^2)	1.226×10^{10}

Table 3 Parameters of catenary mooring cable

Mooring parameters	Value
Number of mooring lines	3
Mooring line length (m)	835.35
Mooring line stiffness (N)	7.536×10^8
Mooring line linear density (kg/m)	113.35
Anchor depth (m)	200
Anchor radius (m)	837.6
Fairlead depth (m)	14
Fairlead radius (m)	40.87

3.2 Fully coupled method

This study establishes an integrated aero-hydro-servo-mooring coupled numerical framework to simulate the nonlinear interactions among aerodynamic, hydrodynamic, and mooring loads under complex environmental conditions. The framework adopts a time-domain iterative coupling strategy for solving the interactions between external forces and platform motions. The aerodynamic module employs blade element momentum theory to calculate instantaneous aerodynamic forces and moments acting on the rotor, nacelle, and tower, which are subsequently applied to the platform equations of motion. The three-dimensional potential-flow hydrodynamic model is coupled with the nonlinear restoring characteristics of the mooring system. The coupled solver is then used to calculate the six-degree-of-freedom motions of the floating platform under combined wave excitation and aerodynamic loads. Through bidirectional coupling, the instantaneous platform motions are fed back to the aerodynamic module to update the relative wind velocity and account for motion-induced changes in the inflow conditions. This procedure ensures dynamic consistency within each time step and enables nonlinear coupled simulations of the floating wind turbine system, as illustrated in Figure 2.

**Fig. 2** Numerical method coupling framework

3.3 Numerical validation

The reliability of FAST has been extensively validated through benchmark studies, including the OC3-Hywind spar platform [49] and the OC4-DeepCwind semi-submersible platform [50], with numerical predictions showing good agreement with reference and experimental results. To confirm the fidelity of the present numerical framework, its time-domain simulation histories are cross-verified against OpenFAST benchmarks under a turbulent wind regime. The synthesis of full-field ambient turbulence relies on the TurbSim simulator incorporating the standard Kaimal wind profile. The reference velocity at the hub center is restricted to the nominal rated value of 11.4 m/s, a critical operational state chosen to capture the maximum

rotor thrust and the severest dynamic coupling responses. To represent the metocean environment, a JONSWAP formulation is adopted to prescribe the wave field (characterized by a significant wave height of 1.77 m and a peak spectral period of 7.51 s), which acts in combination with a uniform 0.3 m/s steady current. These parameters are deliberately selected to replicate a typical correlated sea state corresponding to the rated wind speed for realistic validation. The numerical integration spans a total duration of 4500 s, resolved at a constant time step of 0.005 s.

Figure 3 presents the comparison of aerodynamic loading profiles simulated by the developed method against OpenFAST benchmarks. The transient time-series evaluation results show that the evolutionary trends of both remain consistent over the entire simulation window. To further quantify the agreement, Table 4 provides a statistical comparison of rotor power and thrust. The errors are all within 10 %, and these quantitative metrics confirm the high fidelity of the developed time-domain simulator in resolving aerodynamic loads for floating wind turbines.

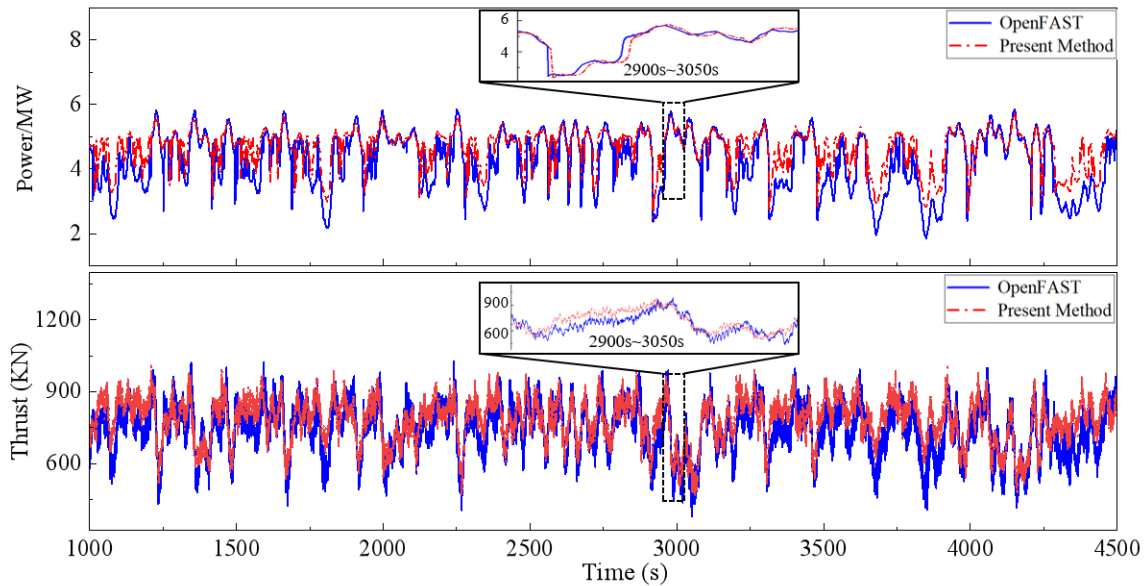


Fig. 3 Comparison of aerodynamic loads

Table 4 Statistical comparison of rotor power and thrust between the present method and OpenFAST

Parameter	Metric	OpenFAST	Present Method	Relative Error (%)
Rotor power (MW)	Max	5.85	5.64	3.59
	Mean	4.75	4.59	3.37
	SD	0.88	0.82	6.82
Rotor thrust (kN)	Max	1038.63	1020.15	1.79
	Mean	741.87	780.12	5.15
	SD	103.07	96.36	6.51

Figure 4 and Table 5 present the comparative results specifically for the platform motion responses. Evidently, the oscillation magnitudes and evolutionary trajectories of the platform pitch computed via the developed framework closely mirror the reference solutions from OpenFAST. The quantitative data detailed in Table 5 further substantiate this high fidelity, revealing that the discrepancies in surge, heave, and pitch motions between the two methods are minimal, with all relative errors strictly constrained within 10 %.

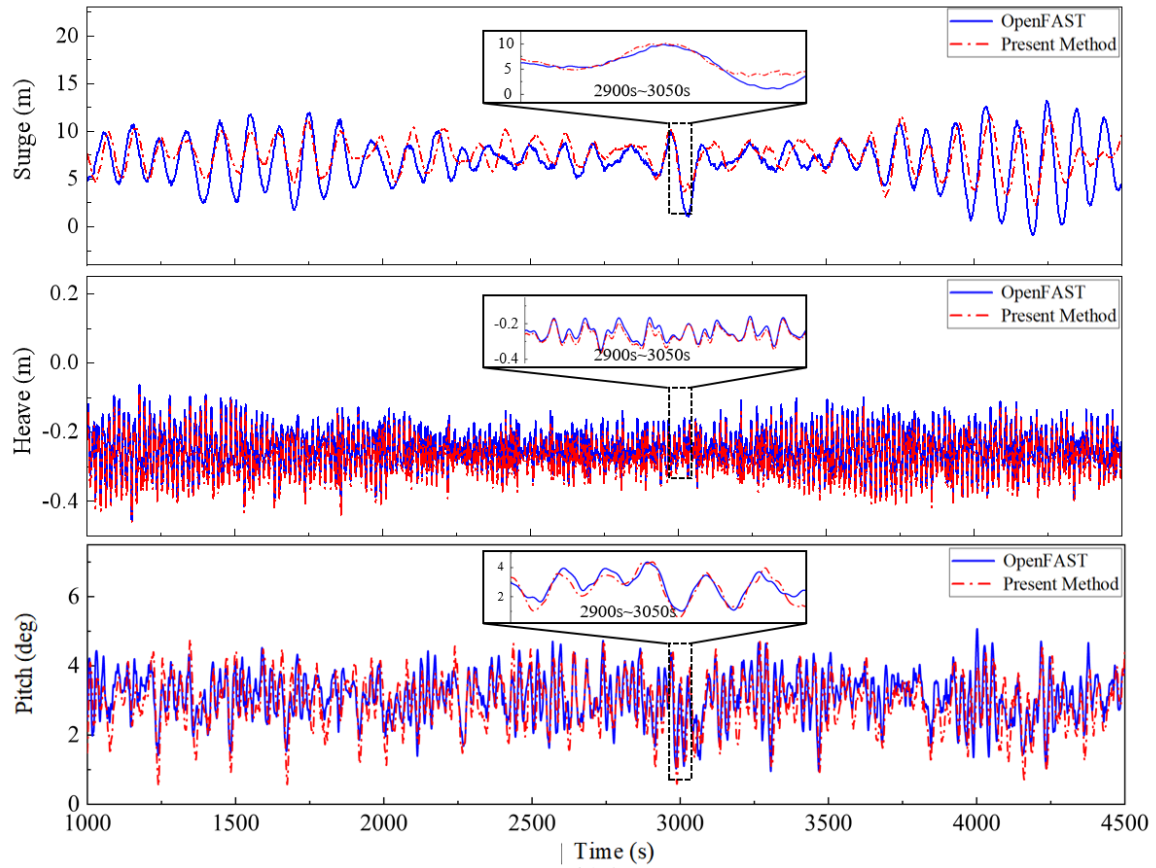


Fig. 4 Comparison of platform movements

Table 5 Statistical comparison of platform surge, heave, and pitch between the present method and OpenFAST

Parameter	Metric	OpenFAST	Present Method	Relative Error (%)
Surge (m)	Max	13.22	11.93	9.80
	Mean	6.89	7.23	4.93
	SD	2.11	1.91	8.30
Heave (m)	Max	-0.063	-0.069	9.52
	Mean	-0.25	-0.27	8.36
	SD	0.0580	0.0581	0.17
Pitch (°)	Max	5.07	4.82	4.93
	Mean	3.10	3.02	2.58
	SD	0.68	0.62	8.82

Figure 5 and Table 6 evaluate the main mooring load characteristics. While the time-domain variation trends remain highly consistent, the quantitative differences are slightly higher than those of the platform motions. Nevertheless, the maximum error for mooring tension remains below 10 %. This minor divergence is fundamentally attributed to differing mooring dynamics principles, specifically line element discretization schemes, seabed touchdown models, and the coupling of structural elasticity with fairlead kinematics. Overall, these combined results confirm the reliability of the developed framework in calculating both platform motions and mooring loads.

