

Article

Dynamic Response of SPAR-Type Floating Offshore Wind Turbine under Wave Group Scenarios

Baolong Liu ^{1,2} and Jianxing Yu ^{1,2,*}

¹ State Key Laboratory of Hydraulic Engineering Simulation and Safety, School of Civil Engineering, Tianjin University, Tianjin 300354, China; liubaolong@163.com

² Tianjin Key Laboratory of Port and Ocean Engineering, School of Civil Engineering, Tianjin University, Tianjin 300354, China

* Correspondence: yjx2000@tju.edu.cn

Abstract: Numerical simulations are performed within the time domain to investigate the dynamic behaviors of an SPAR-type FOWT under wave group conditions. Towards this goal, the OC3 Hywind SPAR-type FOWT is adopted, and a JONSWAP (Joint North Sea Wave Project)-based wave group is generated by the envelope amplitude approach. The FOWT motion under wave group conditions, as well as the aerodynamic, hydrodynamic, and mooring performances, is simulated by our established in-house code. The rotating blades are modelled by the blade element momentum theory. The wave-body interaction effect is calculated by the three-dimensional potential theory. The mooring dynamics are also taken into consideration. According to the numerical results, the SPAR buoy motions are slightly increased by the wave group, while the heave motion is significantly amplified. Both the aerodynamic performance and the mooring tension are also influenced by the wave group. Furthermore, the low-frequency resonant response could be more easily excited by the wave group.

Keywords: FOWT; SPAR; wave group; wave-body interaction; dynamic response

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1. Introduction

With rapid industrial development as well as the population explosion, the demand for electric power in coastal areas has increased significantly over recent decades. As traditional power generation approaches, especially the burning of coal, always create environmental issues such as carbon emissions and air pollution, renewable energies have become a strategic solution and have attracted worldwide attentions. To achieve this goal, turbines have been proposed to transform kinetic energy into electricity [1]. These rotating facilities are driven by environmental loads, such as waves, winds, tides, or currents, etc. Therefore, they seldom produce any greenhouse gases, and they are clean and open to the atmosphere [2].

After many years of development, the wind turbine has become one of the most successful commercial renewable energy generators. Based on the statistical data collected by the global wind energy council, the percentage of global electricity supplied by wind power reached 3.7% in 2015 and continues to increase [3]. However, due to the issues of land limitation and noise, the installation of onshore wind turbines has almost reached its limit. To overcome this problem, different types of fixed or floating foundations have been proposed to support wind turbines above the sea surface in order to utilize the lower-turbulence and higher-strength offshore wind energy. Dong et al. [4,5] investigated the structural vibration of monopile-type fixed offshore wind turbines. They adopted the optimized spectral kurtosis and the ensemble empirical mode decomposition combined algorithm to examine the corresponding vibration of offshore wind turbines. Collu et al. [6] conducted a comprehensive review of FOWTs and established the guidelines for the

FOWT preliminary design. Acero et al. [7] established a numerical model to simulate the dynamic responses of a tripod-type offshore wind turbine during its installation progress. According to previous research, the costs and difficulties of the installation and maintenance of fixed foundations increase exponentially when the water depth exceeds 50 m [8]. As a result, floating offshore wind turbines (FOWTs) are adopted in these deep-water areas.

The common supporting buoys of FOWTs are based on practices from the oil and gas industry [9]. Therefore, SPAR, semi-submersible, Tension Leg Platforms (TLP), and barges are often adopted for FOWTs. As a robust floating system, SPAR shows good hydrodynamic performance under mild and severe scenarios, and the world's first floating wind farm chose this type of buoy to support five 6 MW wind turbines in Scotland [10].

As a novel floating system, the dynamic behaviors of SPAR-type FOWTs are more complicated than other traditional offshore oil and gas platforms. The horizontal dimensions of a SPAR FOWT are much smaller than offshore platforms, but its nacelle is usually located about 100 m above the water plane. In other words, this extremely high tower not only amplifies the wind pressure effect, but also induces an aero-hydro coupling effect between the rotating blades and the SPAR buoy. In this paper, a number of investigations are performed to further explore the comprehensive dynamic behaviors of SPAR-type FOWT systems, according to numerical simulations, scaled model experiments, and prototype-met ocean tests. Based on Python, linked with Modelica and Dymola, Leimeister et al. [11] optimized the design of an OC3 Hywind SPAR-type foundation in order to achieve better hydrostatic and hydrodynamic performances. Yang and He [12] added tuned mass dampers to a SPAR-type FOWT to control the structural vibration. According to their numerical coupled analysis, the TMDs were proven to be effective for tower vibration control. Salehyar et al. [13] established an aero-hydro-elastic dynamic simulation tool to study the non-periodic responses of a SPAR-type FOWT under a snap wave load. Duan et al. [14] conducted 1/50-scale model tests to examine the aerodynamic and hydrodynamic responses of a SPAR-type FOWT, and they found that the gyroscopic effect of the rotating blades significantly affected the yaw motion and other coupled responses. Ruzzo et al. [15] further conducted a 1/30-scale experiment for an OC3 Hywind SPAR-type FOWT and examined its behaviors under more complicated sea scenarios.

Based on the previous research, it is commonly recognized that survival cases (or the ultimate limited states defined by Det Norske Veritas) may cause severe accidents, such as large drift motion, structure breakage, mooring failure, etc. Therefore, most of the classification societies have provided design standards, rules, and recommended practices in order to increase the target safety level and protect the FOWT system from these severe structural safety threats [16]. Apart from extreme sea state, there are also some other offshore scenarios that could increase the transient amplified responses of FOWTs. Taking freak waves or solitary waves as an example, a sudden abnormal increase of wave height may not only cause instable motion, but also affect the energy generation performance due to the hydro-aero coupling effect [17,18]. Therefore, it is necessary to evaluate the dynamic response of FOWTs under these sea states, and in recent years some researchers have organized works to study these effects, both numerically and experimentally [19–21].

On the other hand, ocean waves may appear in groups. Under this so-called wave group scenario, several successive large wave peaks could occur successively, and this large wave may induce damage to ships or marine structures [22]. Therefore, some attention has been paid to this anecdotal wave phenomenon. Numerous works have been carried out to reproduce the wave group and study its fluid dynamics, according to different algorithms, including linear or nonlinear potential flow models [23–25] and space-time evolutionary quasi-determinism theory [26,27], etc. Additionally, several studies have been conducted to study the wave-body interaction on various floating structures, such as ships [28,29], buoys [30], offshore platforms [31], FPSOs [32], wave energy converters [33], and fish cages [34], etc.

In previous studies on the wave-body interaction effect caused by wave groups, the computational fluid dynamics (CFD) approach is usually adopted due to its high accuracy and precision on the prediction of flow field. However, the cost of conducting long-time simulation for a highly-coupled system like FOWTs is rather high. Meanwhile, there is limited existing work on the transient motion of SPAR-type FOWTs under wave groups. In the present work, we adopted a superposition model and Hilbert transformation to generate wave group samples. Then, based on an established in-house coupled aero-hydro-mooring code, the dynamic response of a SPAR-type FOWT was simulated under wave group conditions.

In the following section, the physical problems are first described, and the definition of the configuration and physical parameters of the floating wind turbine system are shown. Subsequently, a brief introduction of the numerical models is provided, as well as the wave group generation approach. Numerical results, including the wave forces and dynamic responses of the system under both irregular waves and wave groups, are then presented. Finally, conclusions are drawn.

