The Impact of Peak Spectral Period in the Design of Offshore Wind Turbines for the Extreme Sea State

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ABSTRACT

Most offshore wind turbines (OWTs) are designed according to the international standard IEC 61400-3 which requires consideration of several design load cases under extreme sea state conditions during which the wind turbine is in survival mode (i.e. the rotor is parked and blades are feathered). Each of these load cases depends on combinations of two random variables, the mean wind speed and the significant wave height, both with a mean return period of 50 years. The response of an offshore wind turbine under wave loading is known to be sensitive to both the significant wave height and a frequency measure of the sea state such as the peak spectral period. The IEC Standard states that design calculations for the extreme sea state should be based on values of peak spectral period which result in the highest loads acting on the structure, but does not provide additional guidance. The Standard does provide a deterministic range for the period of the extreme wave conditioned on the significant wave height and this can be converted to a range of peak spectral period using published empirical relationships. This paper considers an offshore location off the coast of Georgia, where NOAA buoy 41008 is located, and shows that a deterministic range of peak spectral period converted from the range provided in the IEC Standard may not accurately represent measured data. Moreover, the paper shows that the response of a hypothetical offshore wind turbine, installed at this location and supported by a monopile foundation, is sensitive to variation in the peak spectral period, emphasizing the importance of modeling the turbine for an appropriate and possibly site-specific range of peak spectral periods. A probabilistic approach is proposed to find an appropriate and site-specific range of the peak spectral period for the design of offshore wind turbines under the extreme sea state.

KEYWORDS: offshore wind turbine design, monopile, extreme sea state, peak spectral period, significant wave height, joint probability distribution, NATAF model

INTRODUCTION

The most widely used international standard for the design of offshore wind turbines (OWTs) is IEC 61400-3 (IEC 2009). This standard prescribes a suite of design load cases which require an estimation of loads during a variety of operational and environmental conditions. One subset of these load cases considers extreme loads under 50-year storm conditions during which the wind turbine is not operational. The extreme loads depend on the probabilistic estimation of 50-year magnitudes of two environmental hazard intensities: the mean wind speed and the significant wave
height. Typically, the 50-year values of these intensities are estimated independently using extreme value analysis based on a hindcast spanning multiple decades at the location where the wind turbine will be installed. These values are used as inputs to simulate stochastic time series corresponding to extreme turbulent winds and the extreme sea state. Once these time series have been simulated, a structural model is analyzed, 6 times for one hour each time, under both times series simultaneously and the maximum structural response from each analysis is recorded. The wave time series for the extreme sea state is typically based on the JONSWAP spectral model, which requires an additional input parameter, the peak spectral period. The IEC Standard states that the extreme sea state should “take account of the range of peak spectral period appropriate to the [50-year significant wave height]. Design calculations should be based on values of the peak spectral period which result in the highest loads acting on an offshore wind turbine” (IEC, 2009). The IEC Standard does not provide any specific guidance on how to calculate a range of peak spectral period appropriate to the significant wave height. This situation is problematic because there is a small but non-zero probability that the peak spectral period associated with the 50-year significant wave height will coincide with the structural period of the offshore wind turbine. Such coincidence could result in prediction of very large, resonance-driven loads.

In addition to consideration of simultaneous and stochastic time series of wind and wave, the IEC Standard also requires the assessment of loads under two deterministic environmental conditions: first, the simultaneous occurrence of the extreme wave (defined as 1.87 times the 50-year significant wave height) and the reduced steady wind (defined as 1.10 times the 50-year mean wind speed) and, second, the simultaneous occurrence of the reduced wave height (defined as 1.30 times the 50-year significant wave height) and the extreme steady wind (defined as 1.40 times the 50-year mean wind speed). The IEC Standard provides a range of wave periods which must all be considered for the extreme wave described above. This range can be converted to a range of peak spectral periods using published empirical relationships between the period of the extreme wave within an irregular sea state and the peak spectral period of the sea state (API 2002, API 2007).

In this paper, we assume that, if an empirical relationship between the peak spectral period and the extreme wave period is known, the range provided by the IEC Standard for the period of the extreme wave can be directly applied to determine the appropriate range of the peak spectral period. Based on this assumption, we evaluate the IEC Standard by considering a 5MW offshore wind turbine supported by a monopile foundation and installed in a location where a National Oceanic and Atmospheric Administration (NOAA) buoy is located, 35 km off the coast of Georgia in 20 m deep water. For this hypothetical example, we assess (1) whether the resulting range of peak spectral period provides a reasonable estimate of possible peak spectral periods for this location and (2) whether the structural response is sensitive to peak spectral period both within and outside of this range.