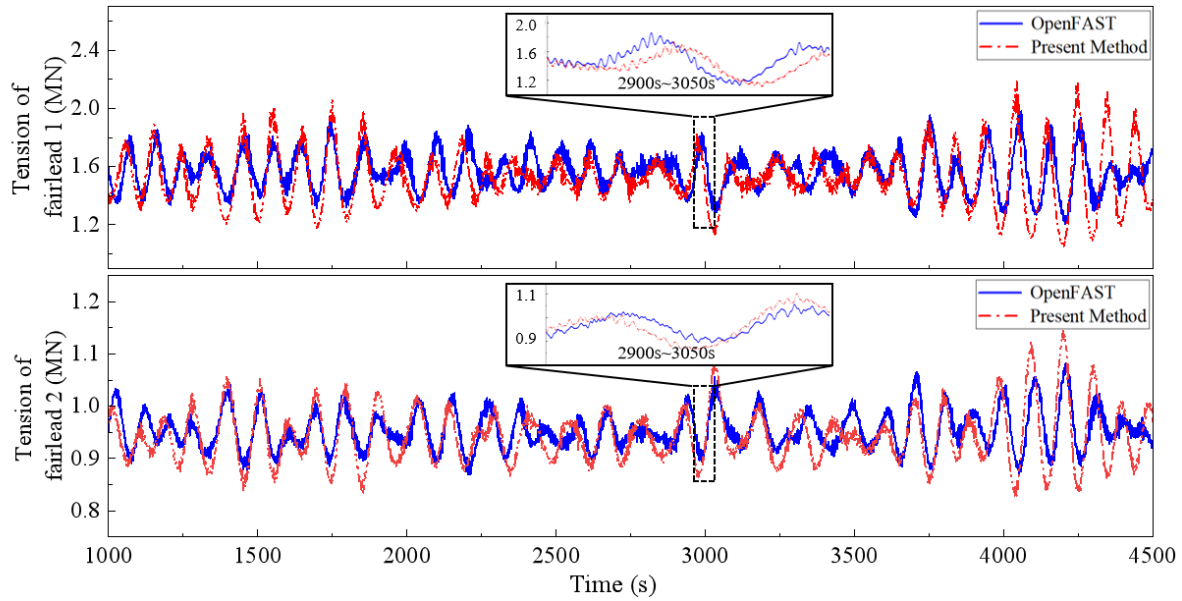


Fig. 5 Comparison of mooring load

Table 6 Statistical comparison of mooring line tension between the present method and OpenFAST

Parameter	Metric	OpenFAST	Present Method	Relative Error (%)
Tension of fairlead 1 (MN)	Max	2.21	2.07	6.33
	Mean	1.54	1.53	0.65
	SD	0.18	0.15	16.6
Tension of fairlead 2 (MN)	Max	1038.63	1020.15	1.79
	Mean	1.00	1.03	3.01
	SD	0.028	0.031	10.71

4. Results and discussion

4.1 Case configuration

To unravel the coupling effects of metocean conditions on the semi-submersible floating wind system and its associated moorings, a parametric sensitivity study comprising thirteen distinct operational cases was conducted via a control-variable scheme (Table 7). The simulation framework captures the turbulent wind inflows using a Kaimal spectrum and establishes the irregular wave fields through a JONSWAP spectrum characterized by a peak enhancement factor of $\gamma = 3.3$. With Case 1 serving as the baseline, Cases 2-4 increase the peak period from 6.5 to 13.5 s while keeping wave height, wind, and current constant; Cases 5-7 increase the wave height from 2.95 to 12.5 m with the wave period, wind, and current held constant; Cases 8-10 increase the wind speed from 3 to 11.4 m/s while maintaining wave parameters and current velocity; and Cases 11-13 increase the current velocity from 0 m/s to 2.0 m/s while wind and wave conditions remain unchanged.

Table 7 Operating condition setting

Case	Peak wave period T_p (s)	Significant wave height H_s (m)	Wind speed U (m/s)	Current velocity V (m/s)
1	8.12	2.95	11.4	0.5
2	6.5	2.95	11.4	0.5
3	10.1	2.95	11.4	0.5
4	13.5	2.95	11.4	0.5
5	8.12	5.3	11.4	0.5
6	8.12	7.6	11.4	0.5
7	8.12	12.5	11.4	0.5
8	8.12	2.95	3	0.5
9	8.12	2.95	6	0.5
10	8.12	2.95	9	0.5
11	8.12	2.95	11.4	0
12	8.12	2.95	11.4	1.2
13	8.12	2.95	11.4	2

4.2 Effects of wave period

4.2.1 Motion response of the platform

Figure 6 and Table 8 present the time-varying dynamic responses and the corresponding statistical summary, respectively, for the platform across distinct wave periods (T_p ranging from 6.5 to 13.5 s). As quantitatively demonstrated in Table 8, the statistical metrics for platform surge, pitch, and mooring tension—such as their maximum values and oscillation ranges—exhibit minimal variation across the parametric sweep. Additionally, the temporal profiles confirm a high synchronization between surge motion and mooring tension, both predominantly driven by low-frequency responses. In stark contrast, the quantitative data reveals that heave motion is highly sensitive to the wave period. Under long-period wave conditions, the heave response is significantly amplified, indicating potential resonance characteristics. Specifically, Table 8 highlights that the maximum heave amplitude peaks at 0.92 m, representing a substantial amplification of approximately 4.35 times compared to the oscillation amplitude observed in the shortest wave period scenario (Case 1).

Figure 7 compares the continuous wavelet transform (CWT) energy density distributions of the platform's three-degree-of-freedom (3-DOF) responses under fully coupled environmental conditions for Case 1 and 4. As the wave period increases, the energy distribution characteristics of the 3-DOF motions in the time-frequency domain exhibit a significant trend of concentration and intensification. Regarding surge and pitch motions, the response energy distribution remains dominated by their respective natural frequencies. The evolution of heave motion is most prominent: as the wave peak period further approaches the heave natural frequency range of the semi-submersible platform, a strong resonance effect is induced. This causes the energy to rapidly evolve from a conventional forced vibration state to a state of high energy density, revealing the intense nonlinear cumulative amplification of vertical excitation forces when the period matches the natural frequency. In summary, changes in the dominant wave period not only lead directly to increased response amplitudes but also fundamentally reshape the energy structure of the platform's heave motion; driven by intense resonant loads, the time-domain oscillation characteristics become more violent and difficult to suppress.

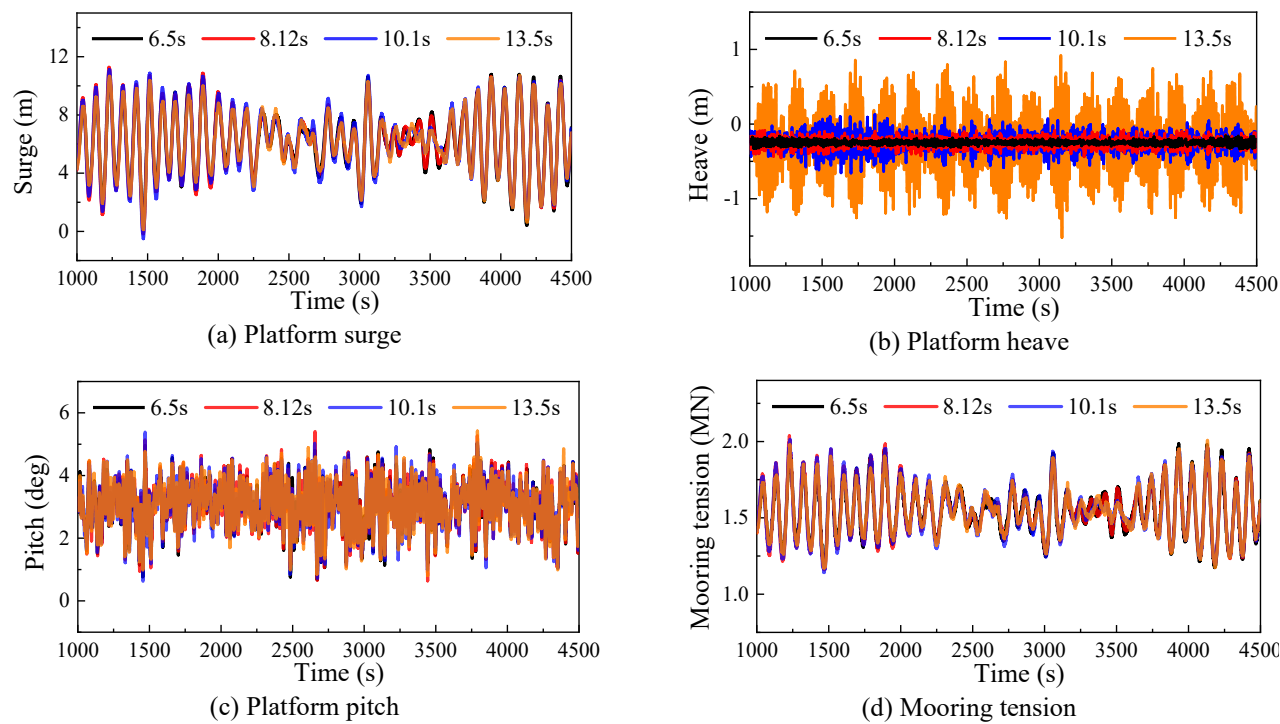


Fig. 6 The effect of wave period on platform motions

Table 8 Statistical summary of platform dynamic responses under different wave periods