2. SPAR-Type FOWT

The FOWT is based on an OC3 Hywind SPAR-type 5 MW baseline horizontal axis wind turbine (see Figure 1). The main dimensions and key parameters of the wind turbine are listed in Table 1, and other detailed information can be found in [35]. Additionally, the parameters of the supporting system [36], including the floating buoy and three uniformly distributed mooring lines, are shown in Table 2. To clearly describe the buoy motion, a Cartesian coordinate system (x, y, z) is defined at the center of the SPAR at the still water plane.

Table 1. Parameters of the NREL 5 MW wind turbine.

Parameter	Value
Rated power	5 MW
Rotor, hub diameter	126 m, 3 m
Cut-in, rated, cut-out wind speed	3 m/s, 11.4 m/s, 25 m/s
Cut-in, rated speed	6.9 rpm, 12.1 rpm
Hub height (from Mean Sea Level)	90 m
CM location (from Mean Sea Level)	64.0 m
Rotor mass	110,000 kg
Nacelle mass	240,000 kg
Tower mass	347,460 kg
Total mass (including tower)	697,460 kg

Table 2. Parameters of the SPAR-type floating foundation and the mooring system.

Parameter	Value
Depth to platform base below the SWL	120.0 m
Elevation to platform top above the SWL	10.0 m
Depth to top of taper below the SWL	4.0 m
Depth to bottom of taper below the SWL	12 m
Platform diameter above taper	6.5 m
Platform diameter below taper	9.4 m
Platform mass, including ballast	7,466,330 kg
CM location below the SWL along platform centerline	89.9155 m
Number of mooring lines	3
Angle between adjacent lines	120 deg
Depth to anchors below SWL (water depth)	320 m
Depth to fairleads below the SWL	70 m

Radius to anchors from the platform centerline	853.87 m
Radius to fairleads from the platform centerline	5.2 m
Unstretched mooring line length	902.2 m
Mooring line diameter	0.09 m

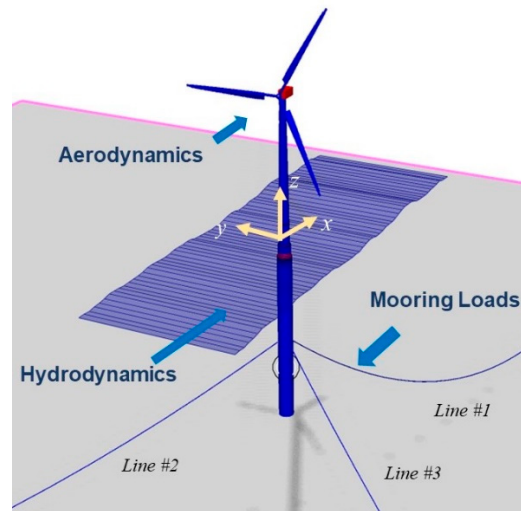


Figure 1. Definition of the physical problems.

3. Methodology

3.1. Numerical Algorithms

The simulations in the present work are based on the in-house coupled code established by Li et al., and it has been validated in previous investigations on the dynamic behaviors of SPAR-type FOWTs [37–39]. This code contains an aerodynamic module based on the blade element momentum (BEM) theory, nonlinear hydrostatic and hydrodynamic models for SPAR buoys, and the nonlinear mooring system module. By adopting aero–hydro–mooring coupling interfaces, these modules are combined to simulate the dynamic response of a SPAR-type FOWT in the time domain. For the three major types of external loads applied to the FOWTs, the prediction algorithms of the hydrodynamics, the aerodynamics, and the restoring loads provided by the mooring system are only briefly introduced in sequence, due to manuscript length issues. Further details of these separate modules can be found in previous publications [37–39].

To be specific, the wave-body hydrodynamic interaction is based on second-order three-dimensional potential theory. In our simulations, the hydrodynamic parameters, including first- and second-order load transfer functions, added mass, and potential damping are initially generated by WADAM in the frequency domain. According to the convolution approach, the wave load under a particular wave elevation can be calculated as follows:

$$F_{wave_1}(t) = \text{Re} \left[\sum_{i=1}^M a_i \exp[i(\omega_i t + \varepsilon_i)] F_1(\omega_i) \right], \quad (1)$$

$$F_{wave_2d}(t) = \text{Re} \left[\sum_{i=1}^M \sum_{j=1}^M a_i a_j \exp[i((\omega_i - \omega_j)t + \varepsilon_i - \varepsilon_j)] F_{2d}(\omega_i, \omega_j) \right], \quad (2)$$

where $F_{wave_1}(t)$ is the time history of the first-order wave load; $F_{wave_2d}(t)$ denotes the history of the second-order difference-frequency wave load; $F_1(\omega_i)$ is the linear transfer function; $F_{2d}(\omega_i, \omega_j)$ is the second-order difference-frequency load transfer functions; and a_i , ω_i , and ε_i represent, respectively, the amplitude, circular frequency, and initial phase of the i -th

wave components. Specifically, there exists another sum-frequency term in the second-order wave load, but it is not included in this work because the natural frequency of the SPAR foundation is too low to be resonated by this high-frequency excitation.

The wind loads applied to the rotating blades have a significant influence on the FOWT, and there are many numerical methods to calculate this dynamic force. As one of the classic algorithms for studying the blade aerodynamics, the BEM method is adopted in the in-house code. To enhance the ability to deal with the unsteady loads, several corrections, including the dynamic stall model, tip and hub loss correction, Glauert correction, and buoy-motion induced velocity, are also considered.

Additionally, there are two mooring system modules established in this code. One is based on the quasi-static catenary model, and the other is a fully nonlinear cable dynamic model. The former model has higher processing speed and lower CPU time cost, but the latter can simulate both the mooring force and the dynamic behavior of the mooring cables. In this work, the catenary mooring module is adopted. When the transient location of the fairlead is calculated, the current line shape can be solved by the catenary equation. Therefore, the internal tension in the mooring line is simultaneously predicted by solving the catenary equation.

A governing equation is established in the time domain in order to simulate the dynamic behaviors of the FOWT under complicated offshore scenarios and the corresponding environmental forces. By establishing a local coordinate system at the center of gravity (COG) of the SPAR-type FOWT, 6-DOF displacement, velocity, and acceleration can be obtained from the following equation:

$$(\mathbf{M} + \mathbf{A}_\infty) \ddot{\mathbf{x}}(t) + \int_0^t \mathbf{h}(t - \tau) \dot{\mathbf{x}}(\tau) d\tau + \mathbf{D}\mathbf{f}(\dot{\mathbf{x}}) + \mathbf{K}(\mathbf{x})\mathbf{x} = \mathbf{q}(t, \mathbf{x}, \dot{\mathbf{x}}), \quad (3)$$

where $\mathbf{M}$ is the mass matrix of the FOWT, $\mathbf{A}_\infty$ is the added mass when the frequency approaches infinite, and $\mathbf{h}(t)$ is the retardation function based on the convolutional method. $\mathbf{D}$ is the nonlinear damping matrix and $\mathbf{K}$ is the restoring stiffness matrix related to the submerged part of the SPAR buoy. $\mathbf{q}$ is the exciting force vector, which includes incident and diffraction wave forces on the buoy, aerodynamic force on the rotor, wind pressure on the tower, and the nonlinear restoring forces provided by the mooring cables and the coupling effects of buoy motion. $\mathbf{x}, \dot{\mathbf{x}}, \ddot{\mathbf{x}}$ represent the position, velocity, and acceleration vectors of the origin, respectively.

