Dynamic Response and Mooring Fracture Performance Analysis of a Semi-Submersible Floating Offshore Wind Turbine under Freak Waves

Baolong Liu and Jianxing Yu *

State Key Laboratory of Hydraulic Engineering Intelligent Construction and Operation, Tianjin Key Laboratory of Port and Ocean Engineering, School of Civil Engineering, Tianjin University, Tianjin 300350, China; liubaolong_tju@163.com
* Correspondence: yjx_tju@163.com

Abstract: Among the extreme sea scenarios, freak waves pose a serious threat to offshore structures, potentially leading to structural failure, such as mooring line failure, floater capsizing, or structural damage. In this study, we conducted a numerical investigation on the transient performance of a semi-submersible floating offshore wind turbine (FOWT) equipped with a redundant mooring system under the influence of freak waves and mooring failure. Firstly, we analyzed the dynamic responses of an intact-mooring-system FOWT under a freak wave. Next, we examined the effect of mooring failure on the transient responses. The results indicate that floater motions exhibit significant differences in the interval of freak wave crests. The impact of freak waves increases the blade tip deformation and tower root bending moment, while also affecting the tension of the mooring line and the aerodynamic performance of the wind turbine. Consecutive fracture with an interval of 20 s significantly increases surge motion and reduces output power. When mooring lines break separately with an interval of 400 s, the amplification in the responses is noticeably lower compared to consecutive fracture cases.

Keywords: floating offshore wind turbine (FOWT); freak wave; mooring fracture; transient response

1. Introduction

Energy is the key driver of economic growth and development. A reliable energy supply is essential for the advancement of all sectors of society [1]. As one of the renewable energy sources, wind energy contributes to the diversification of the energy supply. Utilizing wind energy to generate electricity reduces dependence on traditional fossil fuels, helping to combat climate change and curb global warming [2]. Power generation is the core component of a wind turbine system, which enables a sustainable and clean energy supply by converting wind energy into electricity [3]. Deep-water areas, which tend to have higher average wind speeds and more stable wind directions, allow floating offshore wind turbines (FOWTs) to access stronger wind resources than those available to onshore wind farms. This expansion increases the areas where wind energy can be effectively utilized [4].

When operating FOWTs, they can be exposed to extreme sea conditions—for example, storms and typhoons [5], high-speed currents [6], extreme waves [7], and so on. Among them, the occurrence of freak waves usually induces an extremely large wave crest and amplifies the buoy motion, which may also result in significant wave impacts on floating systems, increasing the risk of the FOWT experiencing structural damage or even capsizing [8].

Freak waves have a significantly higher amplitude than normal irregular waves, which means that an extremely prominent but thin peak could be observed, resulting in strong energy and little correlation with its neighboring waves. Furthermore, the freak wave’s existence is very short, and its influence will fade quickly [9]. From the above features, we
can infer that the freak waves accumulate enormous energy in a very short time, which can cause major damage once they impact the offshore structures [10].

Scholars have organized numerous studies on the motion response of each FOWT under normal sea scenarios, while the effects of freak waves have attracted more attention. Luo et al. [11] adopted the focused wave theory to generate freak waves, and they analyzed the influence of freak wave crest positions on the motions of a tension-leg platform (TLP) via model tests. Chang et al. [12] paid attention to the nonlinear wave loads on the TLP that were caused by the freak wave. The results showed that the TLP will undergo violent motion under freak waves with higher peaks, so that both large amplitudes and high-frequency responses are observed in the tendon tensions. Wang et al. [13,14] further investigated the effects of different components in the freak wave loads, and the results showed that the low-frequency motion, mostly represented by the surge, is mainly affected by the second-order different-frequency wave loads, while the second-order sum-frequency wave loads affect the high-frequency motions in heave and pitch. Rudman et al. [15] studied the influence of incident directions. The results showed that the mooring tension increased with the incident angle but had little effect on the floating foundation’s motion. Russo et al. [16] conducted experimental research on the dynamic loads and response of a spar-buoy wind turbine with pitch-controlled rotating blades. The experiments were designed specifically to compare different operational environmental conditions in terms of wave steepness and wind speed.

Ruzzo et al. [17] and Li et al. [18] each investigated the dynamic responses of a spar-type FOWT under freak waves during normal operation. Large oscillations in pitch and surge were observed in both numerical simulations. Luo et al. [19] investigated the impact heights of different freak waves. They found that even if the freak wave’s impact height on the floating platform was relatively low, the impact pressure on the floater deck was still high, and a large surge motion was also observed. Qu et al. [20] incorporated the effects of current into the wave energy spectrum and analyzed the dynamic response of an SFWT under the interaction of freak waves and steady currents. A notable common remark among those studies was that the whole system remained intact during the abnormal wave, but the damage to the structure was not included.

Due to the transient impact and large drift motion under freak waves, FOWTs may suffer different types of damage, such as mooring line failure [21], blade breakage [22], tower fracture [23], floater sinking or capsizing [24], etc. Among these, the mooring line failure is one of the most critical accidental load cases, which is always recommended to be investigated by different classification societies. To be specific, it is widely recognized that a missing mooring line increases the floater motion as well as the tension in the other remaining lines, which may pose a serious hazard to the structural stability of the FOWT.

