Structural Response and Load Prediction Analysis of Offshore Monopile Wind Turbines under Long-Period Marine Seismic Actions: Postprint

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Abstract

With the development of offshore wind turbines toward higher flexibility and deeper waters, and given that offshore seismic motions exhibit pronounced long-period components, the structural safety of wind turbines faces substantial threats. To investigate the structural dynamic response characteristics of offshore wind turbines under long-period offshore seismic excitations, this study adopts the 5 MW monopile-fixed wind turbine developed by the National Renewable Energy Laboratory (NREL) of the United States as the research object. First, based on the K-NET database and the offshore seismic long-period component characteristic index βl, offshore ground motions are classified. Subsequently, using the open-source software OpenFAST, and considering three operating conditions—normal operation, parked turbine, and emergency shutdown—under combined action of turbulent wind and earthquake, the tower motion responses and seismic loads on the tower are extracted and analyzed, with particular emphasis on the influence of the long-period components of offshore ground motions. Finally, on the basis of existing load prediction models, and incorporating the influence of the long-period characteristics of offshore seismic motions, a more accurate prediction model for extreme tower loads is proposed. The results indicate that under offshore long-period seismic motions, both the tower motion response and the seismic load on the tower are much larger than those under conventional seismic motions. When the earthquake intensity is relatively small, aerodynamic effects amplify the structural response, whereas when the earthquake intensity is relatively large, the damping effect within the aerodynamic action reduces the structural response of the tower. The proposed load prediction model that accounts for the long-period effects of seismic motions can be used for more accurate calculation of extreme tower loads under offshore seismic excitations.

Full Text

Preamble

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Structural Response and Load Prediction Analysis of Offshore Monopile Wind Turbines Under Long-Period Sea Area Earthquake Actions

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Abstract

Offshore wind turbine structures are becoming increasingly flexible and are being deployed in deeper waters. Historic offshore earthquake ground motions contain significant long-period components, posing substantial threats to the structural safety of wind turbines. To investigate the dynamic response characteristics of offshore wind turbines under long-period sea area seismic motions, this study focuses on a monopile fixed-bottom wind turbine using the OpenFAST open-source software developed by the National Renewable Energy Laboratory (NREL) of the United States. The study first classifies seismic motions using the long-period component characteristic index β based on the K-NET offshore seismic database. Subsequently, under combined turbulent wind and seismic actions, three operational conditions are examined: normal operation, parked turbine, and emergency shutdown. The tower motion responses and seismic loads are extracted and analyzed, with particular emphasis on the effects of long-period components in sea area ground motions. Finally, based on existing load prediction models and accounting for the influence of long-period characteristics of sea area ground motions, a more accurate extreme load estimation model for the tower is proposed. The results demonstrate that both tower motion responses and seismic loads under long-period sea area ground motions are significantly greater than those under conventional ground motions. At low seismic intensities, aerodynamic effects increase structural responses, while at high seismic intensities, the damping effect within aerodynamic actions reduces tower structural responses. The proposed load estimation model that considers long-period ground motion effects can be used for more precise calculation of extreme tower loads under sea area seismic actions.

Keywords: long-period offshore earthquake; structural dynamic response; offshore monopile turbine; OpenFAST; aerodynamic damping

1. Introduction

The pollution-free and renewable nature of wind energy makes wind power generation one of the most promising power generation methods in the new energy sector. Offshore wind development offers advantages such as low turbulence intensity and minimal environmental impact. According to statistics from the Global Wind Energy Council [1], the cumulative global offshore wind capacity reached 57.6 GW in 2023, the highest on record, with China' s total offshore wind capacity reaching 25.6 GW. China' s coastal wind farm areas are located in the Pacific Ring of Fire seismic belt, where numerous earthquake categories exist. Historically, the Yellow Sea, Bohai Sea, and Southeast Sea areas have experienced multiple earthquakes above magnitude 6 [2-3], causing enormous economic losses.

Offshore ground motions are influenced by complex seabed soil structures and are affected by factors such as epicentral distance, exhibiting significant long-period components in both horizontal and vertical directions [4-5], with spectral characteristics showing peaks shifting toward longer periods [6-7]. The primary frequency design of wind turbines (shown in the green interval in [Figure 1: see original paper]) and the long-period components of ground motions exhibit an unfavorable trend of converging toward each other.

Numerous scholars have conducted research on the impact of seismic loads on wind turbine structural safety. Ji Liang et al. [8] used ANSYS to simultaneously consider turbine structural responses and compared them with International Electrotechnical Commission standards and Japanese codes. Dai Kaoshan et al. [9] employed finite element methods to study the maximum tower top displacement of turbines under various seismic actions and explored mathematical relationships between tower damage levels and PGA (peak ground acceleration). Ishihara et al. [10] used semi-empirical formulas to evaluate seismic excitation effects on 400 kW and 2.0 MW turbines. Haciefendioğlu [11] performed stochastic seismic response analysis on two types of turbines based on finite element models.