After gathering these modules together, an aero-hydro-mooring coupled simulation model is established. The governing Equation (3) can be numerically solved by the Runge-Kutta fourth order method in the time domain. After the buoy motions have been acquired for each time step, the external loads can be updated based on their corresponding algorithms, and these terms are adopted for the next time step until the whole simulation duration is achieved. The flow chart of the numerical code is displayed in Figure 2.

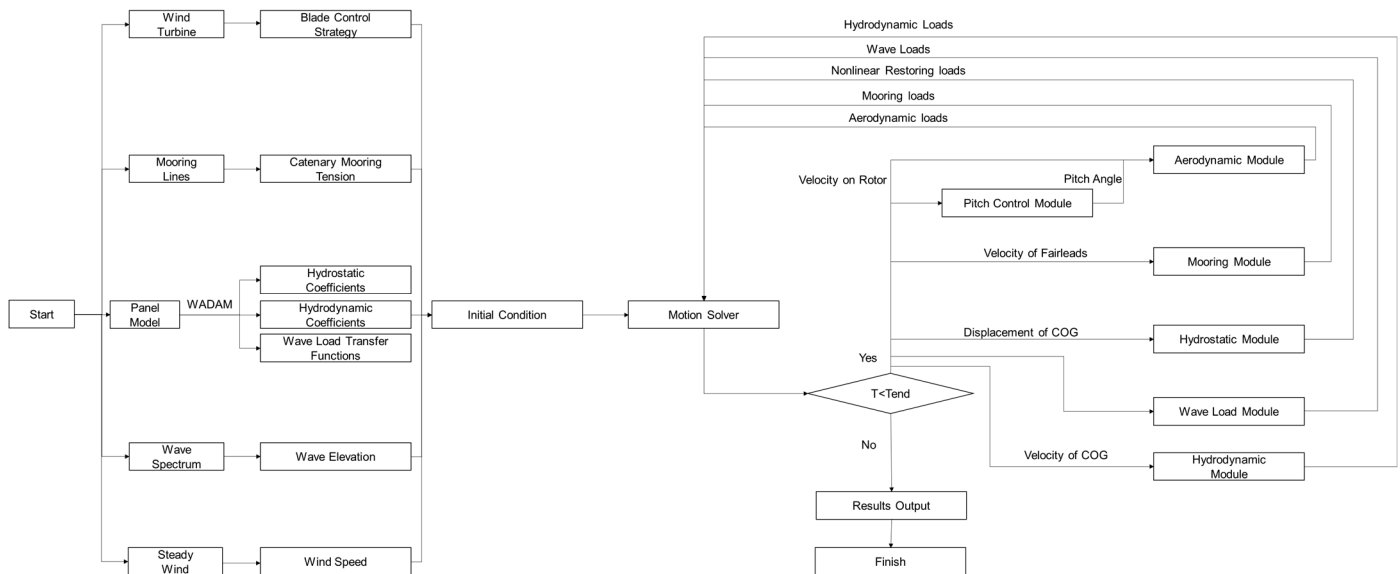


Figure 2. Flow chart of the numerical simulation tool.

3.2. Numerical Model of a Wave Group

For most offshore floating structures, their motions and dynamic responses have been observed to be sensitive to incident waves. It is usually recognized that a positive correlation exists between the motion amplitude and the wave height. However, due to the irregularity, there are various types of unusual wave surfaces that may cause extreme large motions or other dynamic responses of the floating system. Among these stochastic waves, the effect of wave groups on the hydrodynamic behavior of floating buoys has attracted a significant amount of attentions in recent decade. In this section, the numerical procedure of wave group regeneration is explained.

Based on the Longuet–Higgins model, the time histories of stochastic wave elevation, $\eta(t)$, can be reproduced numerically or experimentally according to the following equation:

$$\eta(t) = \sum_{i=1}^N a_i \cos(k_i x - \omega_i t + \varepsilon_i), \quad (4)$$

where k_i denotes the wave number of the i -th wave component. Although the same wave spectrum is adopted, significant distinctions will exist between the wave series when choosing different parameters. To be specific, the initial phase angles of irregular waves are uniformly distributed in a range from 0 to 2π . Additionally, for specific focused waves, such as freak waves, etc., a part of the initial angle is modulated to concentrate the extreme wave height at the allocated time and position [40]. However, it should be noted that there are also some other nonlinear algorithms to generate stochastic waves, such as the Schrödinger equation and the high-order spectral method, etc. These higher-order algorithms can describe the nonlinear effect of the wave elevation, especially for larger waves. The extreme wave amplitudes might be slightly different between the linear and nonlinear algorithms. To this end, it should be noted that the wave generation method might affect the dynamic responses of the FOWT.

Based on this basic algorithm, wave group time series are generated by the JON-SWAP spectrum. The wave envelope contains the key information of the wave group, which is highly influenced by the group factors. Therefore, several parameters are defined to simulate the phase spectrum. The traditional envelope amplitude approach was originally proposed by Rice [41], and it has been improved by introducing group height factor (GFH) and group length factor (GLF) to control the empirical wave envelope spectrum [28,42]. The wave envelope spectrum is as follows:

$$S_A(f) = \begin{cases} [0.042 + 0.019(f/f_{PA})] \pi m_{0\eta} (GFH)^2 / f_{PA}, & 0 \leq f \leq f_{PA} \\ 0.085 e^{-\frac{1}{3.1}(f/f_{PA})} \pi (GFH)^2 / f_{PA}, & f > f_{PA} \end{cases}, \quad (5)$$

According to Equation (5), the group height factor (GFH) is defined as $\sqrt{2\sigma_A / \bar{A}}$. The group length factor (GLF) is equal to f_p/f_{PA} . Generally, when the GFH is larger than 0.7, the value of GLF is in the range of 10 to 28. On the other hand, when the GFH is smaller than 0.7, the GLF will be from 5 to 15. [42] In these equations, f_p and f_{PA} are the frequencies corresponding to the peak values of the wave spectrum and wave envelope spectrum, respectively, $m_{0\eta}$ denotes the zeroth order moment of the wave spectrum, and σ_A and $\bar{A}$ represent the variance and mean value of the wave envelope, respectively.

After we acquire both the wave spectrum and the wave envelope spectrum, the time histories of the wave elevation, $\eta'(t)$, and the wave envelope elevation, $\eta_A(t)$, can be found by substituting the corresponding group and other wave parameters, e.g., significant wave height, H_s , peaked period, T_p , GFH , and GLF , etc., into Equations (4) and (5). The envelope

line, $A_1(t)$, can then be calculated by adding $\left(\frac{\pi}{2} m_{0\eta}\right)^{1/2}$ to $\eta_A(t)$. This is followed by calculating the phase angle, $\varphi(t)$, of the wave elevation, $\varphi'(t)$. This can be acquired based on the following formula: $\varphi(t) = \arctan[\eta_h'(t)/\eta'(t)]$, where $\eta_h'(t)$ is the Hilbert transformation of $\eta'(t)$. Finally, the time history of the wave group free surface can be generated as followings:

$$\eta_A(t) = A_1(t) \cos[\varphi(t)], \quad (6)$$

Figure 3a displays the time history of a particular wave group. A sample of an irregular wave is shown in Figure 3b for comparison. In order to make the results more distinguishable, we have also snapshot the envelopes for each wave elevation. According to the results of the wave envelope, it can be seen that the wave crests arrive at the offshore structures continuously, and the variation of the amplitudes slowly changes in a certain period. On the other hand, the crests of irregular waves oscillate more severely than those of wave groups. In other words, the wave energy may be significantly more concentrated in the wave group.