Many scholars have studied the effects of mooring line fracture in recent years, especially for those FOWTs with non-redundant mooring systems. Li et al. [25] conducted time-domain simulations to investigate the transient response of spar-type FOWTs in mooring failure cases, based on a fully nonlinear dynamic algorithm for both intact and broken lines. It was found that the mean position of each degree of freedom (DOF) changed significantly after the damage, and the heave motion was changed due to the different weights of the remaining broken lines. Lin et al. [26] approximately estimated the drift trajectory and output power of the OC4 DeepCwind semi-submersible floating offshore wind turbine in an offshore wind farm under different environmental loads and line disconnection cases. They found that double line failure would induce more severe drift motion. Gao et al. [27] considered the effects of wind, waves, and currents to investigate the applicability of a fracture-mechanics-based (FM-based) method for calculating the fatigue life of FOWT mooring lines in the time domain. The results show that the FM-based method can usually estimate the fatigue life of FOWT mooring lines reasonably well. Zhang et al. [28] proposed a new, fully submersible platform and analyzed the effects of line failure on the platform’s kinematic characteristics, as well as the remaining lines. The simulation results show that line failure mainly affects the sway, roll, and yaw responses, which are closely related to
the stiffness and symmetry of the mooring system. Once a mooring line suddenly fails, the
equilibrium of the mooring is disturbed and the mooring forces are redistributed. However,
it should be pointed out that these transient effects were investigated under the normal
operational or extreme survival scenarios. Common irregular waves were adopted in
those analyses.

Nevertheless, both sudden amplified external environmental loads and the changes
in the floating system will undoubtedly induce transient responses, such as oscillations,
drift motions, or other subsequent damages. In this work, we will examine dynamic FOWT
behaviors under a combined accidental case, in which the FOWT suffers both sudden
mooring-line breakage and the extremely large wave impact load caused by a freak wave.
To be specific, the time histories of freak waves are generated based on the phase angle
modulation method, and the aero–hydro–structural coupled model is established for a
semi-submersible FOWT to perform the dynamic calculations under the freak wave and
mooring line failure.

In Section 2, the physical problem is first described, showing the configuration of the
FOWT system and the definition of the physical parameters. In Section 3, the theoretical
model is briefly introduced, and the method of generating the freak wave is presented.
Section 4 illustrates the validation of the model, and Section 5 gives the numerical results
and analysis, including the dynamic response of the FOWT under different operating
conditions. Section 6 summarizes the whole work and gives an outlook for the future.

2. Physical Problem

The object of this study consists of an upwind three-bladed NREL-5 MW wind turbine,
a nacelle, an 80 m tall tower, and a semi-submersible floating foundation positioned by
nine mooring lines, as shown in Figure 1.

![Figure 1. Schematic diagram of the FOWT structure and the environmental loads.](image)

The semi-submersible foundation [29,30] adopted in this work is a new type of semi-
submersible floating foundation with three columns, which is proposed for the specific
offshore sea scenario in the South China Sea. Based on the general arrangement of other
common semi-submersible FOWTs, such as DeepCwind, WindFloat, etc., the main body
consists of three cylindrical columns, with three pontoons below the cylinders, which
provide sufficient buoyancy and stability for the FOWT. The columns are connected by
three square braces in order to improve the structural strength. The overall layout is in
the form of an equilateral triangle, and the basic structure type is shown in Figure 2. The
corresponding the main dimensions can be observed in Table 1.
Parameters of the NREL-5MW wind turbine.

To perform the aero–hydro coupled analysis of this semi-submersible FOWT, the blades and the nacelle of the NREL-5MW wind turbine (the National Renewable Energy Laboratory, US) [31] were adopted; its corresponding parameters are listed in Table 2.

Table 2. Parameters of the NREL-5MW wind turbine.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>5 MW</td>
</tr>
<tr>
<td>Wind direction</td>
<td>Leeward</td>
</tr>
<tr>
<td>Number of blades</td>
<td>3</td>
</tr>
<tr>
<td>Shafting transmission efficiency</td>
<td>0.944</td>
</tr>
<tr>
<td>Wind wheel radius</td>
<td>63 m</td>
</tr>
<tr>
<td>Propeller hub radius</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Cut-in/rated/cut-out wind speed</td>
<td>3 m/s, 11.4 m/s, 25 m/s</td>
</tr>
<tr>
<td>Rated speed</td>
<td>12.1 rpm</td>
</tr>
<tr>
<td>Hub height</td>
<td>90 m</td>
</tr>
<tr>
<td>Height of center of gravity</td>
<td>64.0 m</td>
</tr>
</tbody>
</table>

The NREL-5MW wind turbine tower is designed based on the onshore wind turbine model. The diameter of the tower root is 6 m, the thickness of the cylinder wall is 0.027 m, the diameter of the tower top is 3.87 m, and the thickness of the cylinder wall is 0.019 m. The diameter and wall thickness change linearly along the height direction. As steel was chosen to establish the tower, the axial and shear Young’s modulus are 210 GPa and 80.8 GPa, respectively. Considering the structure of the coating, bolt, welding, and flange on the tower, which are not included in the wall thickness, the equivalent density of the tower column is recorded as 8.5 t/m³. The relevant structural parameters are as described in Ref. [32].
As another major difference from other FOWTs, the mooring system adopts a redundant design to increase the safety and robustness of the whole floating system. Specifically, the mooring system design of European floating wind turbines generally starts from the perspective of investment cost, and it usually uses three mooring lines arranged at an interval of 120 deg for positioning. Considering the 65 m water depth of the project, the wind and wave conditions are worse than those in the North Sea of Europe. In this study, the adopted mooring system has nine mooring lines, which are divided into three groups with an interval of 120 deg. Each group of three mooring lines is connected to the column and arranged in parallel. The mooring line arrangement scheme is shown in Figure 3.