	Surge(m)		Heave(m)		Pitch (°)		Mooring tension (MN)	
	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Case 1	10.791	6.198	-0.097	-0.248	5.03	3.069	1.985	1.549
Case 2	11.278	6.192	-0.078	-0.251	5.40	3.07	2.037	1.549
Case 3	11.122	6.201	0.127	-0.257	5.38	3.07	2.014	1.55
Case 4	10.717	6.167	0.92	-0.262	5.42	3.061	2.008	1.546

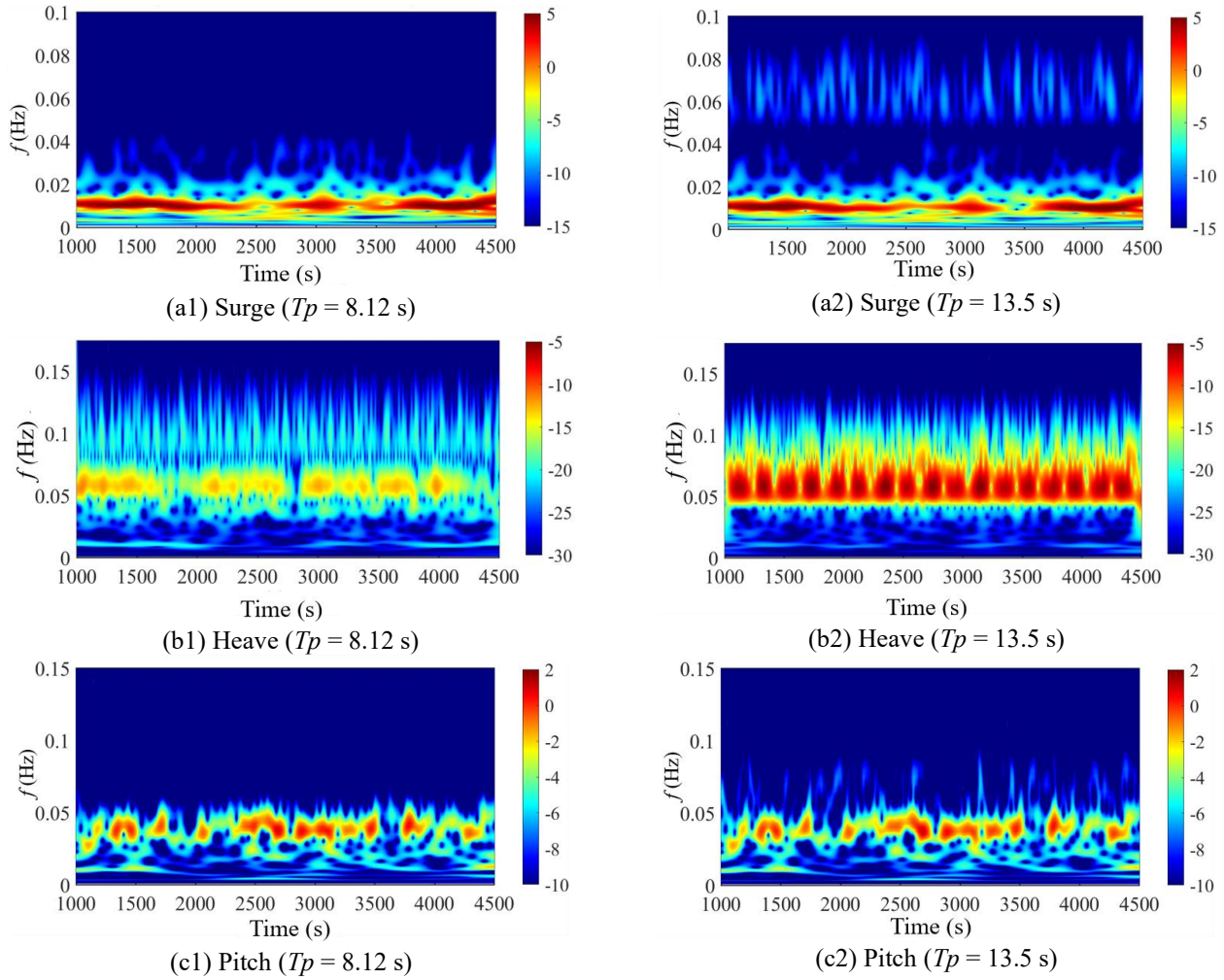


Fig. 7 Continuous wavelet transform energy density distributions of platform responses under different wave periods

4.2.2 Aerodynamic performance of the turbine

Figure 8 and Table 9 present the transient time histories and statistical characteristics of the turbine's aerodynamic responses under different wave periods. As indicated by the statistical results, variations in wave period have only a minor influence on both rotor thrust and power output, with relative changes remaining within 5 %. This behavior is attributed to the fact that resonance-induced heave is predominantly manifested as vertical rigid-body motion of the rotor. Consequently, this motion has only a limited influence on the relative inflow velocity and blade angle of attack across the rotor-swept area. Furthermore, the turbine's pitch control system effectively suppresses aerodynamic fluctuations induced by low-frequency heave motion. Because the characteristic frequency of heave motion is much lower than the dominant aerodynamic response frequency and lies within the effective operating range of the pitch controller, its influence on aerodynamic power and thrust remains limited. Since the quantitative analysis indicates that variations in wave period have only a minor influence on aerodynamic responses (deviations < 5 %), no further wavelet analysis is conducted for the aerodynamic responses under different wave periods.

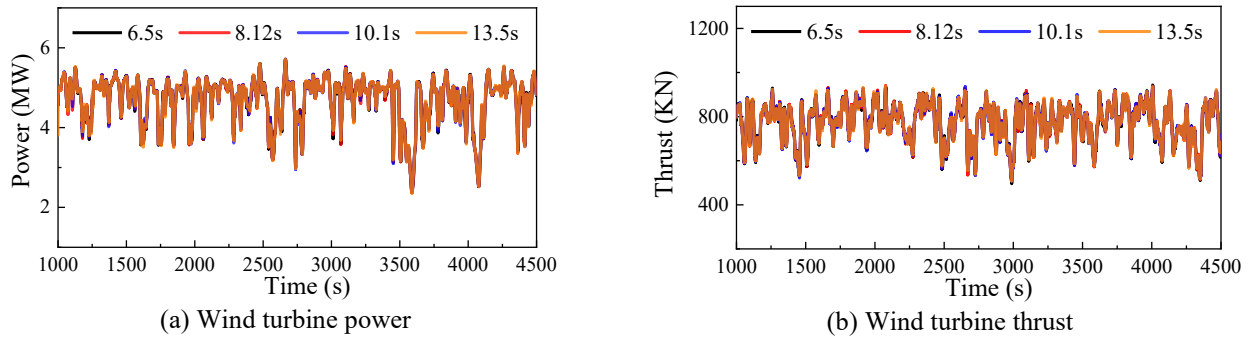


Fig. 8 The effect of wave period on aerodynamic loads

Table 9 Statistical summary of aerodynamic loads under various wave periods

	Rotor power (MW)		Rotor thrust (KN)	
	Max	Mean	Max	Mean
Case 1	5.705	4.701	943.187	773.786
Case 2	5.706	4.7	941.244	773.483
Case 3	5.72	4.703	936.921	774.558
Case 4	5.709	4.702	935.135	774.227

4.3 Effects of wave height

4.3.1 Motion response of the platform

Figure 9 and Table 10 present the platform response time histories and corresponding statistical characteristics, respectively, for significant wave heights (H_s) ranging from 2.95 to 12.5 m. As summarized in Table 10, the response amplitudes of surge, heave, pitch, and mooring tension all increase nonlinearly with increasing wave height. Specifically, the surge oscillation range increases from 10.79 m under mild wave conditions to 16.57 m under extreme conditions, representing a 53.6 % increase. Similarly, the pitch oscillation range increases from 5.03° to 8.84° (75.7 %), indicating the significant influence of wave excitation on the platform's motion stability. Meanwhile, the amplitudes of heave motion and mooring tension also increase substantially. Under the highest wave condition, all platform responses reach their maximum amplitudes, while the mooring tension exhibits pronounced transient peaks. These results indicate that increasing wave height enhances wave excitation, thereby imposing greater demands on platform station-keeping performance and increasing fatigue loading of the mooring system.