The paper is organized as follows. First, background on the relationship between significant wave height and peak spectral period is provided. Next, the location of NOAA buoy off the coast of Georgia is described and measurements of the extreme
sea state are provided and compared with a range calculated deterministically. Following this, details and results of a structural model of a 5MW OWT are provided with emphasis on the sensitivity of the structural response to variation in the peak spectral period. Finally, a probabilistic approach to calculate the appropriate range of peak spectral period conditioned on the significant wave height is proposed.

BACKGROUND

The IEC Standard requires consideration of a deterministic range of periods $T$ of the maximum wave in a sea state. The range is given by,

$$11.1\sqrt{H_s/g} \leq T \leq 14.3\sqrt{H_s/g}$$  \hspace{1cm} (1)

where $H_s$ is the significant wave height, $g$ is gravity, and $T$ is the period of the maximum wave. The design wave is the wave with period $T$ that leads to maximum loads on the structure. Although the range of $T$ provided by the IEC Standard is not referenced, the authors believe that the equation originated in Baltrop (1991). The recommended practice, API-RP2A (2002), which is used to design oil and gas offshore structures in the U.S., provides a range of the expected ratio between the peak spectral period of a sea state $T_p$ and the period of the maximum wave $T$,

$$1.05 \leq T_p/T \leq 1.2$$  \hspace{1cm} (2)

In addition, the API standard API 2INT-MET (2007), which provides guidance on hurricane conditions in the Gulf of Mexico, states that the ratio of the peak spectral period to the period of the maximum wave can be assumed to be between 1.08 and 1.12. In this paper, the range of maximum wave period provided in Equation (1) is converted to a range of peak spectral period by using Equation (2) and multiplying the lower bound of the range in Equation (1) by 1.05 and the upper bound of the range by 1.2, resulting in the range for the peak spectral period given as,

$$11.7\sqrt{H_s/g} \leq T_p \leq 17.2\sqrt{H_s/g}$$  \hspace{1cm} (3)

This range is referred in the remainder of this paper as the deterministic range of the peak spectral period.

SITE INFORMATION AND MEASUREMENTS

The validity of Equation (3) is assessed for an offshore site off the coast of Georgia where NOAA buoy 41008 is located. This particular site was selected for this study because it had a long duration of data (24 years) and because it was located in a water depth that was sufficiently shallow (20 m) to be viable for the installation of an offshore wind turbine supported by a monopile. The location of this site is mapped in Figure 1 and specifications of the site are provided in Table 1. The buoy measurements used in this paper include the significant wave height, defined as usual to be the average of the top one third of recorded wave heights in a given time interval, and the peak spectral period, the period corresponding to the maximum
density of a spectral representation of the sea state. Both quantities are determined based on a 20 minute time interval and are reported hourly.

![Figure 1](image1.png)

**Figure 1.** The location of NOAA Buoy 41008, 35 km off the coast of Georgia.

Since this paper is focused on the extreme sea state described in the IEC Standard, extreme values of the significant wave height and corresponding peak spectral periods are extracted from the hourly measured data using the method of 9-Largest Order Statistics (9-LOS). An example of a similar approach is presented by Guedes and Soares (2004). A scatter plot of the extreme values of the significant wave height and the corresponding peak spectral periods are provided in Figure 2. Superimposed on this plot are two curves, indicating the upper and lower bounds of the deterministic range of peak spectral period presented in Equation (3).

![Figure 2](image2.png)

**Figure 2.** Extreme value measurements of significant wave height $H_s$ and corresponding peak spectral period $T_p$ extracted from NOAA buoy 41008. The upper and lower bounds of the deterministic peak spectral period range presented in Equation (3) are superimposed.

Comparing the measured extreme values with the upper and lower bounds of Equation (3), it is obvious that many measured values fall outside the upper and lower bounds. In total, 16% of the measurements are outside the range with 6% of the measurements above the upper bound and 10% of the measurements below the lower bound. The variability of the measurements above the upper bound is much larger.
than the variability of measurements below the lower bound. For this particular site, it is clear that, over a duration of 24 years, there are many instances where measurements are outside the deterministic range in Equation (3). Since this paper is focused on the design of offshore wind turbines for the extreme sea state, a logical question is whether this observation has a significant influence on the structural demands on an offshore wind turbine subjected to the extreme sea state, or, in other words, how sensitive is the response of an offshore wind turbine to variation of the peak spectral period. The next section addresses this question for a specific 5MW wind turbine installed supported by a monopile foundation.