![Diagram of mooring system](image)

**Figure 3.** Layout of the mooring system.

A single mooring line consists of three different sectional chain parts. The upper end, around the splash zone, is an R3S anchor chain with a length of 20 m. The middle section is an R3-grade anchor chain with a length of 131 m. The bottom section is an M2-grade anchor chain with a length of 280 m. The main parameters of each anchor chain are shown in Table 3.

<table>
<thead>
<tr>
<th>Mooring Line Segmentation</th>
<th>Bottom Part</th>
<th>Middle Part</th>
<th>Top Part</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ingredients</td>
<td>M2</td>
<td>R3</td>
<td>R3S</td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>208</td>
<td>122</td>
<td>122</td>
</tr>
<tr>
<td>Length (m)</td>
<td>280</td>
<td>131</td>
<td>20</td>
</tr>
<tr>
<td>Dry weight (kg/m)</td>
<td>861</td>
<td>296.2</td>
<td>296.2</td>
</tr>
<tr>
<td>Breaking tension (kN)</td>
<td>24,140</td>
<td>11,365</td>
<td>12,690</td>
</tr>
<tr>
<td>Axial stiffness (kN)</td>
<td>3,690,000</td>
<td>1,270,000</td>
<td>1,270,000</td>
</tr>
</tbody>
</table>

### 3. Methodology

#### 3.1. Dynamic Model of the FOWT

In this work, the aero–hydro–structural coupled dynamic model was established to calculate the numerical performances of the semi-submersible FOWT. On the one hand, the environmental loads were calculated based on the corresponding numerical algorithm. Specifically, the aerodynamic loads on the blades were simulated based on the unsteady blade element momentum algorithm, while the wave impacts on the floater were achieved by the three-dimensional potential theory. On the other hand, the rigid–flexible coupled numerical model was established to predict the transient responses of the semi-submersible FOWT after the accidents. The time histories of the buoy’s rigid motion were predicted by the Cummins convolutional equation, while the slender structures, including the blades, tower, and mooring lines, are numerically modeled as beams or bars, and their dynamic os-
cillations are solved by the finite element method. Each algorithm will be briefly introduced in the following subsections.

3.1.1. Three-Dimensional Potential Theory

For those large-volume floaters, such as the floating platforms and supporting foundations of the FOWTs, the potential theory is widely used to calculate the wave loads on the wet surface. Commonly, the frequency–time transformation (FTT) algorithm is used to calculate the time histories of the fluid dynamics, including the hydrostatic, incident, diffraction, and radiation loads. Therefore, we usually divide the velocity potential term \( \Phi \) in the flow field into three parts, which are the incident term \( \Phi_I \), diffraction term \( \Phi_D \), and radiation term \( \Phi_R \), as shown in Equation (1):

\[
\Phi = \Phi_I + \Phi_D + \Phi_R. \tag{1}
\]

For both the incident and diffraction terms, the wave loads are solved based on the Laplace equation and corresponding boundary conditions in the frequency domain.

The wave loads on the buoy can be divided into three parts: the first-order wave load \( F_{\text{Wave}1}(t) \), the second-order wave load \( F_{\text{Wave}2}(t) \), and third-order and above loads \( F_{\text{Wave}(3+)}(t) \). Therefore, the wave loads can be written as follows:

\[
F_{\text{Wave}}(t) = F_{\text{Wave}1}(t) + F_{\text{Wave}2}(t) + F_{\text{Wave}(3+)}(t) \tag{2}
\]

where the first two terms are the Volterra series expansions of wave loads up to the second order, while \( h^{(1)} \) and \( h^{(2)} \) are the linear and second-order impulse response functions, respectively. The wave load linear transfer function (LTF) and quadratic transfer function (QTF) are achieved in the frequency domain. According to previous investigations, both linear and higher-order wave loads are influenced by freak waves, so we used the FFT algorithm to transfer the frequency-dependent transfer functions into time histories, based on the following relationships in Equation (3). The corresponding theory can be found in Ref. [25].

\[
F_{\text{Wave}1}(t) = \text{Re} \left[ \sum_m \sum_n \tilde{\xi}_m H_m^{(1)}(\omega_m) e^{i \omega_m t} \right], \quad F_{\text{Wave}2}(t) = \text{Re} \left[ \sum_m \sum_n \tilde{\xi}_m \tilde{H}^{(2+)}_m H^{(2\pm)}_m e^{i (\omega_m + \omega_n) t} + \sum_m \sum_n \tilde{\xi}_m \tilde{H}^{(2-)}_m H^{(2\pm)}_m e^{i (\omega_m - \omega_n) t} \right]. \tag{3}
\]

where \( H^{(1)}(\omega) \) is the first-order wave excitation force transfer function, \( H^{(2\pm)}_m(\omega) \) is the second order sum-frequency wave force QTFs, \( H^{(2-)}_m(\omega) \) is the second-order differential frequency wave force QTFs, \( \tilde{\xi}_m \) is the complex Fourier component of the wave height at frequency \( \omega_m \), and \( \tilde{\xi}^*_m \) is the conjugate component of \( \tilde{\xi}_m \).