Figure 10 compares the continuous wavelet transform (CWT) energy density distributions of the platform's 3-DOF responses under fully coupled environmental conditions for Case 1 and 7. As wave height increases, the time-frequency energy distributions of the 3-DOF motions exhibit expanded high-energy regions and increased energy density. Regarding surge motion, the energy composition is dominated by low-frequency slow-drift components; however, high wave height conditions significantly strengthen the low-frequency energy core, reflecting the combined driving effects of first-order and second-order wave forces. Heave motion exhibits strong sensitivity to changes in wave height, with its energy distribution evolving from a sparse and discrete state under low wave conditions to a continuous and dense state under high wave conditions, revealing a drastic nonlinear amplification effect of vertical excitation forces as wave height increases. Pitch motion is characterized by a comprehensive intensification of low-frequency energy, where the significant increase in high-energy regions within the time-frequency map reveals intensified angular displacement fluctuations under extreme sea states. In summary, increasing wave height not only increases response amplitudes but also significantly modifies the motion energy distribution of the platform, resulting in stronger and more pronounced time-domain oscillations under high-energy wave excitation.

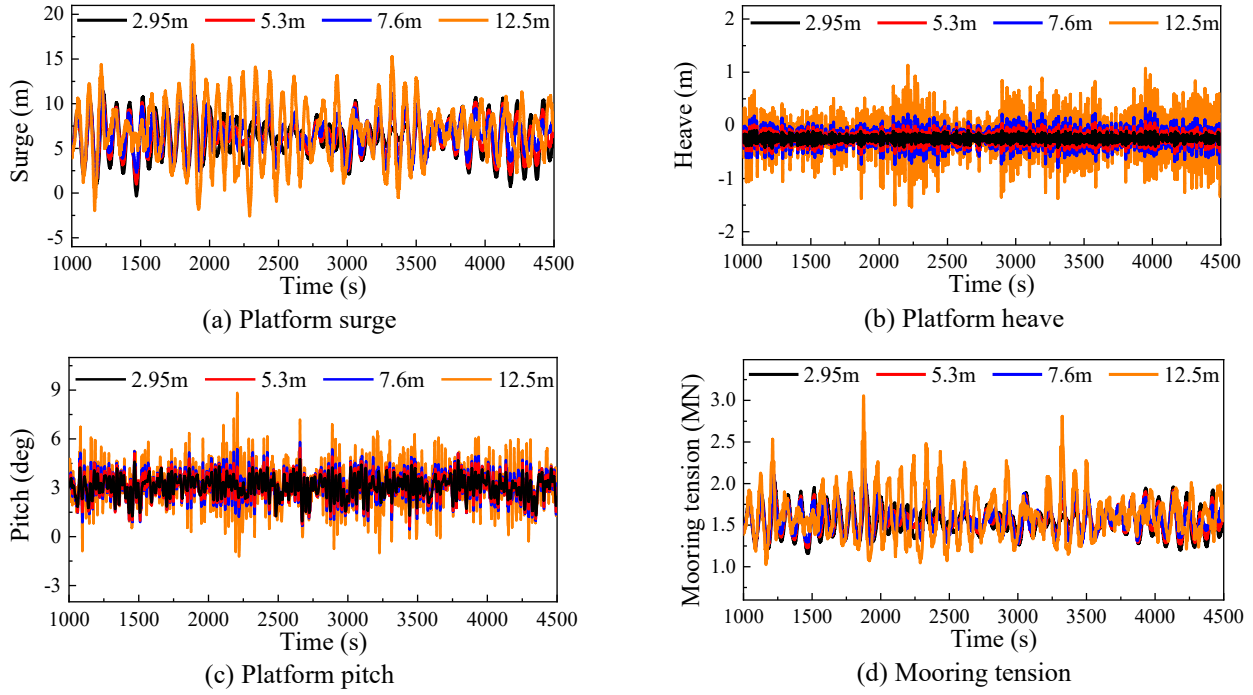


Fig. 9 The effect of wave height on platform motions

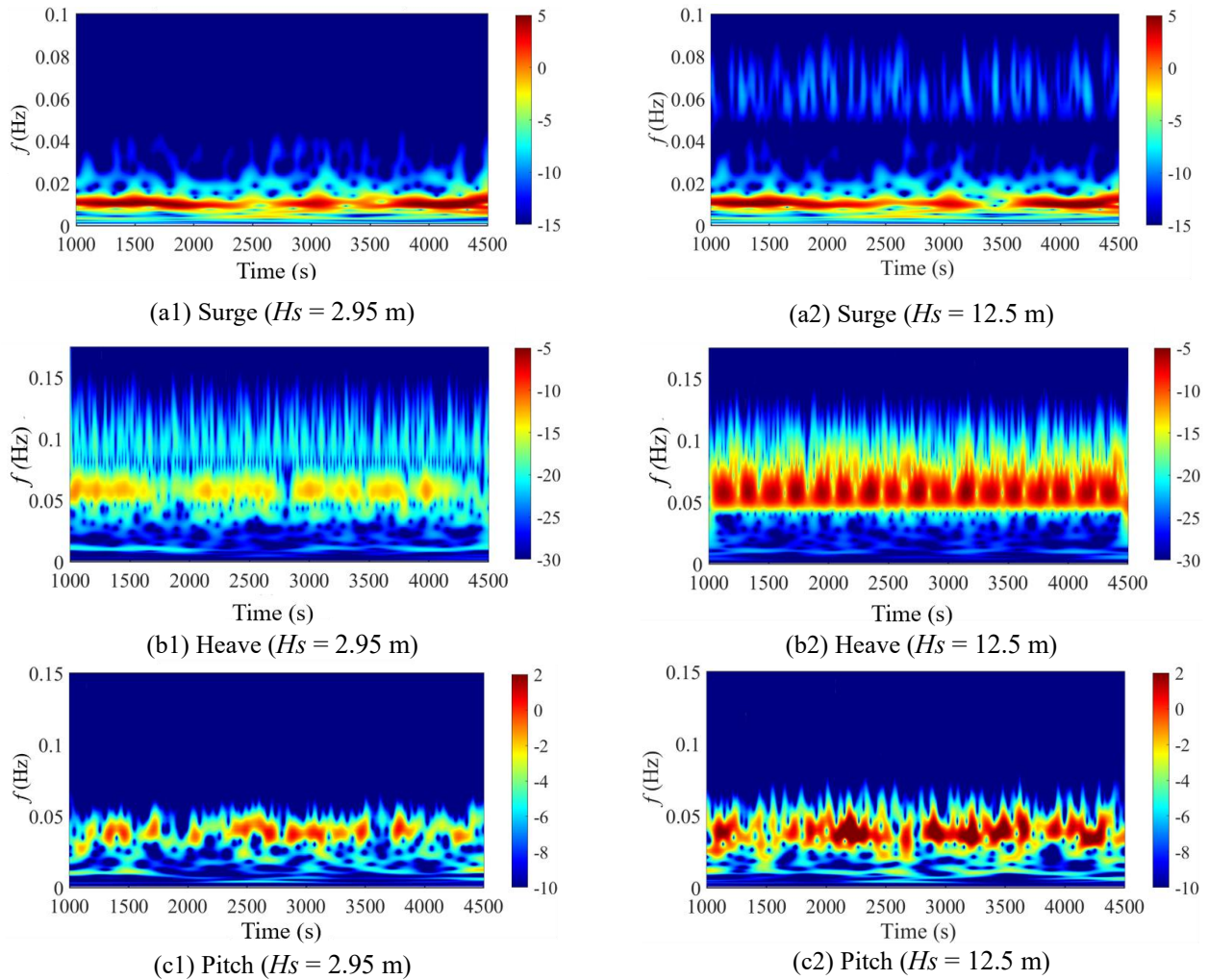


Fig. 10 Continuous wavelet transform energy density distributions of platform responses under different wave heights

Table 10 Statistical summary of platform dynamic responses under different wave heights

	Surge (m)		Heave (m)		Pitch (°)		Mooring Tension (MN)	
	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Case 1	10.791	6.198	-0.151	-0.248	5.03	3.069	1.985	1.549
Case 5	11.441	6.317	0.07	-0.242	5.455	3.08	2.039	1.557
Case 6	12.399	6.464	0.313	-0.237	5.913	3.097	2.18	1.57
Case 7	16.572	6.81	1.13	-0.202	8.838	3.17	3.055	1.623

4.3.2 Aerodynamic performance of the turbine

Figure 11 and Table 11 present the transient time histories and statistical characteristics of the aerodynamic responses of the wind turbine under different wave heights. As corroborated by the statistical data in Table 11, the output power exhibits high aerodynamic robustness due to the effective regulation of the pitch control system. The data reveal that the power responses for all cases overlap significantly, maintaining a stable mean value near the rated power with a minimal fluctuation range. By contrast, the rotor thrust exhibits a noticeable increase in load fluctuations with increasing wave height. Although the mean rotor thrust remains nearly unchanged under different sea states, the fluctuation amplitude increases significantly with wave height, reaching a maximum increase of 28.2 %. Under severe sea states, the rotor thrust exhibits stronger high-frequency fluctuations and higher peak values. This behavior indicates that large platform motions, particularly surge and pitch, significantly modify the relative inflow conditions across the rotor swept area under severe sea states, thereby increasing aerodynamic thrust fluctuations.

Figure 12 compares the continuous wavelet transform (CWT) energy density distributions of the rotor's aerodynamic responses under fully coupled environmental conditions for Cases 1 and 7. The increase in wave height triggers a significant evolution of the system's energy structure and induces cross-frequency coupling. Under low wave conditions, the aerodynamic response energy is primarily concentrated in the ultra-low frequency region (below 0.05 Hz), governed by wind turbulence, platform slow-drift motions, and the pitch control system. In contrast, the time-frequency energy distribution under high wave conditions exhibits distinct multi-peak characteristics: in addition to a substantial jump in the intensity of the low-frequency core energy band, dense high-energy "hotspots" emerge within the 0.05-0.1 Hz range. This phenomenon profoundly reveals that under extreme sea states, the resonant energy induced by nonlinear forces, together with the first-order wave-frequency excitation, has partially penetrated the effective bandwidth boundary of the wind turbine control system. This energy is deeply coupled into the aerodynamic response system, resulting in a stepwise increase in pulsation energy across the entire frequency domain.