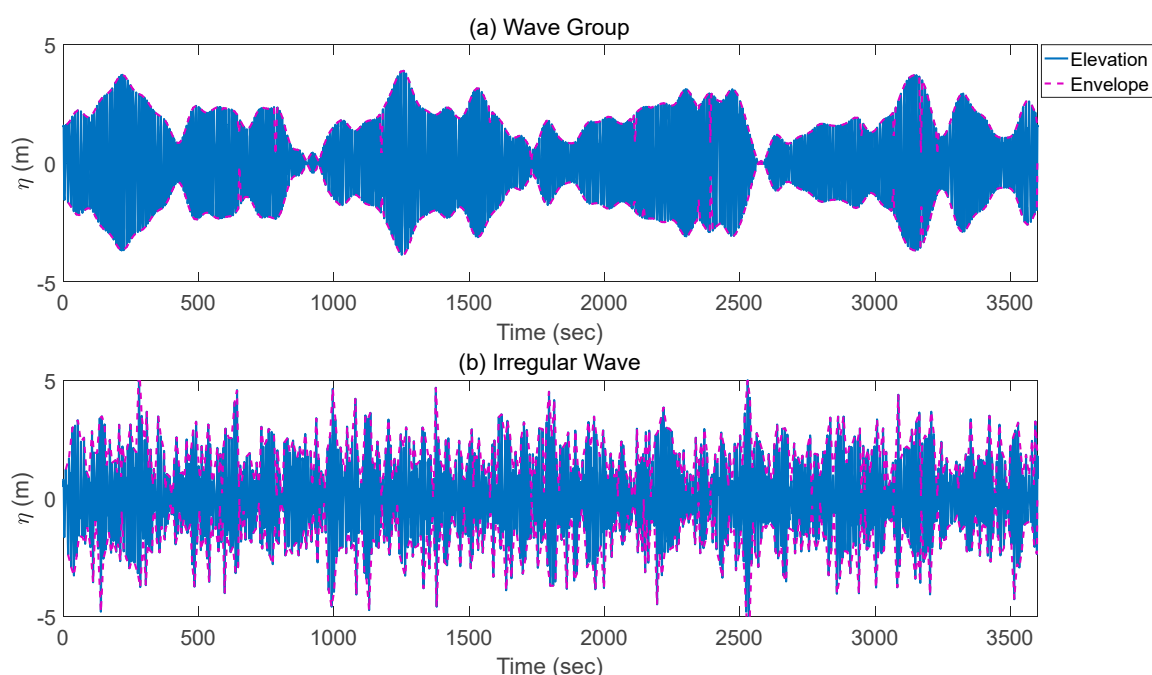


Figure 3. Time histories of irregular wave and wave group.

In order to examine whether the energy distribution of the wave elevations follow the target spectrum, power spectral density estimations were performed based on Welch's overlapped segment averaging estimator. The measured spectra, as well as the target JONSWAP spectrum, are shown in Figure 4a. It can be seen that both power density spectra agree well with the original JONSWAP spectrum. Specifically, the wave envelope spectrum of the wave group is displayed in Figure 4b. The peak can be observed in the low-frequency range, and the corresponding frequency is approximately 0.03 rad/s. From this aspect, the wave group may induce low-frequency resonant responses.

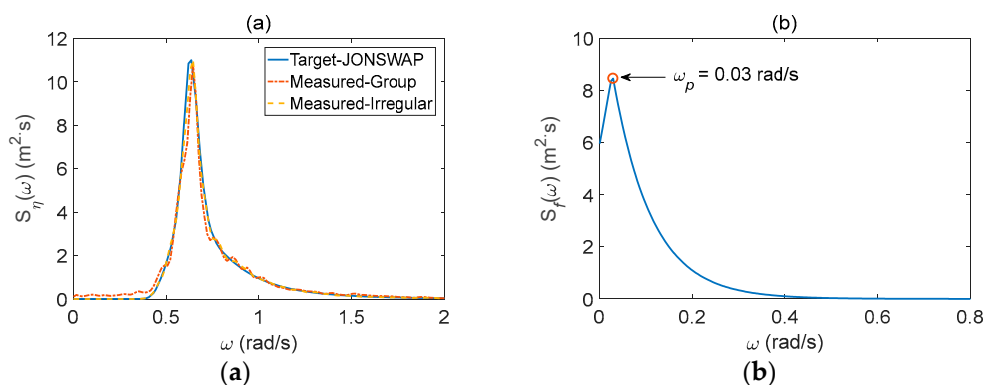


Figure 4. Power Spectra of free surface and wave envelope. (a) wave elevation; (b) wave envelope.

4. Validation

To investigate the dynamic performance of the SPAR-type FOWT under wave groups, our numerical in-house aero–hydro–mooring coupled code [21,40] was adopted. The rated scenario, as Table 3 shows, was chosen to generate the wave and wind series. Firstly, a brief validation work was organized by comparing our simulation results with those of FAST in order to show the feasibility of our code. The influence of wave groups on the dynamic performance of the FOWT system, including buoy motion, aerodynamic behavior, and mooring loads was then investigated. The effects of different wave groups was also further investigated.

Table 3. Parameters of scenario.

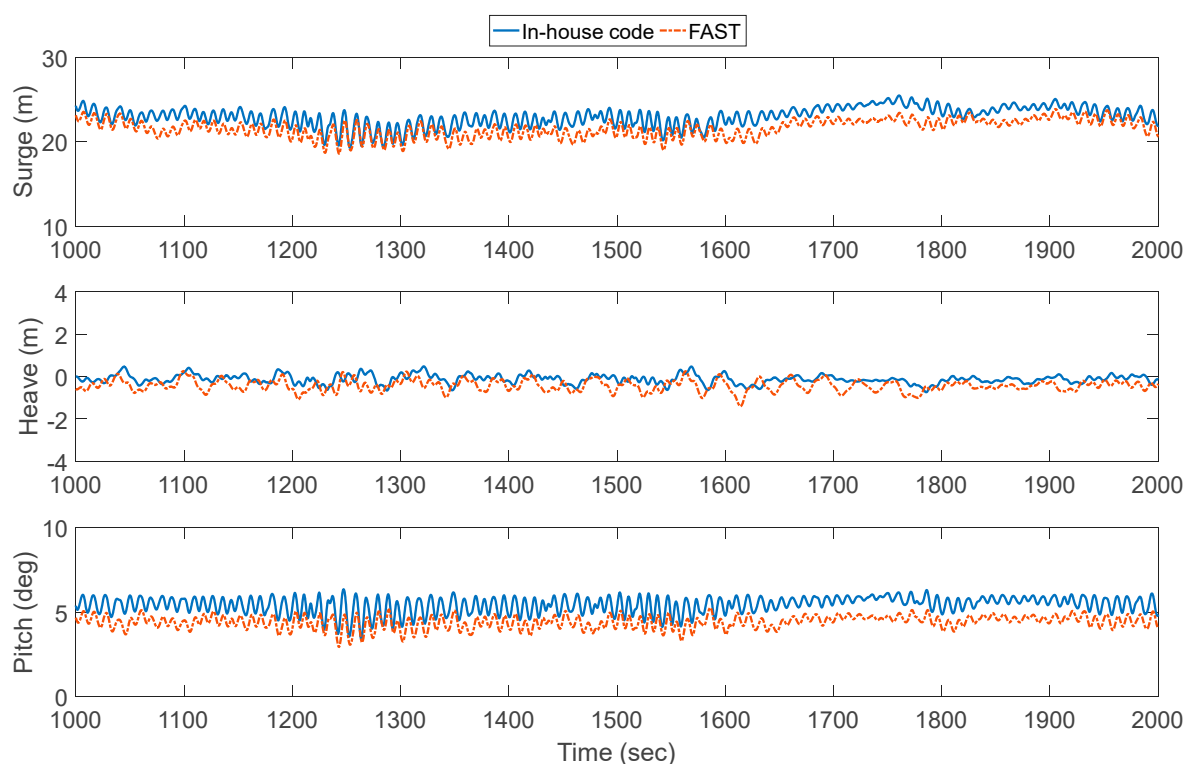
Parameter	Value
Significant wave height	6 m
Peak period	10 s
Simulated time	3600 s
Time step	0.1 s
Group length factor	23.3
Group height factor	0.734
Wind speed	11.4 m/s
Incident wave and wind direction	0 deg