3.1.2. Blade Element Momentum Theory

In this work, the blade element momentum theory, which combines the momentum principles with the blade element division theory, was adopted to perform the aerodynamic performance evaluation. The iteration progress was used to achieve the axial and tangential induction factors. After that, the thrust and the moment on each blade element were calculated based on the following equations:

\[
dT = 4\pi \rho \nu_0^2 a(1 - a) dr, \tag{4}
\]

\[
dM = 4\pi^3 \rho \nu_0 \omega_r (1 - a) a' dr, \tag{5}
\]

where \( dT \) represents the thrust exerted by the blade element, \( dM \) represents the torque generated by the blade element, \( r \) denotes the distance between the blade element and the shaft, \( \rho \) symbolizes the air density, \( \nu_0 \) signifies the wind speed, \( \omega_r \) represents the rotor speed, and \( a \) and \( a' \) indicate the axial and tangential induction factors, respectively.
To predict the unsteady performance more accurately, some corrections are adopted, such as dynamic inflow correction, skewed wake correction, tip and hub loss corrections, etc. More details can be found in Ref. [7].

### 3.1.3. Governing Equation of the Buoy

For an FOWT subjected to various loads, including aerodynamic, hydrodynamic, and mooring loads, the coupled governing equation for the six degrees of freedom of the buoy can be formulated as follows (Ref. [7]):

\[
(M + A_\infty) \ddot{x}(t) + \int_0^t h(t - \tau) \dot{x}(\tau) d\tau + K(x(t)) = q(t, x, \dot{x}),
\]

where \(M\) represents the mass matrix of the buoy, \(A_\infty\) denotes the frequency-dependent added mass matrix associated with the surrounding water, and \(K\) signifies the stiffness matrix related to the inherent structural stiffness. \(x, \dot{x}, \ddot{x}\) denote the vectors of position, velocity, and acceleration of the buoy, respectively. \(q\) represents the external excitation loads, encompassing first-order and second-order wave loads, mooring restoring forces, and aerodynamic loads exerted on the rotor. In addition, the convolutional method is used to convert the added mass and potential flow damping, which vary with frequency, into a hysteresis function for calculation, where \(h(t)\) represents the hysteresis function.

### 3.1.4. Dynamic Modeling of Flexible Structures

In this study, beam elements were employed to establish dynamic models for flexible structures encompassing blades and tower. The deformation of beam elements is contingent upon various factors, including their topological configuration, structural dimensions, cross-sectional shapes, material properties, and boundary conditions. When analyzing the deformations of these elements, it is necessary to make certain reasonable assumptions and simplifications. For instance, lateral deformations resulting from axial tension are often neglected, as well as torsional resistance. Moreover, the finite element method is utilized for discretization. The mass and elastic stiffness matrices for each finite element can be represented as follows:

\[
m_e = \int_0^l \rho_e N^T N dx,
\]

\[
k_{el} = \int_0^l E I \left( \frac{d^2 N}{dx^2} \right)^T \left( \frac{d^2 N}{dx^2} \right) dx,
\]

where \(\rho_e\) and \(l\) are the density and length of the finite element, respectively. \(N\) is the shape function matrix, \(E\) is the elastic modulus, and \(I\) is the section moment of inertia.

### 3.2. Numerical Algorithm of the Freak Wave Generation

Klinting and Sand gave a more comprehensive and strict definition of freak waves [33]. The definition is as follows: Assume that the time-ordered wave height sequence is \(H_1, H_2, \ldots H_{j-1}, H_j, H_{j+1}, \ldots H_n\). If the wave is classified as a freak wave train, the following three criteria need to be met: \(H_j \geq 2H_{j-1}, H_j \geq 2H_{j+1}, H_j \geq 2H_{j+1} \text{, and } \eta_j \geq 0.65H_j\) where \(H_{j-1}\) is a wave train height of the freak wave front, \(H_j\) is the freak wave’s extreme wave train height, \(H_{j+1}\) is the wave train height after the freak wave, and \(\eta_j\) is the peak height above the waterline of the freak wave train; that is, the extreme wave train height of the freak wave needs to be greater than or equal to twice the significant wave height, the former wave train height, and the latter wave train height, and the peak height above the waterline of the freak wave train must be greater than or equal to 0.65 times the extreme wave train height of the freak wave [34].