Table 11 Statistical summary of aerodynamic loads under various wave heights

	Rotor power (MW)		Rotor thrust (KN)	
	Max	Mean	Max	Mean
Case 1	5.705	4.701	943.187	773.786
Case 5	5.817	4.695	1065.73	771.053
Case 6	5.865	4.686	1087.59	767.515
Case 7	5.955	4.661	1208.924	756.253

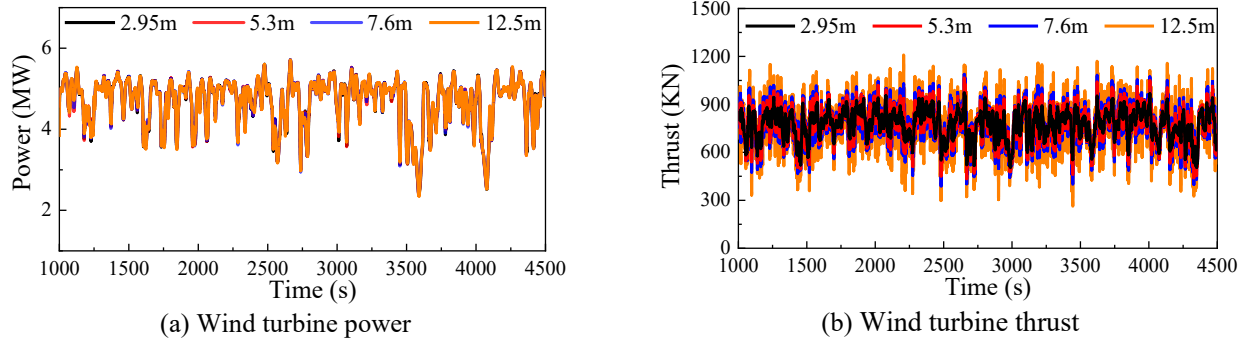


Fig. 11 The effect of wave height on aerodynamic loads

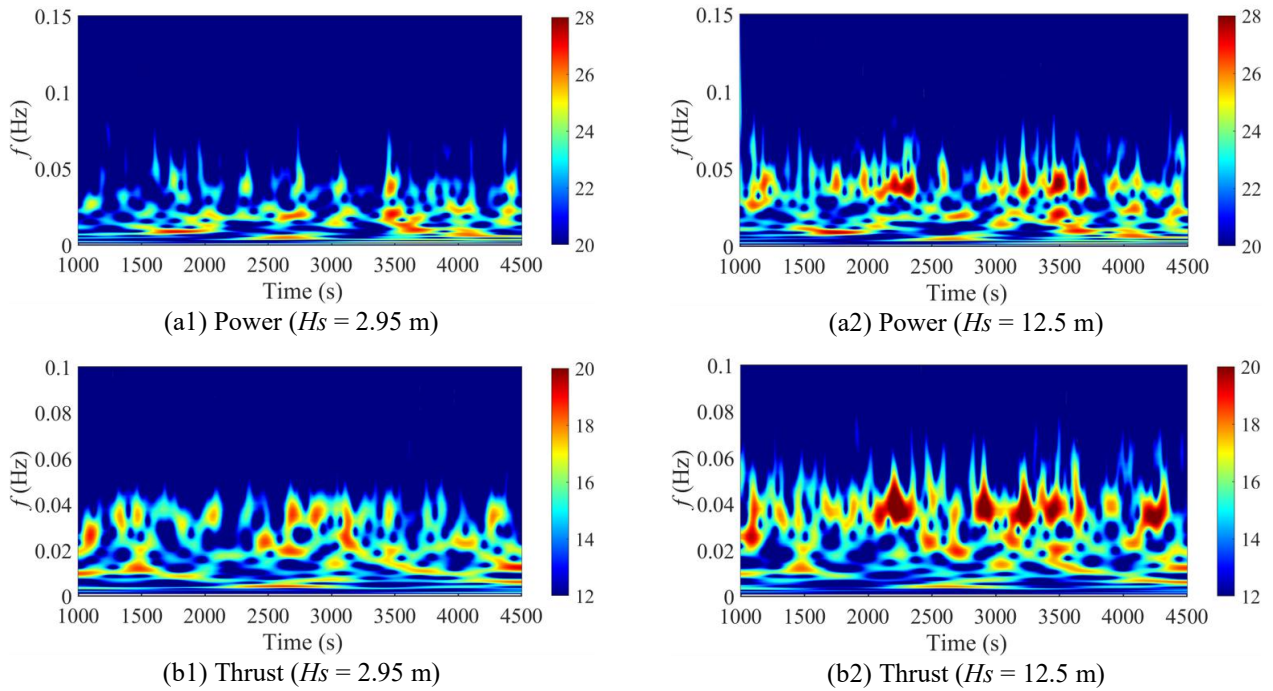


Fig. 12 Continuous wavelet transform energy density distributions of aerodynamic responses under different wave heights

4.4 Effects of wind speed

4.4.1 Motion response of the platform

Figure 13 and Table 12 present the platform's time-varying dynamic responses and quantitative characteristics, respectively, across distinct wind speeds (transitioning from 3 m/s to the rated speed). As quantitatively detailed in Table 12, both the equilibrium positions (mean values) and the fluctuation intensities of the platform motions exhibit significant sensitivity to wind speed variations. Specifically, the statistical metrics confirm that the mean values of surge displacement and pitch angle increase substantially as the wind speed approaches the rated value. This phenomenon is primarily attributed to the continuous enhancement of rotor thrust that peaks at the rated wind speed, resulting in larger steady offsets and inclinations of the platform. Regarding oscillation amplitudes, the quantitative data highlight that the surge and pitch fluctuations become more intense at the rated wind speed, reflecting aeroelastic-induced low-frequency oscillation effects under high wind loads. In stark contrast, Table 12 reveals that the heave motion is relatively insensitive to wind speed variations, with its statistical oscillation amplitudes remaining largely stable. This indicates that the dynamic excitation of wind loads on the platform's vertical degree of freedom is significantly lower than that of wave loads. Furthermore, the variation trend of mooring tension is highly synchronized with the surge displacement; the documented increases in its mean and extreme peak values in Table 12 rigorously reflect the dominant influence of the platform's steady offset on the mooring system loads.

Figure 14 compares the continuous wavelet transform (CWT) energy density distributions of the platform's 3-DOF responses under fully coupled environmental conditions for Cases 1 and 9. The elevation of wind speed primarily results in a significant expansion of response energy within specific frequency bands. For surge motion, the low-frequency energy intensity at the rated wind speed is notably higher than that at 6 m/s, with the energy spots exhibiting greater continuity along the time axis; this reveals that the slow-drift excitation induced by turbulent wind is continuously intensified as wind speed increases. In the time-frequency maps of pitch motion, the rated wind speed case displays dense energy in the low-frequency region, indicating that aerodynamic and hydrodynamic loads produce stronger cross-frequency coupling effects near the rated wind speed. However, the time-frequency energy distribution of heave motion shows a high degree of similarity between the two wind speeds, demonstrating once again from a frequency-domain perspective that the influence of wind speed variation on the platform's vertical dynamic response characteristics is extremely limited.

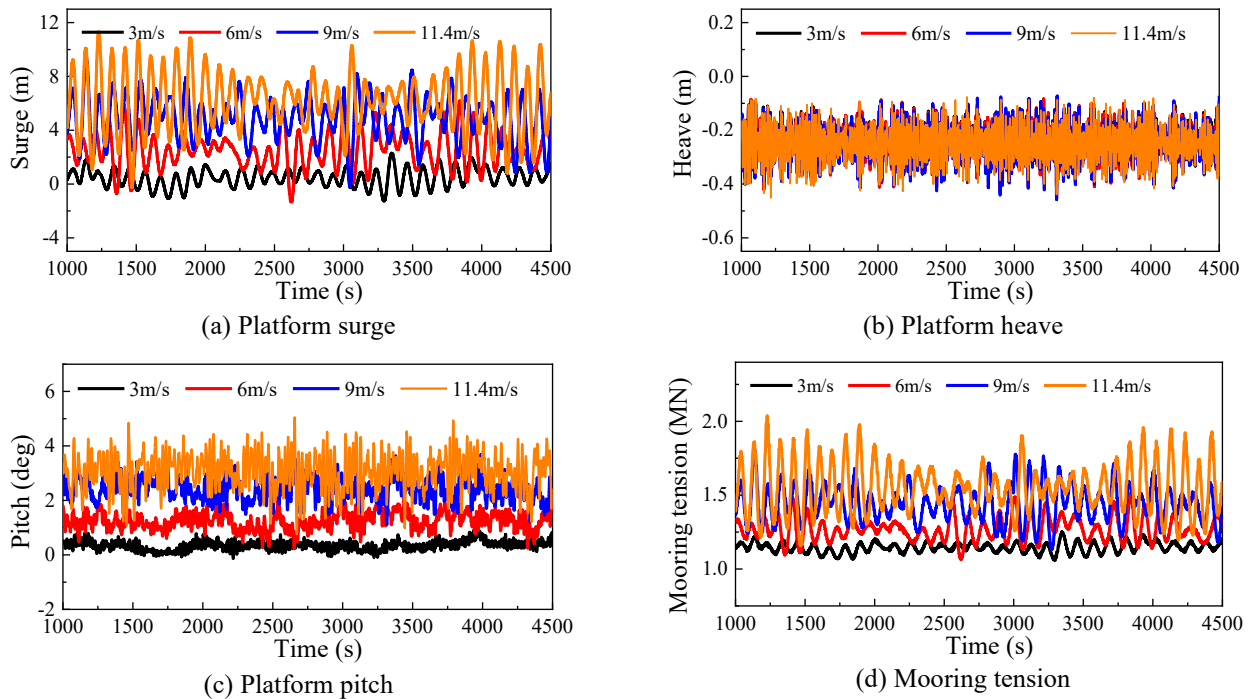


Fig. 13 The effect of wind speed on platform motions

Table 12 Statistical summary of platform dynamic responses under different wind speeds