Current domestic and international seismic load dynamic analysis for offshore wind turbines primarily relies on land-based structural seismic design codes and theories. The validity of the above methods for analyzing large monopile offshore turbines under long-period seismic actions in offshore areas requires further scientific verification. Offshore seismic records are limited, making research on long-period ground motion characteristics in offshore areas a critical issue for evaluating the seismic performance of large fixed offshore turbines.

[Figure 1: see original paper] shows a schematic illustration of the spectral distribution of complex environmental loads on wind turbine structures [6-7]. Addressing these issues, this study employs the NREL 5MW standard offshore monopile wind turbine as the research object. Within the OpenFAST computational framework, seismic records from the K-NET offshore seismic network are selected and filtered. The study explores the dynamic response analysis of large offshore wind turbines under combined wind and seismic actions, investigates the contribution and coupling mechanism of load components, examines the influence mechanism of long-period seismic actions on structural response characteristics, and proposes a seismic load prediction model.

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2. Numerical Methods and Model Setup

2.1 Research Object and Numerical Method

This study uses the 5.0 MW wind turbine developed by the National Renewable Energy Laboratory (NREL) as the research object. The horizontal-axis wind turbine has a hub height of 87.6 m and a rotor radius of 63 m. The substructure is a monopile with a diameter of 6 m. Basic information is provided in , with main structural parameters listed in . Additional relevant parameters can be found in the literature [12].

This research is based on OpenFAST, a time-domain analysis tool for aero-hydro-servo-elastic coupled structural dynamic response developed using multi-body dynamics [13]. To address the limitation that OpenFAST has no seismic analysis function, Asareh et al. [14] added seismic motion capabilities to OpenFAST under the Seismic module support. The principle simplifies the coupling between the wind turbine mudline foundation platform and soil into a spring-dashpot system with stiffness K and damping C. The expressions for damping C and seismic load F are:

$$
\begin{aligned}
K &= m\omega^2 \\
C &= 2\zeta m\omega \\
F_{\text{target}} &= m\ddot{u}_{\text{target}} + C\dot{u}_{\text{target}} + K(u_{\text{target}} - u_{\text{actual}})
\end{aligned}
$$

where m is the total mass of the wind turbine, ω is the angular frequency of the vibration input simulator, ζ is the damper damping ratio, $\ddot{u}_{\text{target}}$ and $\dot{u}_{\text{target}}$ are the target displacement, velocity, and acceleration of the seismic input, and u_{actual} is the actual displacement at the structural platform. The target displacement takes the seismic ground motion input at the mudline. The logic relationship of each module is shown in [Figure 2: see original paper].

2.2 Wind Load Input

The wind field where the turbine is located is a full-domain three-dimensional turbulent wind field [15], generated by the open-source program Turbsim. The mean wind speed at hub height is the rated wind speed of 11.4 m/s. The turbulence wind spectrum is defined as Kaimal, with turbulence intensity taken as 19.8% according to the specification. The wind field dimensions are 160 m × 160 m. The three-dimensional full-domain turbulent wind field at different moments is shown in [Figure 3: see original paper].

In the numerical calculation, the induced velocity field is calculated based on the Generalized Dynamic Wake (GDW) model. The aerodynamic lift, drag, and pitching moment on each blade element are computed using Blade Element Momentum (BEM) theory and integrated to obtain total aerodynamic forces acting on the wind turbine structure.

2.3 Seismic Motion Selection and Load Input

This study focuses on horizontal seismic action. Offshore seismic motion data from the K-NET seismic network are selected and processed. Following the long-period seismic screening method proposed by Li Xuehong et al. [7], the long-period component characteristic index β is used to characterize the significance of long-period components in ground motions. The index β is defined as the square-weighted average of the seismic amplification factor spectrum:

$$\beta_l = \frac{\sum_{T_i \in [2,10]} \beta(T_i) \cdot S_a^2(T_i)}{\sum_{T_i \in [2,10]} S_a^2(T_i)}$$

where β_l is the weighted average of the seismic amplification factor spectrum, T_i are the discrete periods of the equal-distance acceleration response spectrum in the range [2,10] seconds, $S_a(T_i)$ are the corresponding spectral acceleration values, and PGA is the peak ground acceleration. Ground motions with $\beta_l > 0.4$ are classified as long-period, those with $0.2 \leq \beta_l \leq 0.4$ as medium-long period, and those with $\beta_l < 0.2$ as conventional ground motions.

provides basic statistical information for the selected long-period offshore seismic motions ($\beta_l > 0.4$). To investigate response differences between long-period and conventional ground motions, the average amplification factor β spectra curves are calculated for each group. The records with β value curves farthest from the average curve are selected as input ground motions. [Figure 4: see original paper] shows the seismic amplification factor β spectra curves and their average values for three types of ground motions.