There are two main methods to generate freak waves; one is linear, and the other is nonlinear. On the one hand, the nonlinear method is usually used to study the instability of
nonlinear wave modulation. In this work, numerical wave-making was carried out based on the linear method of the Longuet-Higgins model, where the superposition method is simple and fast, and the generated waveform is stable. This is also a common method for laboratory simulation of wave-making. The wave elevation is shown as follows:

$$\eta(x, t) = \sum_{n=1}^{N} a_n \cos(\kappa_n x - \omega_n t + \epsilon_n)$$  \hspace{1cm} (9)

In this work, the improved phase angle modulation method was used to develop the freak wave simulation program \[35\]. In this method, the frequency vector is scrambled and divided into two groups (A and B) randomly, with a total of $M$ parts. The first $M_1$ wave elements from group A are used as background waves, and the wave elevation $\eta_i = a_i \exp[i(kx - \omega_i t + \epsilon_i)]$ corresponding to the frequency is calculated in complex form. The phase angles $(\kappa_n x - \omega_n t + \epsilon_n)$ are randomly selected within $(0, 2\pi)$. The randomness of this part of the wave elements ensures that the generated freak waves are consistent with the actual sea conditions before and after the focusing time. The remaining $M_2$ wave elements from group B are modulated by modulating its initial phase angle $(\kappa_m x - \omega_m t + \epsilon_m)$ within $(0, \pi/2)$ to create focusing conditions for freak wave generation, where elevation is defined as $\eta_j = a_j \exp[i(kx - \omega_j t + \epsilon_j)]$. The cosine function is used to superimpose the wavefront of the wave element to achieve the effect of wavefront focusing. This ensures that the wave surface can converge into extreme waves at the focusing moment and the focusing position, which satisfies the freak wave criterion. Therefore, the wave surface equation in this program is recorded as follows:

$$\eta(x, t) = \sum_{n=1}^{M_1} a_n \cos(\kappa_n x - \omega_n t + \epsilon_n) + \sum_{m=1}^{M_2} a_m \cos(\kappa_m x - \omega_m t + \epsilon_m),$$  \hspace{1cm} (10)

where $\eta$ is the wave elevation at position $x$ and time $t$, which is a summation of the original wave components $M_1$ and the modulated components $M_2$; $k$ is the wave number; $\omega_i$ is the frequency; and $\epsilon_i$ is the phase. In this research, the first group of $M_1 = 400$ components $\omega_n$ were randomly selected from $\omega_{0,i}$ to generate the background irregular wave, whose phase angles $\epsilon_n$ were randomly selected within $(0, 2\pi)$. The rest of the wave components were used in the second group ($M_2 = 600$) with a modulated phase angle $(\kappa_m x - \omega_m t + \epsilon_m)$ within $(0, \pi/2)$ to create focusing conditions for freak wave generation. The freak wave parameters are shown in Table 4. Cai et al., observing the sea area of China, found that freak waves appeared under sea conditions suitable for wind turbine operations, with an average wave height of less than 2 m \[36\]. So, the significant wave height $H_s$ is 3 m in the present work, and the spectral peak period is 10 s.

### Table 4. Freak wave parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral peak period $T_p$</td>
<td>10 s</td>
</tr>
<tr>
<td>Significant wave height $H_s$</td>
<td>3 m</td>
</tr>
<tr>
<td>Frequency-domain range $\omega_m \sim \omega_n$</td>
<td>0.05–2 rad/s</td>
</tr>
<tr>
<td>Number of constituent waves $M$</td>
<td>1000</td>
</tr>
<tr>
<td>Number of random waves $M_1$</td>
<td>600</td>
</tr>
<tr>
<td>Simulation duration $t$</td>
<td>1600 s</td>
</tr>
<tr>
<td>Time interval $\Delta t$</td>
<td>0.1 s</td>
</tr>
<tr>
<td>Focus moment $t_c$</td>
<td>800 s</td>
</tr>
<tr>
<td>Focus location $x_c$</td>
<td>0 m</td>
</tr>
</tbody>
</table>

Based on the improved phase angle modulation method mentioned above, a numerical analysis program was written for the determination of freak waves after batch simulation. In order to statistically determine the generation possibility of freak waves from all waves,
we adopted four parameters to judge the conditions: \( a_1 = H_j / H_s \), \( a_2 = H_j / H_{j-1} \), \( a_3 = H_j / H_{j+1} \), and \( a_4 = \eta_j / H_j \). When the values of the parameters met the following conditions at the same time—\( a_1, a_2, a_3 \geq 2, a_4 \geq 0.65 \)—the wave could be defined as a "freak wave". We used the spectral parameters of Table 4 to develop an in-house code to generate 2000 wave trains, and we counted the parameters of each wave satisfying the judgment conditions. The statistical results are shown in Figure 4, where the number of waves meeting \( a_1 \) is 1638 (81.9% of the total), the number of waves meeting \( a_2 \) is 818 (40.9% of the total), the number of waves meeting \( a_3 \) is 410 (20.5% of the total), and the number of waves meeting \( a_4 \) is 28 (1.4% of the total). Also, the total number of freak waves is the same as the number of the waves meeting \( a_4 \), so the possibility of generating a freak wave is about 1.4% when using the present spectral parameters. When the wave meets \( a_4 \), the wave is a freak wave, so \( a_4 \) is the most stringent condition, which means that the height of the wave crest \( \eta_j \) has the most important effect on the generation of freak waves.

![Figure 4. The possibility statistics on various parameters of generated waves.](image)

Among the series of freak waves generated, the freak wave surface time history with the best waveform, no other extreme wave effects, and no other wave groups was selected. The simulated freak wave time history curve is shown in Figure 5a,b. The wave loads in three DOFs are shown in Figure 5c. This shows that the freak wave has a very high wave crest, which accompanies high wave loads in three DOFs. This would cause a high influence on the floater and mooring lines.