	Surge (m)		Heave (m)		Pitch (°)		Mooring tension (MN)	
	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Case 1	10.791	6.198	-0.097	-0.248	5.03	3.069	1.985	1.549
Case 8	2.294	0.477	-0.073	-0.23	0.902	0.346	1.251	1.147
Case 9	6.181	2.56	-0.083	-0.244	2.265	1.253	1.517	1.271
Case 10	9.493	4.883	-0.072	-0.249	3.689	2.412	1.819	1.441

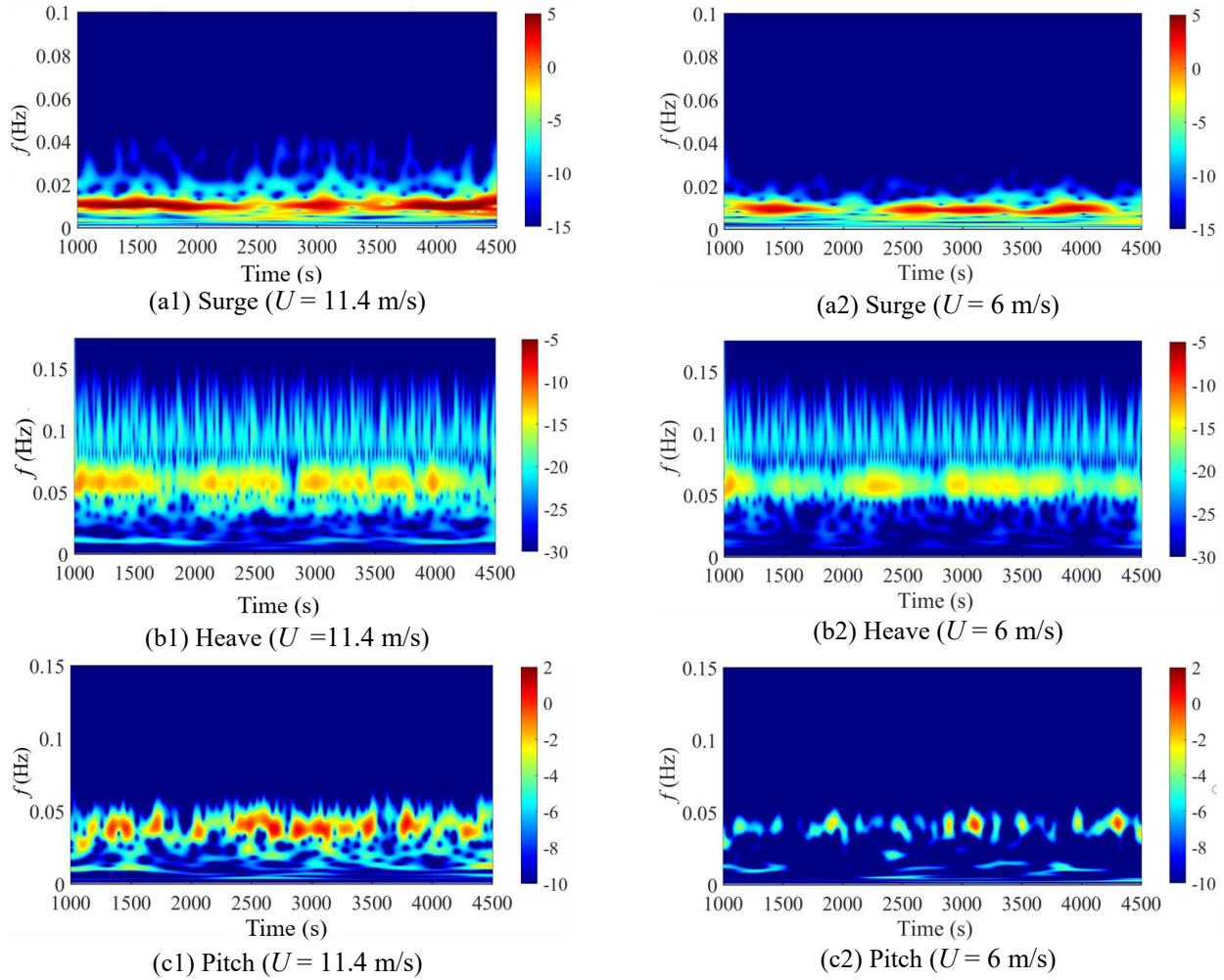
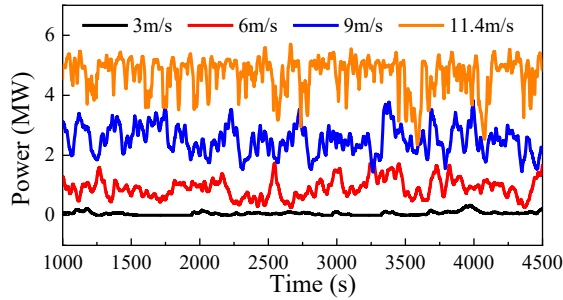


Fig. 14 Continuous wavelet transform energy density distributions of platform responses under different wind speeds

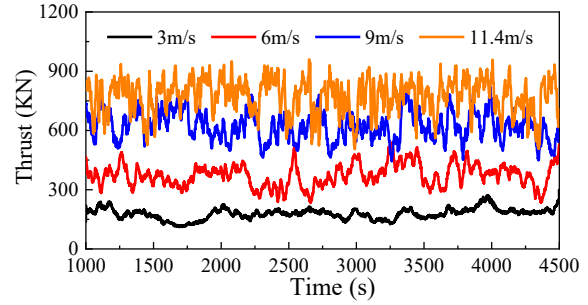
4.4.2 Aerodynamic performance of the turbine

Figure 15 and Table 13 present the transient time histories and statistical characteristics of the turbine's aerodynamic responses under different wind speeds. The results indicate that wind speed is the dominant factor governing power output and rotor thrust. As wind speed increases toward the rated value, the mean power output and rotor thrust increase progressively. The response fluctuations also increase with wind speed. Under rated wind conditions, both power and thrust exhibit the largest transient fluctuations, with the difference between the peak and mean values reaching its maximum. These results indicate that the increase in available wind energy enhances power production while simultaneously strengthening unsteady aerodynamic responses induced by turbulent inflow and coupled platform motions, resulting in larger aerodynamic load fluctuations.

Figure 16 compares the continuous wavelet transform (CWT) energy density distributions of the rotor's aerodynamic responses under fully coupled environmental conditions for Cases 1 and 9. Contrasting the sub-rated and rated inflow scenarios demonstrates that the elevation of wind speed drives an all-encompassing transition of aerodynamic response energy within the frequency domain. Under design operating velocities, the aerodynamic loads and power output display a logarithmic energy enhancement relative to the partial-load scenario. Regarding the frequency distribution, the energy is highly concentrated in 0-0.5 Hz, which profoundly reflects the dominant role of the long-period components of turbulent wind and the platform's slow-drift motion in governing the aerodynamic response. Notably, under the high wind speed condition, the high-energy hotspots (red regions) in the time-frequency maps are distributed more densely and continuously along the time axis. This reveals that near the rated wind speed, the random wind energy captured by the system significantly intensifies the non-stationary oscillation characteristics of the aerodynamic response.