In previous works, the numerical tool and each separate module were used to simulate the dynamic performance of an OC3 Hywind SPAR-type FOWT under many different wave scenarios. Specifically, the natural frequencies are summarized in Table 4, based on the simulation results of numerical relaxation tests. It can be seen that the predictions on natural features are in agreement with FAST results and other works.

Furthermore, the predictions of the dynamic responses under the wave group is validated with FAST. The same sample of wave elevation, as shown in Figure 2a, is adopted. The time histories of buoy motions, including surge, heave, and pitch, are displayed in Figure 5.

Table 4. Natural frequencies of SPAR-type FOWT.

	Surge (rad/s)	Heave (rad/s)	Pitch (rad/s)
Our work	0.050	0.207	0.211
FAST	0.050	0.201	0.214
Ruzzo et al. [15,43]	0.031	0.199	0.202
Salehyar [44]	0.044	0.198	0.228
Bae et al. [45]	0.05	0.20	0.22
Ma et al. [46]	0.050	0.201	0.220
Yue et al. [47]	0.050	0.200	0.223

**Figure 5.** Time histories of the SPAR-buoy motion simulated by the in-house code and FAST.

According to the time histories in Figure 5, it can be seen that there are few differences between the predictions regarding SPAR displacement under the same scenario. On one hand, the wave-frequency oscillations predicted by our in-house code agree well with those obtained by FAST. On the other hand, the natural-frequency responses have the same variation trend, such as the low-frequency components in surge and the near-wave-frequency responses in heave and pitch.

However, it can also be noticed that the average values do not match well between the numerical solutions, even though the differences are minor. In fact, this slight difference is caused by the blade-pitch controlling strategy and the nonlinear coupling nonlinear restoring stiffness. For simplification, the quasi-static blade-pitch controlling algorithm is adopted in our in-house simulation tool, but the PID-based algorithm is used in FAST [35]. Moreover, based on the geometric relationship of the SPAR body, the coupling hydrostatic effect [48] is derived and taken into account in the present work, while this nonlinear term is not included in FAST. Due to these contributors, the distinguishing average positions of the SPAR buoy were observed.

5. Results and Discussion

To further study the dynamic behaviors of SPAR-type FOWTs under wave groups, the time histories of FOWT responses are displayed and discussed in the following subsections. Furthermore, for comparison, the dynamic performance under the irregular wave scenario (as Figure 3b shows) is also documented. Among the results, three major elements are emphatically focused on: the SPAR buoy motions, the aerodynamic performance on the rotating blades, and the extreme tensions in the mooring lines. In the following subsections, Case 1 is defined as the wave group scenario, while Case 2 represents the irregular wave case. To remove the start-up effect, samples (32,000) in the range from 400 s to 3600 s were collected for the statistic results, and these are displayed in Figure 6. According to directly comparing the time histories, three main issues are discussed in the following subsections: buoy motion, rotor response, and mooring tension.

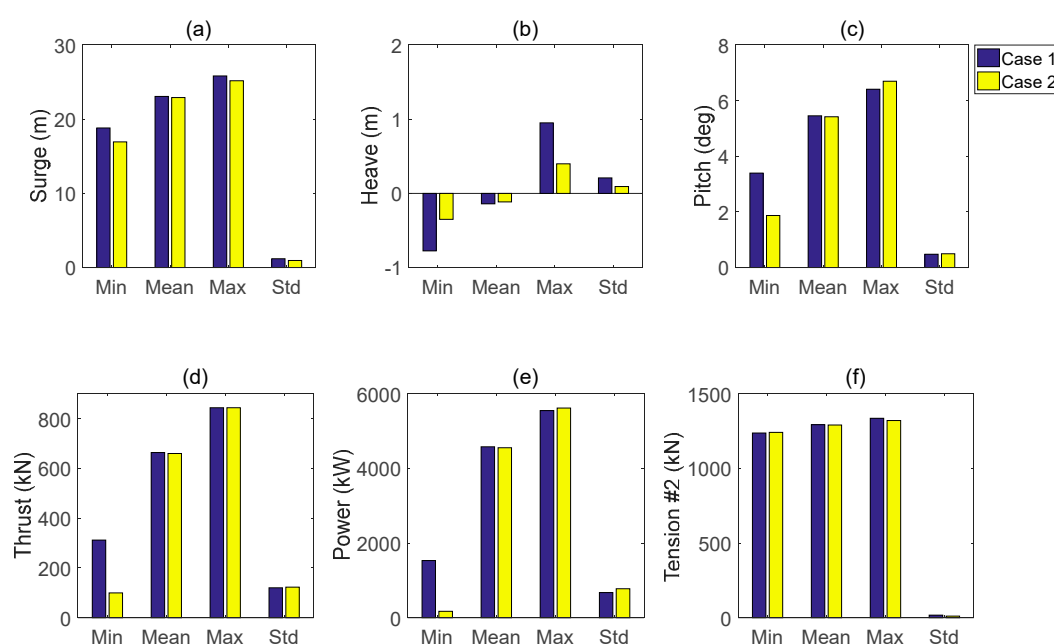


Figure 6. Statistical results of both cases. (a) Surge; (b) Heave; (c) Pitch; (d) Thrust; (e) Power; (f) Tension #2.

5.1. Buoy Surge Motion

Among all the differences between fixed and floating offshore wind turbines, the motion of the support foundation is one of the most noticeable factors to influence the overall system. The time histories and power density spectra of SPAR buoy motions are shown and discussed in the following paragraphs. Specifically, the envelope curves for each of the time histories are examined, as well as their corresponding power density spectra.

Figure 7a displays the time histories of surge motions under the wave group, as well as its envelope. According to the envelope curves in Figure 7a, we can see that the variation of the surge motion slowly changes in a certain period under the wave group. Additionally, according to the surge motion responses under the stochastic wave in Figure 7b, we can see that the variation of the surge motion under the irregular wave is more severe than that under the wave group. Moreover, by comparing the envelope curves in both figures, it was also found that the oscillation of the wave group in Figure 7a is much slighter than that under the normal stochastic wave. However, this difference is relatively small.

The power density spectra of surge motion under both cases are shown in Figure 7c, and those of the motion envelopes are shown in Figure 7d. According to both spectra, we

see that there are two dominant frequencies in the motion spectra, including the low-frequency and the wave-frequency responses. However, the responses of the envelope curve keep decreasing with the frequency. In other words, the wave frequency oscillation is not significant in the motion envelope.