![Figure 5. Time series of freak wave elevation and wave loads. The red circle means peak.](image)
4. Validation

In order to verify the feasibility of the model, the numerical simulation of free decay was carried out first. Under the condition of no environmental load, the initial displacement was applied to each DOF and released freely, and the free decay of single-DOF tests on the FOWT was simulated. The time series of corresponding motion are shown in Figure 6. The natural period of each DOF motion was calculated, as shown in Table 5. The natural frequencies of the system’s motion are far away from the actual sea wave frequency range, and the possibility of resonance with the first-order wave load is low, which is conducive to the stability of motion in waves. Compared with the free decay motion test results of the model test carried out by Zhao et al. [29], it can be seen that the results are in good agreement, as shown in Table 5, and the method has been validated by Li et al. in their research on FPSO and spar-type FOWTs to ensure the results in freak waves [37,38].

![Figure 6. Time series of free decay motions.](image)

**Table 5.** Natural period of a semi-submersible FOWT with three columns.

<table>
<thead>
<tr>
<th>DOF</th>
<th>Our Work Natural Period</th>
<th>Zhao et al. [29] Natural Period</th>
<th>Relative Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge</td>
<td>52.86 s</td>
<td>59.48 s</td>
<td>11.13%</td>
</tr>
<tr>
<td>Sway</td>
<td>53.57 s</td>
<td>58.66 s</td>
<td>8.68%</td>
</tr>
<tr>
<td>Heave</td>
<td>24.25 s</td>
<td>24.12 s</td>
<td>0.05%</td>
</tr>
<tr>
<td>Pitch</td>
<td>23.25 s</td>
<td>23.12 s</td>
<td>0.06%</td>
</tr>
</tbody>
</table>

5. Results

This section calculates and analyzes the dynamic response characteristics of the semi-submersible FOWT under the action of freak waves. First, we define the environmental conditions. The wave type is freak wave, the time series of which is shown in Figure 5. The wind type is steady wind, with a speed of 11.4 m/s. In Section 5.1, we first study the
dynamic responses of the FOWT under freak waves to explore the effect of freak waves on the buoy motion and mooring line tension. Based on the results of dynamic analysis, we set a series of fracture cases to research the mooring fracture performance caused by freak waves in Section 5.2.

5.1. Dynamic Responses under Freak Waves

The time series and wavelet plots of buoy motion under freak waves are shown in Figure 7. The results in the time series of buoy motion show that 3-DOF motions all increase after the freak wave. We used the method of wavelet analysis to study the temporal evolution of energy, and the results show that the energy density in the spectrum experiences an immediate increase at the beginning of the freak waves (800 s). Specifically, there is an obvious enlargement in the low-frequency surge motion after the freak wave, which would pose a dangerous threat to the buoy and mooring lines. This is why we conducted a series work on the analysis of broken lines, and we performed the fast Fourier transform of the dynamic response under freak waves, as shown in Figure 8. It can be seen that the motion amplitude occurs at the wave frequency of 0.628.

![Figure 7](image-url)  
**Figure 7.** Time series and wavelet plots of buoy motions under freak waves: (a) Surge. (b) Heave. (c) Pitch.
We also simulated the dynamic responses of mooring lines under freak waves, as shown in Figure 9. This shows that the tension of the mooring lines significantly increased, seriously threatening the safety of the mooring lines. When the mooring line’s bearing capacity reaches its limit, the mooring line will break, which is also a great test for the FOWT. Therefore, the motion variations when the mooring lines fracture due to extreme sea conditions are discussed in the next subsection.

5.2. Dynamic Responses under Mooring Line Fracture

The various mooring line fracture scenarios are depicted in Figure 10, illustrating the following conditions: Case 1, where Lines #4 and #7 fracture at 800 s (the focal time of the freak wave); Case 2, where Lines #4 and #7 fracture at 800 s, followed by Lines #5 and #8 fracturing at 820 s; and Case 3, where Lines #4 and #7 fracture at 800 s, followed by Lines #5 and #8 fracturing at 1200 s. Specifically, when the fracture time arrives, the boundary condition at the fractured point on the mooring lines changes to free from the continuous link. As the maximum load occurs around the fairleads, the broken points are chosen at this position, which means that the whole line would sink to the sea bed after the fracture accident.
5.2.1. Floater Motion

The analysis of foundation motion plays a crucial role in optimizing the design of FOWTs. When subjected to significant surge motion, the floating foundation may deviate from its designated operational position, causing considerable stretching of the mooring lines. Furthermore, the pitch motion of the floating foundation influences wind exposure and relative wind speed, which impact the power generation efficiency of the wind turbine. Additionally, the interaction between mooring fatigue and heave motion further influences the integrity or reliability of the mooring system. In this section, the time histories of motion on the semi-submersible floating foundation under the action of freak waves and fractured mooring line conditions are shown in Figure 11. The motions of surge, heave, and pitch were selected for analysis.