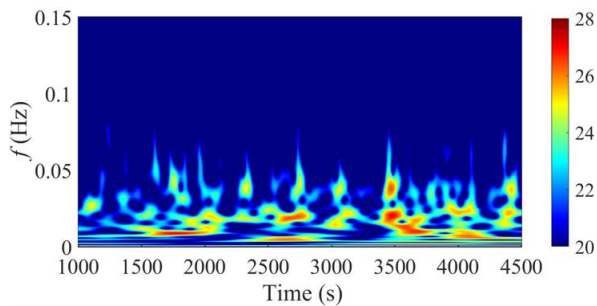
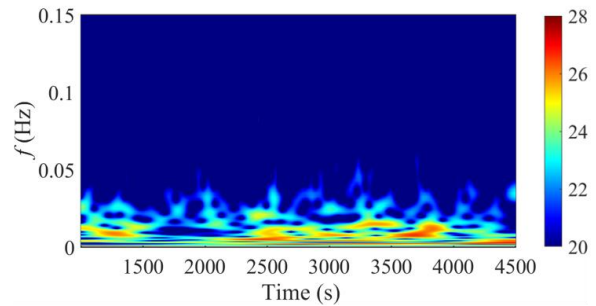
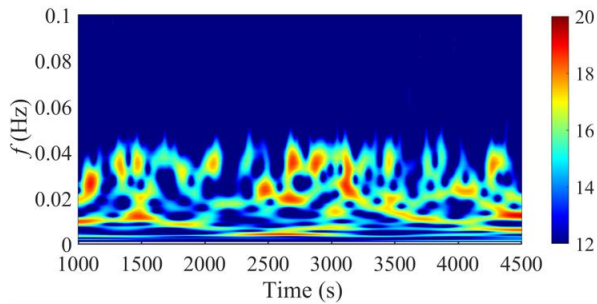
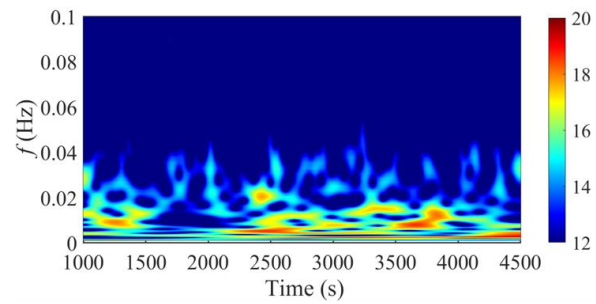
(a) Wind turbine power



(b) Wind turbine thrust

Fig. 15 The effect of wind speed on aerodynamic loads**Table 13** Statistical summary of aerodynamic loads under various wave periods

	Rotor power (MW)		Rotor thrust (KN)	
	Max	Mean	Max	Mean
Case 1	5.705	4.701	943.187	773.786
Case 8	0.333	0.061	298.821	178.102
Case 9	1.843	0.906	537.388	372.766
Case 10	3.844	2.517	820.986	622.84

(a1) Power ($U = 11.4$ m/s)(a2) Power ($U = 6$ m/s)(b1) Thrust ($U = 11.4$ m/s)(b2) Thrust ($U = 6$ m/s)**Fig. 16** Continuous wavelet transform energy density distributions of aerodynamic responses under different wind speeds

4.5 Effects of current velocity

4.5.1 Motion response of the platform

Figure 17 and Table 14 present the platform's time-varying dynamic responses and quantitative characteristics, respectively, across distinct current velocities. Observing the parametric sweep where current velocity transitions from 0 to 2.0 m/s, the influence of current loads on the platform motions is primarily manifested as a significant increase in the steady offset. Since the viscous drag force elicited by the current varies with the square of the flow speed, the equilibrium position of the platform in the surge direction undergoes a distinct physical drift as the velocity increases, with the mean offset increasing by approximately

12.9 %. This increase in displacement directly drives a stepwise rise in the mean mooring tension. In contrast, the oscillation amplitudes across all degrees of freedom (DOFs) do not change significantly with current velocity, and the fluctuation frequencies and amplitude characteristics remain highly consistent. This indicates that current load, acting as a quasi-steady excitation, primarily contributes to altering the system's static equilibrium state and the tension levels of the mooring system.

Figure 18 compares the continuous wavelet transform (CWT) energy density distributions of the platform's three-DOF responses under fully coupled environmental conditions for Cases 1 and 13. Comparison of the two current velocity conditions (0.5 and 2.0 m/s) shows that variations in current velocity have no significant influence on the time-frequency energy distribution of the platform motions. The energy density distribution characteristics in the time-frequency domain for each degree of freedom exhibit a high degree of similarity under both velocities: surge energy remains firmly locked within the ultra-low frequency slow-drift range, while the energy cores for heave and pitch are stably distributed within their respective natural frequency ranges. Neither the intensity nor the morphology of the high-energy hotspots in the time-frequency maps undergoes significant expansion or migration. This further demonstrates, from a frequency-domain perspective, that current loads do not alter the energy input characteristics of environmental excitations to the system.

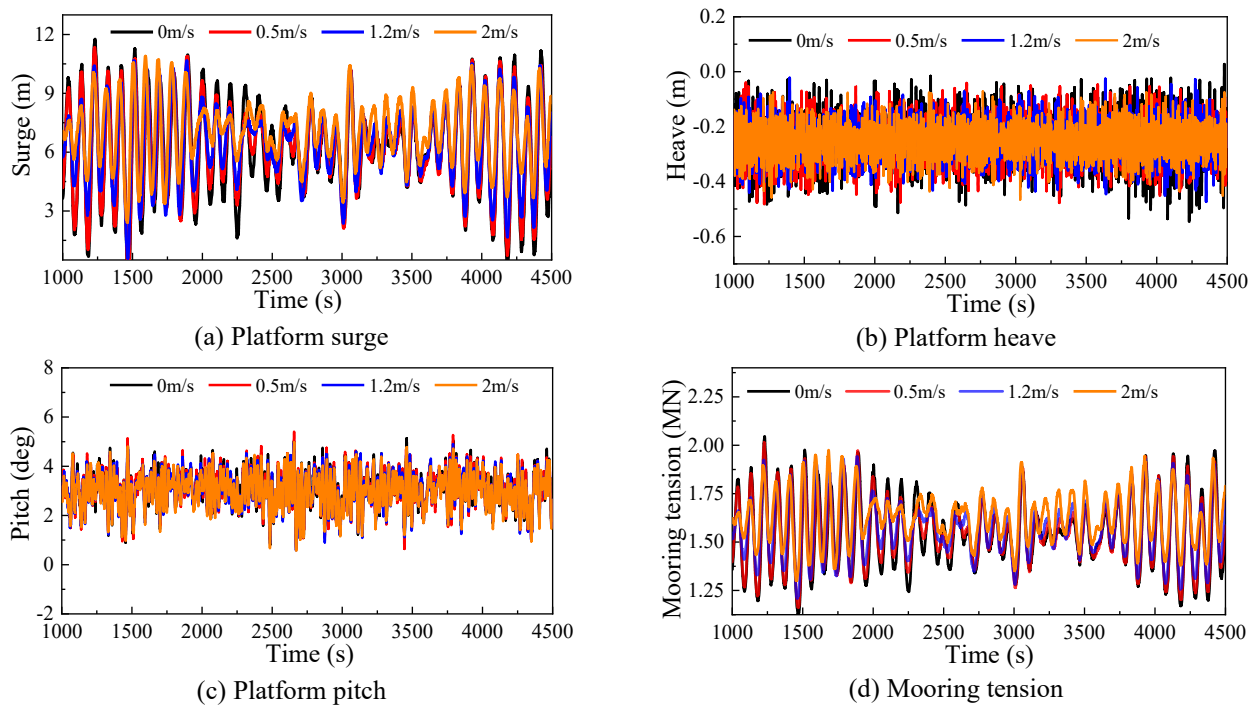


Fig. 17 The effect of current velocity on platform motions

Table 14 Statistical summary of platform dynamic responses under different current velocities

	Surge (m)		Heave (m)		Pitch (°)		Mooring tension (MN)	
	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Case 1	10.791	6.198	-0.097	-0.25	5.03	3.069	1.985	1.549
Case 11	10.86	6.143	-0.036	-0.23	5.137	3.081	2.046	1.544
Case 12	10.662	6.423	-0.022	-0.251	5.053	3.04	1.942	1.571
Case 13	10.896	7.049	-0.071	-0.253	5.166	2.978	1.819	1.627