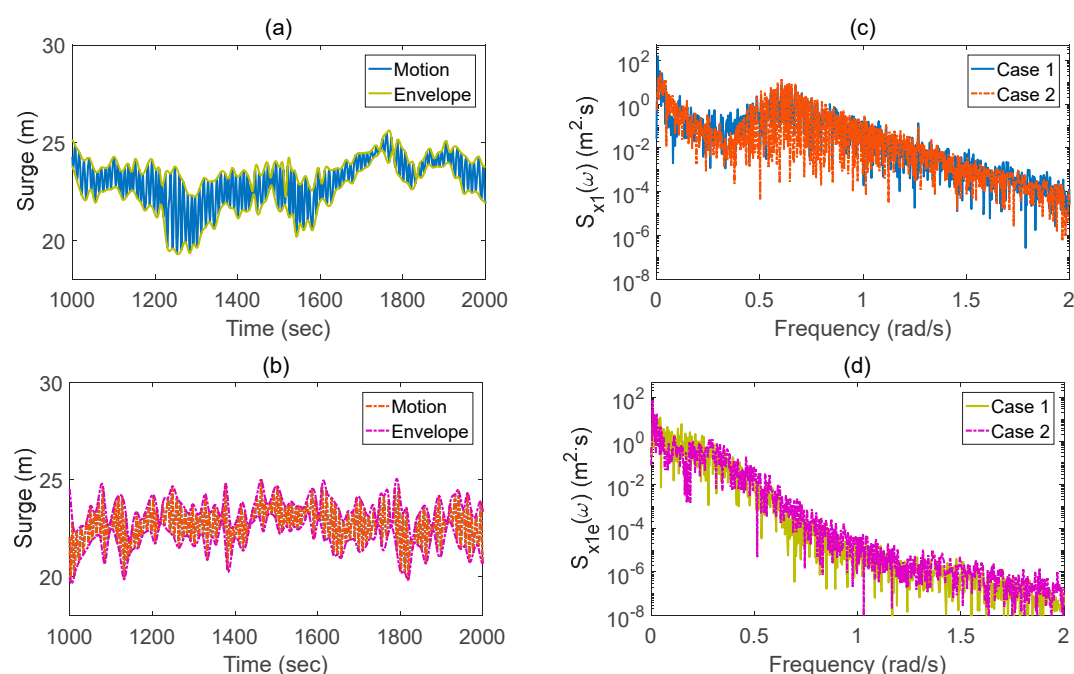


Figure 7. Time histories and power density spectra of surge motion. (a) Time histories under the wave group; (b) Surge responses under the stochastic wave; (c) The power density spectra of surge motion; (d) The power density spectra of surge motion envelope.

5.2. Buoy Heave Motion

According to the natural frequency results, the heave will oscillate at a higher frequency than the surge motion. According to the time histories of heave motion under the wave group and the stochastic wave in Figure 8a and Figure 8b, respectively, the amplitudes of heave motion are larger under the wave group case. Furthermore, the low-frequency oscillations are more significant in Case 1. It can be concluded that the wave group may increase the resonant heave motion, which may induce serious accidents under the survival sea states.

Additionally, according to the power density spectra of heave motion in Figure 8c and those of the heave envelopes displayed in Figure 8d, respectively, we can see that the spectra of heave motion have similar feature to surge, in both cases. Specifically, the dominant responses in heave motion include low-frequency and wave-frequency components, while the most significant response of the heave motion envelope is located in the low-frequency range, and the peak in Case 1 is much higher than that in Case 2.

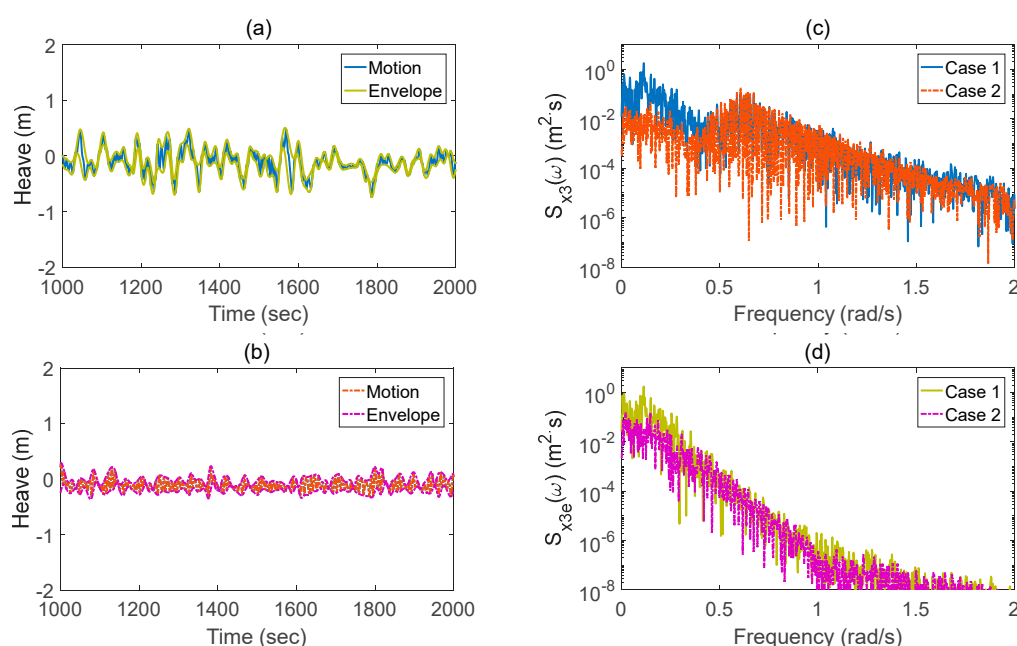


Figure 8. Time histories and power density spectra of heave motion. (a) Time histories under the wave group; (b) Time histories under the stochastic wave; (c) The power density spectra of heave motion; (d) The power density spectra of heave motion envelope.

5.3. Buoy Pitch Motion

Based on previous investigations, the buoy pitch motion has the most significant influence on the operation efficiency of the wind turbine. Figure 9a,b display the time histories of pitch motion under the wave group and irregular waves. Unlike the heave motions, we can see that the wave pitches the SPAR buoy in both cases, but the oscillation amplitudes under the wave group changes less than those under the irregular wave. It seems that the rotation motion of the FOWT occurs in groups, as the wave elevation shows in Figure 2a. On the other hand, the envelope curves in Case 2 change more severely than those under the wave group, as shown in Figure 9a. Furthermore, the maximal amplitude of the curve in Figure 9b is larger than that in Figure 9a, which means that the amplitude of trim angle under the irregular wave is larger than that under the wave group.

The power density spectra of the pitch motions of their envelopes are shown in Figure 9c and Figure 9d, respectively. It shows that the features of the pitch motion spectra are similar to those of heave and surge. However, it is interesting to see that the low-frequency response of pitch motion under the wave group is lower than that under the stochastic wave, but for the same response of pitch motion envelope, the amplitude in Case 1 is greater than that in Case 2. In other words, the wave group will increase the low-frequency pitch motion amplitude variations. However, it should be noted that the influence of the wave group on pitch motion is relative small, but its effect on the envelope curve of the pitch motion is observed in the low-frequency responses.