Figure 11. Motion comparison time histories of semi-submersible floating foundation under fractured mooring line conditions.
As illustrated in Figure 11a, under the influence of freak waves, the surge motion with an intact mooring system peaks at 5.17 m, while maintaining an average of 3.74 m. Comparatively, the equilibrium position of the final surge motion varies depending on the number of fractured mooring lines. In Case 1, where only Lines #4 and #7 were broken at 800 s, the surge motion remained relatively unaffected; the equilibrium position increased from 3.88 m to 6.65 m. However, in Case 2, when Lines #4 and #7 fractured at 800 s, significant transient surge motions occurred first, and the maximum surge was up to 7.91 m. Because the large buoy surge motion caused tension in the mooring lines, we set Lines #5 and #8 to fracture at 820 s, which was the same time as the maximum surge motion. At 830 s, the transient surge increased to 15.70 m, marking a transient increase of 13.01 m from 800 s. In Case 3, the transient surge increased from 6.44 m to 14.66 m at 1200 s, with a transient increase of 8.22 m, which is smaller compared to the transient increase observed in Case 2, where multiple mooring lines broke simultaneously.

As depicted in Figure 11b,c, for heave response with an intact mooring system, the maximum heave motion is 0.94 m, with a similar mean of −1.31 m. As for pitch motion with intact mooring conditions, under freak wave conditions, the maximum pitch motion reaches 2.53 degrees, with the average remaining at 0.64 degrees. Additionally, the time histories of heave and pitch responses reveal minimal variation across different cases of line breakage. This observation confirms the robust stability of the semi-submersible floating foundation with three columns in both heave and pitch DOFs.

5.2.2. Blade Deformation

The variable marine environment and the wind turbine’s height lead to complex and severe blade root loads, which are crucial for determining blade design, assessing reliability, and optimizing structures to ensure long-term stability and cost-effectiveness. Figure 12 illustrates the blade coordinate system of the semi-submersible FOWT, while Figure 13 displays the time history of blade tip deformation under the influence of freak waves with various fracture conditions. In Figure 13, when the mooring system remains intact, there is a notable alteration in blade tip deformation during the freak wave impact at 800 s. However, whether the mooring lines break at 800 s or 1200 s, the relative deformation in the blade tip is not significant, which can be attributed to the outstanding pitch and heave motion performance of the semi-submersible FOWT discussed in this study.

Figure 12. Blade coordinate system of the semi-submersible FOWT.

Figure 13. Time histories of blade tip out-plane deformation under various fractured mooring line conditions. The red circle means peak.
5.2.3. Tower Bending Moment

Analyzing and monitoring the loads of the FOWT tower root under freak wave impacts is crucial for ensuring real-time operational safety by detecting and addressing potential structural issues promptly. In this work, the tower coordinate system adopts a Cartesian coordinate system, as depicted in Figure 14.

![Figure 14. Tower coordinate system of the semi-submersible FOWT.](image)

In Figure 15, the time history of the tower root bending moment under various line breakage scenarios is depicted. It is evident that the impact of freak waves is more pronounced on the bending moment under various fractured mooring line conditions, with the maximum moment reaching \(3.0 \times 10^4\) kN. Interestingly, it was observed that different cases of line breakage have minimal impact on the tower root bending moment. The minimal impact on the tower root bending moment suggests that the structure was likely designed with redundancy or ample safety margins to endure such loads.

![Figure 15. Time histories of tower root bending moment under fractured mooring line conditions.](image)

5.2.4. Mooring Lines

Mooring lines serve an important role in stabilizing offshore FOWTs, with their strength and tension being directly connected to the system’s safety. In this work, Lines #1–3 experience relatively low tension along the wave direction, while Lines #4–9 become critical under extreme sea conditions, particularly when analyzing the safety implications of freak waves. Among them, Lines #4–6 and #7–9 are arranged symmetrically about the x-axis, with Lines #4–6 configured in parallel. Therefore, Line #9 was selected for detailed analysis of mooring line tension under fractured mooring line conditions.

In Figure 16, it can be observed that Line #4 experiences an average tension of 705.7 kN before being subjected to the freak wave. Upon the impact of the freak wave, the tension instantly rises to 794.6 kN, representing only a 12.6% increase. However, the figure illustrates that when Lines #4, #5, #7, and #8 fracture consecutively with an interval of 20 s in Case 2, the mooring tension of Line #9 rises significantly and surpasses that when the lines fracture separately with an interval of 400 s in Case 3. In Case 2, the maximum mooring
tension peaks at 2480 kN at 830 s, while in Case 3 the maximum mooring tension for Line #9 reaches 2050 kN at 1231 s. In conclusion, when the mooring is intact, freak waves have little effect on the tension of the mooring. However, there will be a major impact on other mooring lines if the freak waves cause some of them to break.

![Figure 16. Time histories of mooring tension under fractured mooring line conditions.](image)

5.2.5. Aerodynamic Performance

The output power of the turbine for different line breakage cases is shown in Figure 17, which illustrates that the FOWT primarily operates within its rated power state for most of the time, with a maximum output power reaching 5296.7 kW. However, under the impact of freak waves, the minimum output power dips to 3858.8 kW. This decrease can be attributed to the significant movement induced in the floating foundation and tower by the impact of the freak wave. Particularly, the notable pitch response causes the wind turbine to tilt, altering the relative wind speed of the rotor and leading to instability in the output power.

![Figure 17. Time histories of output power under fractured mooring line conditions.](image)

Additionally, it is evident from the figure that the output power decreases notably when mooring line breakage occurs. Specifically, in Case 2, the output power drops to a minimum value of 3708.6 kW. In Case 3, with the mooring line breakage at 1200 s, the output power slightly decreases to 4550.9 kW but does not reach the minimum value. However, at 1290 s, the output power reaches its minimum of 4181.6 kW.