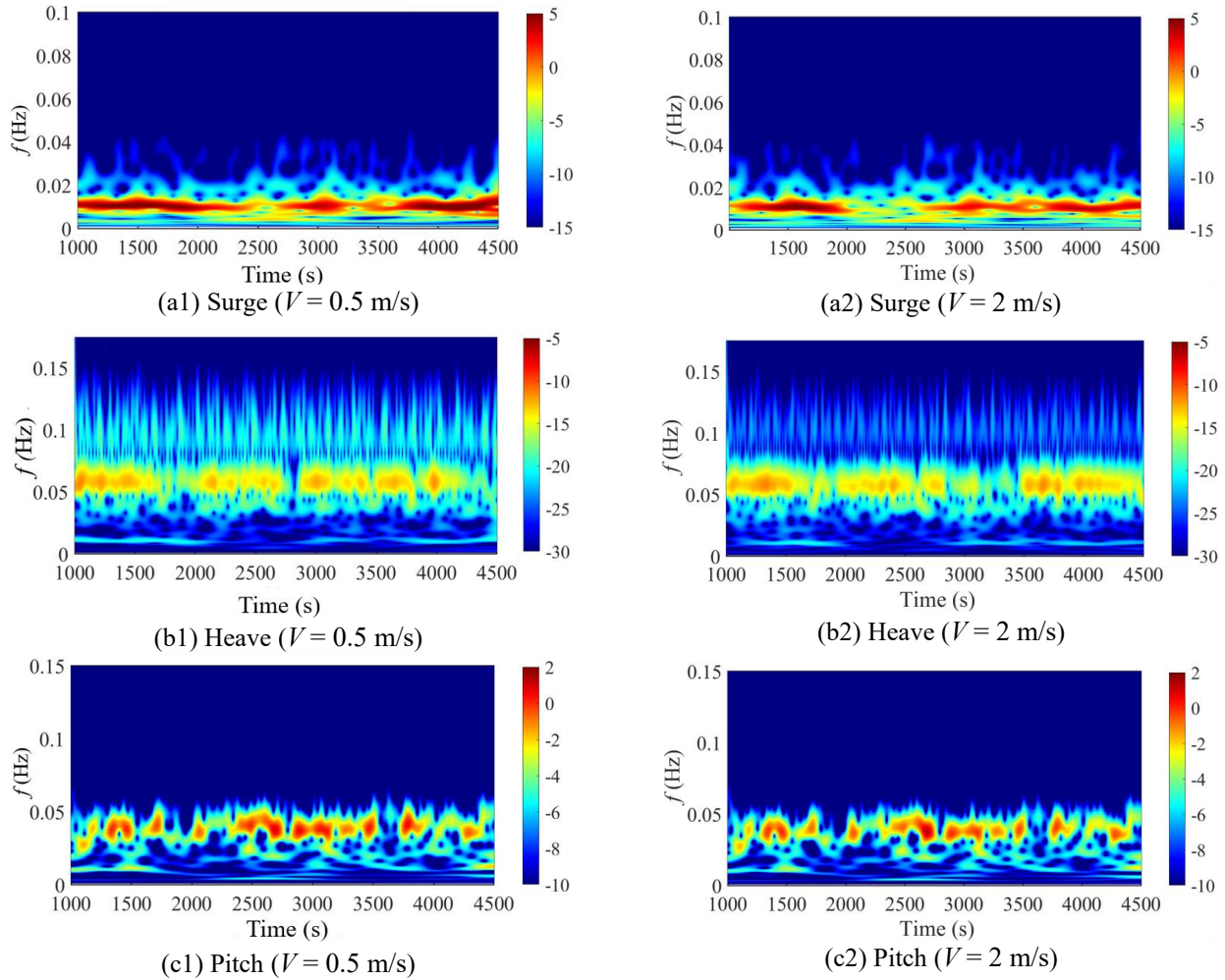


Fig. 18 Continuous wavelet transform energy density distributions of platform responses under different current velocities

4.5.2 Aerodynamic performance of the turbine

Figure 19 and Table 15 present the transient time histories and statistical characteristics of the turbine's aerodynamic responses under different current velocities. As evidenced by the simulations, fluctuations in the ambient current velocity impart virtually no discernible impact on the aerodynamic power capture and thrust loads of the rotor. Within the current velocity range of 0 to 2.0 m/s, the time-history curves for power and thrust across different cases appear highly superimposed, with their mean levels and oscillation envelopes remaining largely consistent. This indicates that although current loads induce a steady offset in the platform's surge displacement, such changes in static displacement do not significantly alter the relative inflow wind speed characteristics within the rotor swept area. This is because ocean currents act as a continuous drag load that offsets the platform to a new baseline position and rebalances the mooring restoring forces. In contrast, the aerodynamic performance is predominantly governed by dynamic factors, including wind speed fluctuations and the wave-induced dynamic oscillation velocity of the platform. Given that the contribution of ocean currents to the platform's dynamic response is limited, the wind turbine's energy capture efficiency and aerodynamic load characteristics likewise exhibit extremely low sensitivity to changes in current velocity. Accordingly, wavelet analysis of the wind turbine's aerodynamic performance across different current velocities is also omitted.

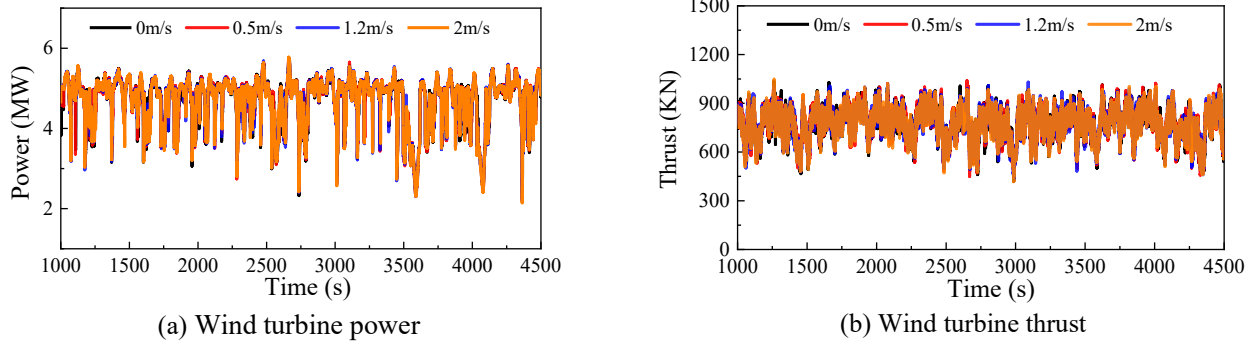


Fig. 19 The effect of ocean currents on aerodynamic performance

Table 15 Statistical summary of aerodynamic loads under various wave periods

	Rotor power (MW)		Rotor thrust (KN)	
	Max	Mean	Max	Mean
Case 1	5.705	4.701	943.187	773.786
Case 11	5.713	4.712	945.261	772.668
Case 12	5.705	4.685	946.334	775.166
Case 13	5.716	4.755	946.137	773.767

5. Conclusion

Driven by a comprehensive aero-hydro-servo-mooring framework, the present research systematically evaluates the FOWT's operational sensitivities to diverse metocean conditions. Specifically, the analysis quantifies how variations in wave characteristics (significant height and peak period), wind speeds, and ambient currents dictate the platform kinematics, cable loading, and aerodynamic efficiency. The primary conclusions are summarized as follows:

(1) Wave loads constitute the dominant factor inducing the platform's dynamic oscillations and nonlinear responses. With regard to the influence of wave period, waves act on the system primarily through a frequency coupling mechanism. As the spectral peak period approaches the natural heave period of the platform, significant resonance amplification occurs, with the peak heave response increasing by up to 4.35 times compared with the reference condition, whereas the responses of surge motion and mooring tension remain much less sensitive to changes in wave period. Although the heave motion exhibits a pronounced amplitude amplification in the resonance region, its influence on the wind turbine aerodynamic performance (output power and rotor thrust) is extremely weak.

(2) In terms of wave height effects, the increase in significant wave height produces an omnidirectional energy intensification effect, driving the platform responses and mooring tension to grow nonlinearly; specifically, the peak surge increases by nearly a factor of 2, and the peak pitch grows by approximately 53.6 %. Time–frequency analysis further confirms that the increase in wave height significantly intensifies the second-order slow-drift excitation, causing the wave-frequency energy to penetrate deeply into the aerodynamic response system, inducing severe transient load fluctuations in the rotor thrust, with the oscillation amplitude increasing by approximately 28.2 %.

(3) Wind load is the core variable determining the steady-state attitude of the platform and the level of aerodynamic energy capture. As the wind speed increases to the rated value, the peak effect of the rotor thrust drives an increase in the mean surge and the pitch angle of the platform, while simultaneously and significantly raising the mooring tension. Regarding aerodynamic performance, higher wind speeds enhance turbulence-induced aerodynamic fluctuations and low-frequency platform motions, causing stronger non-stationary characteristics in the aerodynamic responses and increasing transient fluctuations of rotor thrust.

(4) The primary hydrodynamic consequence of current on the floating wind turbine system is primarily manifested as a steady-state mean offset in the system's equilibrium position. As the current velocity increases, the current thrust significantly elevates the steady offset of the platform and the mean mooring tension, with the mean offset increasing by approximately 12.9 %, and the magnitude of this effect is proportional to the square of the current velocity. However, the study reveals that variations in current velocity exert an extremely weak influence on the amplitude and frequency composition of the dynamic responses in each degree of freedom of the platform. Both the mean and maximum aerodynamic responses of the floating wind system demonstrate an extreme insensitivity to the current field, with total deviations falling short of 1 %.

Although this study provides comprehensive insights into the FOWT's operational sensitivities, certain limitations remain to be addressed in future research. First, the current numerical framework assumes collinear wind, wave, and current conditions. Future work should incorporate misaligned and multidirectional metocean environments to evaluate asymmetric mooring loads and cross-wind dynamic responses. Second, to transcend the limitations of engineering-level aerodynamic and hydrodynamic models under extreme sea states, high-fidelity Computational Fluid Dynamics (CFD) and Fluid-Structure Interaction (FSI) solvers will be integrated to capture complex wake dynamics and nonlinear wave-breaking forces. Lastly, in light of the significant wave-induced transient thrust fluctuations, developing advanced platform-motion-compensated control strategies represents a critical future direction to actively mitigate structural fatigue and enhance aerodynamic stability.

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NOMENCLATURE

T	thrust on individual blade elements	V_a	design wind speed
M	torque on individual blade elements	F_c	current load
V_{rel}	velocity of the blade in relation to the surrounding air	A_c	area of the submerged portion of the floating platform exposed to the current
N	number of blades	ρ_w	seawater density
c	local chord length of the respective blade element profile	V_c	current velocity
C_L	lift coefficients	T_a	tension vector at the mooring element nodes
C_D	drag coefficients	V	shear force vector
θ	inflow angle	R	position vector
r	blade radius	M_a	bending moment vector
Φ	velocity potential	S_e	unstretched length of the mooring element
Φ_I	incident potential	w	linear weight density of the respective mooring segment

Φ_D	diffraction potential	F_h	hydrodynamic forcing vector per unit length
Φ_R	radiation potential	m_e	mass per unit length
F_w	wave force	q	distributed moment load per unit length
$X(\omega_k)$	first-order wave excitation force transfer function.	m	structural mass matrix
$X^-(\omega_k, \omega_l)$	second-order difference-frequency quadratic transfer function	A_∞	instantaneous added mass matrix
F_a	wind load	C	total damping matrix
C_h	height coefficient	K	total stiffness matrix
C_s	shape coefficient	$h(t-\tau)$	retardation function
A_a	area of the wind turbine components exposed to wind	$X(t)$	displacement vector
p_a	wind pressure	$\dot{X}(t)$	velocity vector
ρ_a	air density	$\ddot{X}(t)$	acceleration vector

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