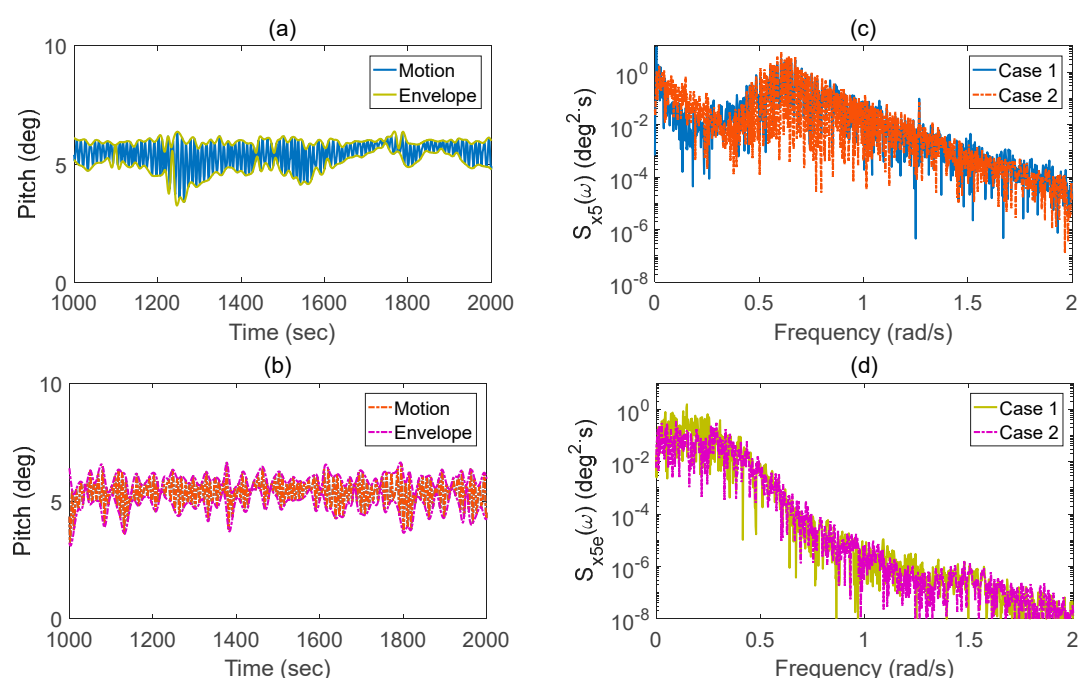


Figure 9. Time histories and power density spectra of pitch motion. (a) Time histories under the wave group; (b) Time histories under the stochastic wave; (c) The power density spectra of pitch motion; (d) The power density spectra of pitch motion envelope.

5.4. Aerodynamic Performance

As the most distinguishable difference between FOWTs and floating O&G platforms, aerodynamic loads play an important role in the dynamic response of the wind turbine system, and the power generation performance is the most important function. The thrust on the rotating blades, as well as the output power, is discussed in the following section. The time histories and spectra of these terms are shown in Figure 10. Generally speaking, the influence of the wave group on the wind turbine is similar to that on pitch motion.

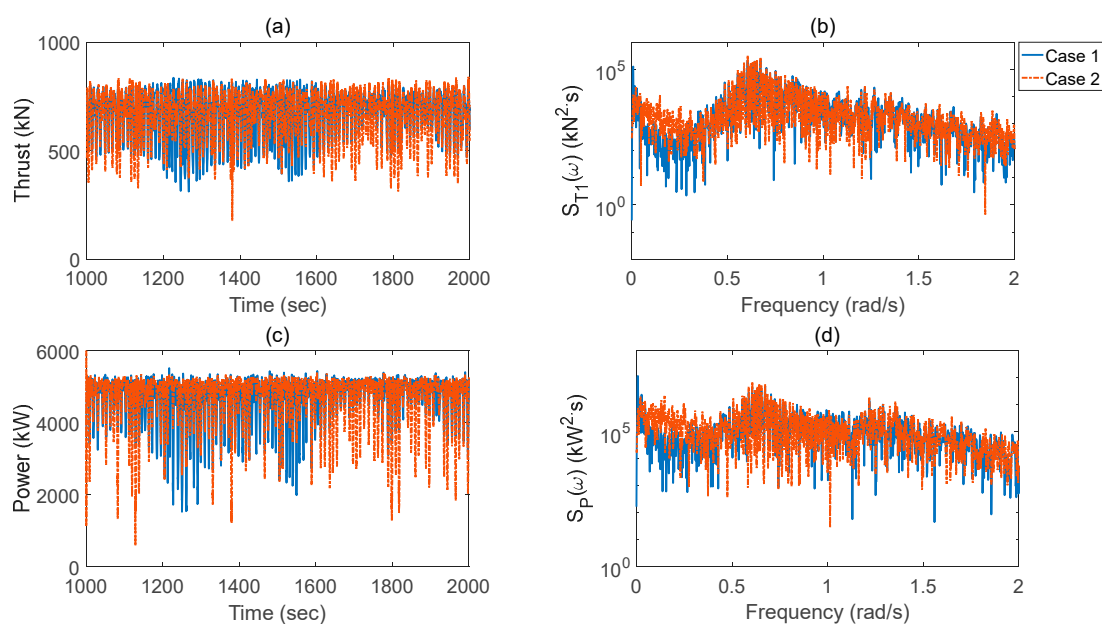


Figure 10. Time histories and power density spectra of thrust and power. (a) Time histories of thrust; (b) The power density spectra of thrust; (c) Time histories of power; (d) The power density spectra of power.

According to the time histories of thrust and power in Figure 10a,c, we can see that the curves in both figures have the same upper boundary. This is contributed to by the pitch angle adjustment system in order to prevent an overloading effect under large wind or buoy motion velocities. Moreover, based on the statistical results in Figure 6 and the time histories, the minimum thrust and output power in Case 2 is smaller than in Case 1. In other words, the oscillations of the aerodynamic loads are larger under the irregular wave. From the response spectra in Figure 10b,d, we can see that the spectra of both thrust and power under the wave group deviates from that under the stochastic wave in the low-frequency range, and this is the main contributor to the reduction of minimum thrust and power.

5.5. Mooring Tensions

The mooring system, especially the mooring tensions, is the key factor in determining whether the FOWT can work safely when in position. The mooring tensions of line #2 under both cases are displayed in Figure 11. It shows that the mooring tension under the wave group case oscillates more than that under the irregular case, so that the maximum tension is also slightly larger, based on the statistical results in Figure 6f. This is caused by the fact that the mooring tension is highly dependent on the distance between anchor and fairlead. Therefore, the features of mooring tension, including both time series and response spectra, are similar to those of SPAR buoy motion, especially the surge motion.