SENSITIVITY OF AN OWT TO PEAK SPECTRAL PERIOD

In this section, a structural analysis is performed to find the sensitivity of the structural response of a specific wind turbine to variation in the peak spectral period and significant wave height of the sea state. The analysis is based on a structural model of the 5MW National Renewable Energy Laboratory (NREL) baseline offshore wind turbine supported by a monopile foundation (Jonkman, 2009). Key specifications of this wind turbine are provided in Table 2. This model has a natural period of 3.5 s and is fixed at the mudline. In this analysis, the turbine is modeled in a parked condition (i.e. the rotor is stationary and blades are feathered) as is prescribed by the IEC Standard for extreme storm conditions. Since this analysis is focused only on the effect of the extreme sea state on the structural response, the wind speed is modeled as steady with a constant value of 20 m/s for all analyses. Waves are modeled as irregular and linear, following a JONSWAP spectrum defined by the significant wave height $H_s$ and the peak spectral period $T_p$.

<table>
<thead>
<tr>
<th>Table 2. Properties of 5MW NREL offshore wind turbine.</th>
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<tbody>
<tr>
<td><strong>Rotor Orientation, Configuration</strong></td>
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<td><strong>Control</strong></td>
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<tr>
<td><strong>Rotor, Hub Diameter</strong></td>
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<td><strong>Hub Height</strong></td>
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<tr>
<td><strong>Monopile Diameter, Thickness</strong></td>
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<tr>
<td><strong>Cut in, Rated, Cut out Wind Speed</strong></td>
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<tr>
<td><strong>Rotor, Nacelle, Tower Mass</strong></td>
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</tbody>
</table>

The analyses are conducted within the program FAST (FAST, 2013), an open source program developed by NREL for the analysis of onshore and offshore wind turbines. In total, the structural model is analyzed for 80 combinations of $H_s$ (5 values) and $T_p$ (16 values). For each combination, six one-hour analyses are simulated and the maximum moment at the mudline for each of the six simulations is recorded. The results of these analyses are presented in Figure 3, which shows the average of the maximum mudline moment from each of the six simulations.
Figure 3. Average maximum mudline moment $M_{mudline}$ for the NREL 5 MW turbine under different combinations of $H_s$ and $T_p$ and a steady wind of 20 m/s. Black line segments correspond to values of $T_p$ within the range of peak spectral period presented in Equation (3).

Figure 3 shows that the absolute value of the percentage change of $M_{mudline}$ between adjacent results, is, on average, less than 10% when $T_p > 6$ s and is decreasing with higher peak spectral periods. This means that, for peak spectral periods above the range described in Equation (3), the structural response is not strongly sensitive to the peak spectral period. However, the percentage change of $M_{mudline}$ increases quickly for $T_p < 6$ s and has an average value of ~40% when $T_p = 3.5$ s, the natural period of structural system. As shown in Figure 2, measurements of $T_p$ for this particular site frequently fall outside the deterministic range and there are a significant number of observations of values of $T_p$ lower than the deterministic range. As shown in Figure 3, the turbine response is highly sensitive to values of $T_p$ below the deterministic range and thus, if the deterministic range presented in Equation (3) were used in the design for this turbine and location, it is possible that a response-controlling and reasonably likely combination of $H_s$ and $T_p$ would not be considered in the design. A more rational approach is to use site-specific data to probabilistically estimate an appropriate range for the peak spectral period conditioned on the significant wave height of the extreme sea state.

PROBABILISTIC APPROACH

In this section, a probabilistic approach is proposed wherein the range of peak spectral period conditioned on the significant wave height of the extreme sea state is estimated from site-specific data based on a target confidence interval. One method to obtain the range corresponding to the target confidence interval is to use the site-specific data to directly calculate conditional distributions of $T_p$ given $H_s$. For the extreme sea state, which considers only extreme value data, this method is not likely to have sufficient data to construct the conditional probability distribution directly. An alternative approach is to obtain the conditional probability distribution, based on an estimation of the joint probability distribution of extreme value data. The joint probability distribution can be estimated using the so-called “Nataf model” (Liu & Kiureghian, 1986, Bucher, 2009) which estimates a joint probability distribution of $T_p$.
and $H_s$ that matches the marginal distributions and covariance of the paired data. The Nataf model is based on a transformation of the original correlated variables $X_i$ to Gaussian variables $V_i$ whose joint density is assumed to be multi-dimensional Gaussian. To transform from original space to Gaussian space, the random variables are mapped individually to standard normal space per the transformation outlined below.