6. Conclusions

In this work, the dynamic response characteristics of a semi-submersible FOWT with three columns under freak waves were analyzed. The influence of line fracture caused by extreme sea conditions on the dynamic responses of the FOWT was studied.
The motions of the floating foundation experienced notable discrepancies in response to freak waves, highlighting the significant influence of these extreme events on the foundation dynamics. The energy density of dynamic responses in the spectrum experienced an immediate increase at the beginning of the freak waves (800 s). Notably, the simultaneous breakage of three mooring lines exerted the most pronounced influence on surge motion response. However, due to the robust heave and pitch stability inherent in semi-submersible floating foundations, minimal disparities were observed in heave and pitch motions under different line breakage conditions. For the blade tip deformation and tower bending moment, the influence of freak waves is significant but is not highly sensitive to various fractured mooring line conditions. The occurrence of freak waves also affects the mooring line tension and power generation performance of the wind turbine.

When four mooring lines break consecutively with an interval of 20 s in Case 2 (Lines #4 and #7 at 800 s, Lines #5 and #8 at 820 s), the floating foundation undergoes a great transient surge motion, with the mean surge increasing from 3.88 m to 12.14 m. Comparatively, the transient surge increase from individual mooring line breakages is less pronounced than when all four lines break simultaneously. Additionally, mooring line breakage has no discernible effect on the heave and pitch motion. The impact of line breakage on the blade and tower is indirectly felt and is relatively minor, and the breakage of mooring lines results in a minimum output power of 3708.6 kW.

In subsequent analyses, a sensitivity analysis of the simulation parameters for freak wave occurrences could be conducted to assess the impact of design parameters on dynamic response characteristics. In the design of structural form, other size and shape selections could be proposed based on the three-column semi-submersible type in this work. By employing the coupling analysis methodology introduced in this work, a floating foundation with more optimized dynamic responses under operating sea conditions and abnormal sea conditions could be obtained. In the future, we would use nonlinear methods to generate freak waves, such as Breather-type methods, NLS-type methods, and the HOS-WG method [39–41]. The problem of third-order loads will also be considered in freak wave generation and dynamic responses on FOWTs [42,43], and freak waves in high-sea states should be studied in future works [44]. We will continue to optimize mooring design to make the system more reasonable.

Author Contributions: Conceptualization, B.L. and J.Y.; methodology, B.L.; software, J.Y.; validation, B.L. and J.Y.; formal analysis, B.L.; investigation, B.L. and J.Y.; resources, J.Y.; data curation, B.L. and J.Y.; writing—original draft preparation, J.Y.; writing—review and editing, B.L.; visualization, B.L. and J.Y.; supervision, B.L.; project administration, B.L. and J.Y.; funding acquisition, J.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in this article (tables and figures).

Conflicts of Interest: The authors declare no conflicts of interest.

References
1. Yolcan, O.O. World energy outlook and state of renewable energy: 10-Year evaluation. Innov. Green Dev. 2023, 2, 100070. [CrossRef]
2. Summerfield-Ryan, O.; Park, S. The power of wind: The global wind energy industry’s successes and failures. Ecol. Econ. 2023, 210, 107841. [CrossRef]


10. Ji, X.; Li, A.; Li, J.; Wang, L.; Wang, D. Research on the statistical characteristic of freak waves based on observed wave data. *Ocean Eng.* 2022, **243**, 110323. [CrossRef]


21. Tang, H.J.; Yao, H.C.; Yang, R.Y. Experimental and numerical study of a barge-type floating offshore wind turbine under a mooring line failure. *Ocean Eng.* 2023, **278**, 114411. [CrossRef]


23. Rostam-Alihou, A.A.; Zhang, C.; Salboukh, F.; Gunes, O. Potential use of Bayesian Networks for estimating relationship among rotational dynamics of floating offshore wind turbine in extreme environmental conditions. *Ocean Eng.* 2022, **244**, 110230. [CrossRef]


34. Majumder, S.; Remya, P.G.; Nair, T.B.; Sirisha, P. Analysis of meteorological and oceanic conditions during freak wave events in the Indian Ocean. Ocean Eng. 2022, 259, 111920. [CrossRef]


38. Li, H.; Li, Y.; Li, G.; Zhu, Q.; Wang, B.; Tang, Y. Transient tower and blade deformations of a Spar-type floating wind turbine in freak waves. Ocean Eng. 2024, 294, 116801. [CrossRef]

39. Wu, Q.; Zhang, H.Q. Breathers, rogue waves and breather–rogue waves on a periodic background for the modified nonlinear Schrödinger equation. Wave Motion 2022, 110, 102890. [CrossRef]

40. Kashima, H.; Mori, N. Aftereffect of high-order nonlinearity on extreme wave occurrence from deep to intermediate water. Coast. Eng. 2019, 153, 103559. [CrossRef]


42. Rongé, É.; Peyrard, C.; Venugopal, V.; Xiao, Q.; Johanning, L.; Benoit, M. Evaluation of second and third-order numerical wave-loading models for floating offshore wind TLPs. Ocean Eng. 2023, 288, 116064. [CrossRef]

43. Khait, A. Third-order generation of narrow-banded wave trains by a wavemaker. Ocean Eng. 2020, 218, 108200. [CrossRef]


Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.