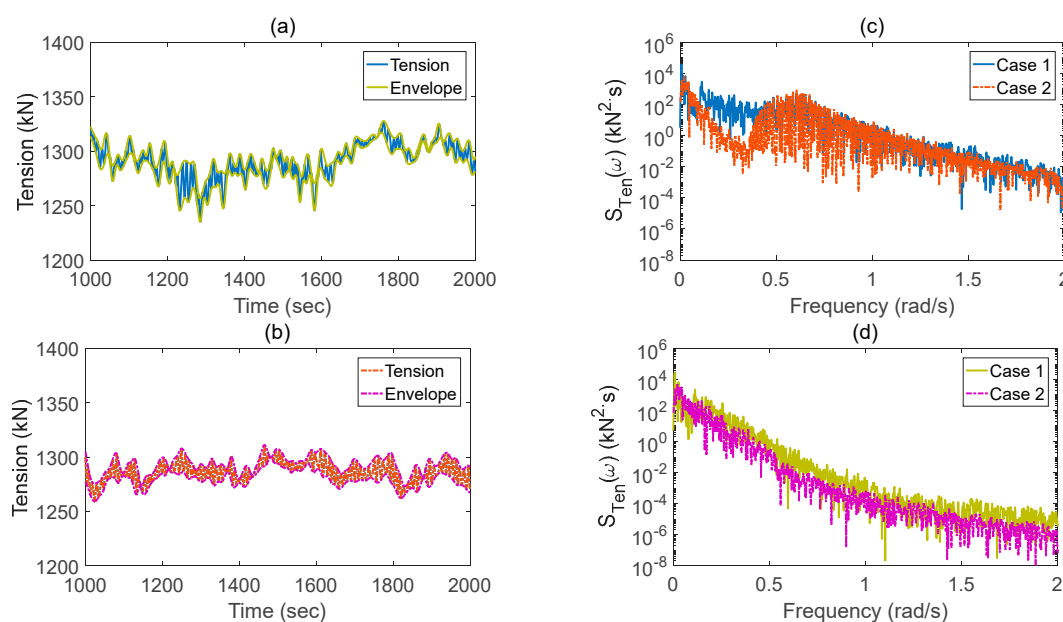


Figure 11. Time histories and power density spectra of mooring tension. (a) Time histories of tension under the wave group; (b) Time histories of tension under the stochastic wave; (c) The power density spectra of tension under the wave group; (d) The power density spectra of tension under the stochastic wave.

6. Conclusions

In this work, a numerical algorithm is adopted to simulate a wave group, which is one of the unusual accidental wave scenarios in offshore areas. Based on the superposition approach, the wave group is generated based on particular parameters, which are used to describe the group features.

Based on the established in-house code, the dynamic behaviors of a Hywind SPAR-type FOWT are simulated under wave group conditions. The results show that the SPAR buoy surge and pitch motions are slightly increased by the wave group, but the increments are not obvious. The heave motion is more significantly amplified under the wave

group. The aerodynamic performance and mooring tension are also influenced by the wave group. Moreover, another interesting phenomenon is that the buoy motion shows group features. In other words, the motion envelope curves under the wave group seem smoother than those under the irregular wave. On the other hand, the oscillations in the surge and pitch motion envelope curves are less under the wave group. However, the heave motion shows the opposite effect. The oscillations of both heave motion and corresponding envelopes are obviously amplified by the wave group. From this aspect, we surmised that the wave group has a more significant influence on the low-frequency responses of buoy motion and aerodynamic performance of the whole FOWT system.

Another phenomenon found in the present study is that the wave group effects on surge, pitch, and aerodynamic performance are relative minor, and these still need to be distinguished. This might be caused by the fact that the differences in the wave loads between the different wave scenarios are minor, as the main shape of the SPAR is slender. Another potential issue that may cause this phenomenon is the selection of the specific group parameters adopted in this simulation. In respect of this, in future works, we will continue to conduct simulations and experiments to further investigate this problem, including more wave groups with different group parameters and other floating foundations, such as semi-submersible foundation, or others.

In conclusion, the natural frequency responses are increased by enlarged corresponding frequency wave loads. Due to these low-frequency wave loads, the resonant motion could be more easily caused under an extreme sea state. The amplified motions will increase system danger under higher operational cases or survival scenarios. Therefore, more attention should be paid to this issue. However, it should be noted that, in the present work, specified wave group series were adopted to perform the simulations. Although this is an initial work to investigate dynamic behavior under a particular wave, the results may have much broader implications. According to the results, we found that the natural frequency resonant motion could be amplified by the wave group. This issue will be more serious under severe sea scenarios, and it may even lead to accidents. From this aspect, these abnormal wave conditions should be taken into consideration.

In previous investigations into the dynamic responses of FOWT, more attention was paid to normal regular and irregular waves under both operational and survival sea states. However, there has been little study carried out on abnormal wave conditions. In this work, we primarily attempted to explore the dynamic performance of FOWTs under abnormal wave conditions, taking wave groups as an example. Although some of the algorithms adopted in this study might be too simplified to thoroughly describe the external loads and coupling effect of the FOWT, we will further improve our numerical model in future works in order to conduct a more profound study on the nonlinear dynamic response of FOWT, especially under abnormal sea scenarios.

However, it should be noted that the wave group series is generated by particular GLF and GLH parameters, and the mild wave height in the operational sea state was adopted to perform the numerical investigations. We understand it is necessary to conduct a broader simulation under different wave conditions in order to fully understand the dynamic features under different wave groups. We will further conduct simulations with different wave group parameters and carry out sensitivity studies. Furthermore, it should be noted that the present validation is based on code-to-code examination. In our future work, we will attempt to organize model tests or even prototype tests and collect more data to further examine our in-house numerical code. We will also push forward 1/50-scale model tests in the wave basin to further investigate dynamic responses under abnormal wave scenarios, such as wave groups, freak waves, etc. Furthermore, in our future work, we will adopt some nonlinear algorithms to examine the nonlinear phenomenon of the wave loads and the dynamic performance of the float.

In fact, there exists another important issue in the investigations of FOWTs, which is to calculate the deformations and stresses on the slenderer structures, such as blades and tower. Although this effect is not included in our present simulations, an aero-hydro-

elastic numerical model based on Kane's equation is being developed, and it has been adopted to perform simulations on floating vertical axis wind turbines [49,50]. In future studies, this coupling in-house code will be developed to study FOWT dynamic performances.

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Abbreviations

BEM	Blade Element Momentum
CFD	Computational Fluid Dynamics
CM	Center of Mass
COG	Center of Gravity
FAST	Fatigue, Aerodynamics, Structures, and Turbulence
GFH	Group Height Factor
GLF	Group Length Factor
FOWT	Floating Offshore Wind Turbine
FPSO	Floating Production Storage and Offloading
JONSWAP	Joint North Sea Wave Project
NREL	National Renewable Energy Laboratory
SWL	Still Water Line
TLP	Tension Leg Platform
TMD	Tuned Mass Damper
A_{∞}	Added mass when the frequency approaches infinite
$\bar{A}$	Mean value of the wave envelope
a_i	Amplitude of i -th wave components
$\mathbf{D}$	Nonlinear damping matrix
ε_i	Initial phase of i -th wave components
F_{wave_1}	Time histories of the first-order wave load
F_{wave_2d}	Time histories of the second-order difference-frequency wave load
$F_1(\omega_i)$	Linear transfer function
$F_{2d}(\omega_i, \omega_j)$	Second-order difference-frequency load transfer function
f_p	Frequency corresponding to the peak values of the wave spectrum
f_{pA}	Frequency corresponding to the peak values of the wave envelope spectrum
H_s	Significant wave height
$\mathbf{h}(t)$	Retardation function
$\mathbf{K}$	Restoring stiffness matrix
k_i	Wave number of the i -th wave component
$\mathbf{M}$	Mass matrix of the FOWT
$m_{0\eta}$	Zeroth order moment of the wave spectrum
η	Time histories of stochastic wave elevation
η^A	Wave envelope elevation

η^h	Hilbert transformation of wave elevation
ω_i	Circular frequency of i -th wave components
φ	Phase angle
$\mathbf{q}$	Exciting force vector
σ_A	Variance of the wave envelope
T_p	Peaked period
(x, y, z)	Cartesian coordinate system
$\mathbf{x}, \dot{\mathbf{x}}, \ddot{\mathbf{x}}$	Position, velocity and acceleration vectors of the origin

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