For each set of horizontal ground motions, the combined seismic motion is normalized and then scaled as needed. The combined seismic acceleration A is defined as the square root of the sum of squares of the longitudinal and transverse components. The wind load and seismic load directions are defined as: x-axis along the wind direction, y-axis across the wind direction, and z-axis along the vertical tower direction.

Following the research results of Asareh et al. [16], the structural damping under seismic excitation considers aerodynamic damping effects. For normal operation, the turbine structural damping should adopt aerodynamic damping, while for parked and emergency shutdown conditions, a damping ratio of 1% is used. The load case grouping is shown in .

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3. Results and Analysis

The OpenFAST software is used to simulate the turbine under the working conditions listed in for dynamic response analysis and load prediction model evaluation.

3.1 Maximum Turbine Response

First, the time histories of tower top displacement response under combined seismic motion type A are analyzed. Under a PGA of 150 m/s^2, the time histories before emergency shutdown are similar for all three conditions. After shutdown is triggered, the turbine brakes and pitches the blades, making the time history curve approach that of the parked turbine. The tower top displacement time histories are consistent across the three conditions when aerodynamic loads are absent, indicating that turbine operating state has minimal influence on cross-wind dynamic response under seismic action.

To quantitatively analyze the relationship between seismic intensity and maximum tower top response, the root mean square values of displacement in the along-wind and cross-wind directions are calculated for each seismic intensity. The variation patterns of maximum displacement response $D_{\max}$ under different working conditions and ground motions are obtained. Under normal operation, $D_{\max}$ shows linear variation with A in the range of 0-0.15.

[Figure 5: see original paper] shows the time histories of horizontal components for a sample record (KNG2011103111451) with PGA = 1 m/s^2. [Figure 6: see original paper] illustrates the NREL monopile offshore turbine under wind and seismic actions.

3.2 Working Condition Setup

To better understand the effects of long-period offshore ground motions on the turbine, three operational states are considered: normal operation, parked turbine, and emergency shutdown. For normal operation, the generator continues producing power during earthquakes. For the parked condition, the generator is off and blades are feathered. Emergency shutdown is triggered when the hub vibration acceleration exceeds 0.1 m/s^2 under seismic load, shutting down the generator and pitching blades until feathered. The PGA variation range is 0-1.5 m/s^2 under three types of ground motions. The load cases are shown in . The numerical simulation time step is 0.005 s, with 400 s of transient response. Seismic excitation is input at 400 s, making the total simulation duration 800 s.

Under long-period offshore seismic actions, the maximum displacement initially increases with a certain slope, which gradually increases and stabilizes. However, this slope remains smaller than that of the parked condition. The displacement maximum tends to level off at 0-0.04. Near this region, the two curves intersect. The slope then gradually increases and stabilizes, but remains smaller than the parked condition. The interaction between blade rotation and turbulent wind is significant. At low seismic intensities, wind loads serve as the primary input and remain constant, while seismic load effects are minimal. At high seismic intensities, the wind load effect is small, and the growth slope under normal operation is less than under parked conditions due to blade rotation.

Under parked conditions, since blades are feathered, the tower top maximum displacement is only affected by seismic loads, resulting in higher structural damping levels. The relationship between tower top maximum displacement and seismic intensity A is linear. Under emergency shutdown conditions, the maximum displacement D_{max} is consistent with normal operation before triggering, but gradually approaches the parked condition after shutdown.

[Figure 7: see original paper] shows time histories of tower displacement under different ground motions and working conditions. [Figure 8: see original paper] illustrates the variation of maximum tower displacement with A.

At low seismic intensities, conventional ground motions produce D_{max} greater than under normal operation. However, under long-period ground motions at the same A, D_{max} under normal operation is smaller than under emergency shutdown. When the seismic intensity reaches 0.5 m/s^2, D_{max} under emergency shutdown becomes greater than under normal operation. As blade pitching begins, structural vibration intensifies and tower displacement response increases. For all seismic conditions, normal operation is most favorable when encountering long-period seismic actions because structural motion is larger under long-period excitation, increasing blade relative motion and thus aerodynamic damping effects, which suppress structural motion response.

Comparing the slope of the parked condition, the slope is 2.17 under conventional ground motions and 9.29 under long-period offshore ground motions. This slope directly reflects the turbine' s response level to seismic loads. The maximum tower top motion response under long-period ground motions is approximately 4.3 times that under conventional ground motions, indicating that long-period seismic actions produce particularly strong responses compared to other earthquake types. Therefore, considering the influence of long-period characteristics of sea area ground motions is essential in wind turbine seismic design.