First, to transform from original space (i.e. $T_p$ - $H_s$ space), represented generally in the equations below as $X_i - X_j$ space, to Gaussian space, all random variables are individually mapped to standard normal space, represented generally in the equation below as $V_i - V_j$ space, by,

$$V_i = \Phi^{-1}[F_{X_i}(x_i)]$$  \hspace{1cm} (3)

where $\Phi$ is the cumulative distribution function of the standard normal distribution such that,

$$E[V_i] = 0, \ E[V_i^2] = 1, \ E[V_iV_j] = \rho'_{ij}$$  \hspace{1cm} (4)

where $E[\cdot]$ is the expectation operator and $\rho'_{ij}$ is the correlation coefficient between random variables in standard normal space. The probability density function of the transformed variables is,

$$f_V(v) = \frac{1}{(2\pi)^{n/2} \sqrt{\det(R_{VV})}} \exp\left(-\frac{1}{2}v^TR_{VV}^{-1}v\right)$$  \hspace{1cm} (5)

where $R_{VV}$ is the matrix of correlation coefficients of random variables in Gaussian space. The probability density function can be transformed to original space as,

$$f_X(x) = f_V(v(x)) \prod_{i=1}^n f_{X_i}(x_i)$$  \hspace{1cm} (6)

where $\varphi$ is the probability density function of the Gaussian distribution. The correlation coefficient in normal space can be found through an iterative solution of the following equation,

$$\sigma_{x_i}\sigma_{x_j}\rho_{ij} = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} (x_i - \bar{X}_i)(x_j - \bar{X}_j) f_{X_i,X_j}(x_i,x_j,\rho'_{ij}) \, dx_i \, dx_j$$  \hspace{1cm} (7)

where, $\sigma_{x_i}$ is the standard deviation of random variable $X_i$.

Having an estimate of the joint probability distribution of $H_s$ and $T_p$, the conditional distribution of $T_p$ given $H_s$ can be calculated as,

$$f_{T_p|H_s}(t_p, h_s) = \frac{f_{T_p,H_s}(t_p, h_s)}{f_{H_s}(h_s)}$$  \hspace{1cm} (8)

For NOAA buoy 41008, the joint probability distribution of the extreme values of $H_s$ and $T_p$ is presented in Figure 4, assuming a Generalized Extreme Value probability distribution for the marginal distributions of $H_s$ and $T_p$. 
Using Eq. 8, the cumulative distribution function (CDF) and the probability density function (PDF) of $T_p$ given $H_s$ can be calculated. The results of which are shown in Figure 5 for discrete values of $H_s$. 

**Figure 4.** Joint probability distribution function of $H_s$ and $T_p$ using the NATAF model and measurements for extreme values obtained at NOAA buoy 41008.

**Figure 5.** Conditional distribution of $T_p$ given $H_s$ presented as a) PDFs for different $H_s$ and b) CDFs for different $H_s$. 

$H_s (m)$

<table>
<thead>
<tr>
<th>$H_s$</th>
<th>$T_p (s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 m</td>
<td>4  6  8  10 12 14 16 18</td>
</tr>
<tr>
<td>3 m</td>
<td>0  0.2 0.4 0.6 0.8 1</td>
</tr>
<tr>
<td>4 m</td>
<td>0  0.2 0.4 0.6 0.8 1</td>
</tr>
<tr>
<td>5 m</td>
<td>0  0.2 0.4 0.6 0.8 1</td>
</tr>
<tr>
<td>6 m</td>
<td>0  0.2 0.4 0.6 0.8 1</td>
</tr>
</tbody>
</table>
Figure 6. $H_s$ and $T_p$ extreme values obtained at NOAA buoy 41008. Ranges of $T_p$ based on Eq. (3) and based on a 90% confidence interval are superimposed.

Using the conditional distribution of $T_p$ given $H_s$, ranges of $T_p$ with an appropriate confidence interval can be calculated. Figure 6 shows a range of $T_p$ corresponding to a 90% confidence interval. For most values of $H_s$, this range includes more of the data than the range corresponding to Eq. (3), thus, for this site and for most values of $H_s$, the range corresponding to Eq. (3) has a confidence interval less than 90%.

CONCLUSIONS

In this paper, a deterministic approach to calculate the appropriate range of peak spectral period given the significant wave height for the extreme sea state is assessed. Comparison of this range with 24 years of measurements from NOAA buoy 41008 shows that there are many instances when the measurements are outside of the deterministically calculated range and that the variability of the measurements above the range is greater than the variability below the range. A structural analysis shows that for the NREL 5MW OWT, located at the site of NOAA buoy 41008 and supported by a monopile, the mudline moment is much more sensitive to variability below the deterministic range of the peak spectral period than to variability above the deterministic range. A probabilistic method to calculate a confidence interval of peak spectral period conditioned on the significant wave height for the extreme sea state is proposed. The procedure is illustrated for NOAA buoy 41008 and starts with extracting extreme values of the significant wave height and their corresponding peak spectral periods from measurements, fitting a joint probability distribution to the data using the Nataf model, and then using this joint distribution to calculate a conditional distribution of $T_p$ given $H_s$. The results show that, for a 90% confidence interval at NOAA buoy 41008, the range of the peak spectral period is on average larger than that calculated using the deterministic approach.

ACKNOWLEDGMENTS

This work was supported in part by the US National Science Foundation through grants CMMI-1234560 and CMMI-1234656 and by the Massachusetts Clean Energy Center.
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