To further investigate the influence of ground motion long-period characteristics on structural response, based on Hall' s research [17], the maximum displacement has the following approximate relationship with the turbine' s first natural frequency f_n and ground motion A:

$$D_{\text{max}} = k \cdot \frac{A}{(2\pi f_n)^2}$$

where k is the tower top motion effect coefficient. For conventional ground motions ($\beta_l < 0.2$), $k_1 = 0$; for medium-long period ground motions ($0.2 \leq \beta_l \leq 0.4$), $k_2 = 1$; and for long-period offshore ground motions ($\beta_l > 0.4$), $k_3 = 4.06$

at $f_n = 0.33$ Hz. The k values effectively predict turbine response under seismic excitation and evaluate the dynamic response effects of long-period sea area ground motions on tower top characteristics.

Considering the direct impact of ground motions on turbines, [Figure 9: see original paper] shows the variation of maximum tower top acceleration with A for different working conditions and ground motions. The maximum acceleration is calculated as the average of the square root of the sum of squares of maximum along-wind and cross-wind accelerations.

3.2 Tower Load Prediction Model

For high-rise horizontal-axis wind turbines under seismic loads, bending moment loads dominate structural design checks. Various prediction models have been developed for tower extreme bending moment loads. For the tower ultimate bending moment load at height h, the IEC standard provides the following estimation formula [18]:

$$M_{\mathrm{IEC}} = (M_{\mathrm{rotor}} + M_{\mathrm{nacelle}}) \cdot \frac{H_t - h}{H_t}$$

where M_{rotor} and M_{nacelle} are the masses of the rotor and nacelle, respectively, and H_t is the total tower height.

Germanischer Lloyd (GL) proposed a similar expression [19] for tower ultimate bending moments under shutdown conditions:

$$M_{\mathrm{GL}} = \frac{1}{2} M_{\mathrm{tower}} \cdot A \cdot (H_t - h)$$

where M_{tower} is the tower mass.

Building upon these specifications, Prowell et al. [20] proposed the following expression using the square root of sum of squares (SRSS) method to estimate tower bending moments:

$$M_{\mathrm{Prowell}} = \sqrt{M_{\mathrm{wind}}^2 + M_{\mathrm{seismic}}^2}$$

Considering that previous studies did not address the seismic response of wind turbine systems, an improved expression is proposed based on the response coefficient k from the previous section:

$$M_{\mathrm{proposed}} = k \cdot \sqrt{M_{\mathrm{wind}}^2 + M_{\mathrm{seismic}}^2}$$

where k varies for different sea area ground motion groups. For normal operation conditions, the proposed extreme bending moment load under seismic action is compared with predictions from different models at various A intensities. For parked conditions, the calculated extreme bending moment values under seismic excitation are smaller than operating conditions. Emergency shutdown extreme loads increase compared to parked conditions. The variation of maximum bending moment with A is nearly linear, and the increase magnitude grows with tower height.

[Figure 10: see original paper] shows the maximum tower bending moments and predictions from different models under various earthquakes. The Prowell model provides accurate predictions for conventional ground motions but cannot predict tower ultimate bending moments under medium-long period and long-period offshore ground motions. The proposed model shows significantly smaller differences between predicted and simulated values, particularly for long-period seismic responses.

The error analysis between predicted values x and simulated values x^* is defined as:

$$\varepsilon_r = \frac{|x - x^*|}{x^*} \times 100\%$$

[Figure 11: see original paper] shows the error values of maximum tower bending moments under different prediction models. The proposed model has the smallest prediction errors for all A values, with emergency shutdown errors being minimal. Normal operation errors are larger than emergency shutdown because aerodynamic damping dissipates seismic energy, resulting in smaller bending moment maxima.

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4. Conclusions

This study performs numerical calculations on a 5MW offshore monopile wind turbine considering long-period characteristics of sea area ground motions. Through analysis of combined wind-seismic actions and turbine operating states, the influence of long-period characteristics on turbine dynamic response is explored, yielding the following conclusions:

1. Under parked turbine conditions, both tower top displacement and acceleration responses increase linearly with seismic intensity A. The average maximum tower top motion response caused by long-period ground motions is approximately 4.3 times that under conventional ground motions.
2. Under normal operation, aerodynamic effects increase structural response at low seismic intensities due to blade rotation and turbulent wind interaction, resulting in higher structural damping levels. At high seismic intensities, aerodynamic damping reduces turbine response values.

3. When emergency shutdown occurs during long-period sea area earthquakes, it cannot effectively reduce turbine response values. The best strategy is to maintain normal operation.
4. The improved tower ultimate bending moment prediction model considering sea area ground motion long-period effects provides accurate load calculations for wind turbine seismic design, particularly for long-period offshore seismic actions.

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