Limiting Wave Conditions for the Safe Maintenance of Floating Wind Turbines

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Abstract. This paper investigates the limiting wave conditions at which a wind turbine technician can complete maintenance activities safely and effectively on a 15MW floating offshore wind turbine. Through linear, frequency-domain statistical analysis of floating turbine motion and applying acceptable motion limits for technician working, significant wave height and peak wave period limits are investigated. It was found that over the range of wave conditions considered, the turbine nacelle motion did not exceed the motion limits for technician working considered in this analysis. Further analysis found that the turbine nacelle motion increased with increasing significant wave height and was also significantly influenced by peak wave period. The impact of differing wave characteristics is also investigated through the use of different wave energy spectra and also found to have an impact on turbine nacelle motion.

1. Introduction

From the small demonstration projects, currently making up less than 100MW, it is estimated that the installed capacity of floating wind worldwide has the potential to reach almost 11GW by 2030 and up to 70GW by 2040 [1]. However, there are still areas of uncertainty around offshore floating wind, and understanding and reducing these uncertainties is one potential route to reduce the levelised cost of energy (LCOE) at a commercial scale. For all offshore wind projects, the operational phase is the longest phase of the project lifecycle, and the costs associated with this phase are significant. It is estimated that over 25% of the cost for an offshore wind farm can be attributed to operations and maintenance [2]. Therefore, the direct cost savings, as well as the indirect cost savings on project financing associated with project risk in this phase, can have a significant impact on LCOE for floating wind projects.

One of the uncertainties in the operational phase of a floating offshore wind farm is around the impact that the change to floating foundations will have on the range of wave conditions in which maintenance activities can be safely undertaken. Floating wind turbines, due to their dynamics, will suffer from higher accelerations (especially at nacelle level), and therefore wave conditions that may be deemed acceptable for carrying out maintenance on a fixed-foundation turbine may not be acceptable for a floating wind turbine. The ability to carry out maintenance on an offshore wind turbine is dependent on the ability of wind turbine technicians to access the turbine, and to be able to safely and effectively work on it. Due to the wave-induced dynamics in a floating turbine, the wave conditions are likely to have an increased impact on both of these, compared to fixed-foundation turbines, and therefore requires consideration in maintenance planning for floating wind turbines.

Up to now, limited work has been done on assessing the accessibility to complete maintenance on floating wind turbines due to their motion. Martini et al applied a frequency-domain analysis, considering the 5MW NREL OC4 semi-submersible platform and a crew transfer vessel (CTV) with fender to assess CTV accessibility for a site located in the North Sea, near Aberdeen [3]. Limits were placed on the contact force between the fender and platform, and also the relative rotation between the two. It was found that, for the case-study site, there was an average accessibility of 23.7%. This work was then extended by Guanche et al to assess the accessibility of a service vessel (SOV) with a motion-compensated walkway [4]. The maximum allowable relative motion between the walkway and the turbine platform, due to the walkway's motion compensation system, was applied as the limiting condition, and it was found that the SOV can operate in much greater wave heights than the CTV, up to 5m wave height. The motion conditions that wind turbine technicians can work safely and effectively under were investigated in detail by Scheu et al [5]. It was found that the guidance on technician working limits for floating wind turbines was very limited, but available guidance from other industries, for example guidance published by Nordforsk, could be interpreted and used. Through modelling of turbine motion for four different platform designs, it was found that applying these limits for technician working, the turbine accessibility for maintenance was reduced by up to 5% compared to using only wave height as a limiting condition for accessibility.

The objective of this paper is to estimate the range of wave conditions (considering both significant wave height and peak wave period) during which wind turbine technicians can safely and effectively carry out maintenance tasks which require working within the wind turbine nacelle on a 15MW floating offshore wind turbine. The approach taken in this paper is a statistical frequency-domain analysis of the motion response of a 15MW semi-submersible wind turbine to a range of different wave conditions. These motions are then compared to motion limits for technician working to determine whether these limits are exceeded and, if so, under which wave conditions. This will determine the range of wave conditions during which allowable technician working motion is achieved. This approach is summarised in Figure 1.
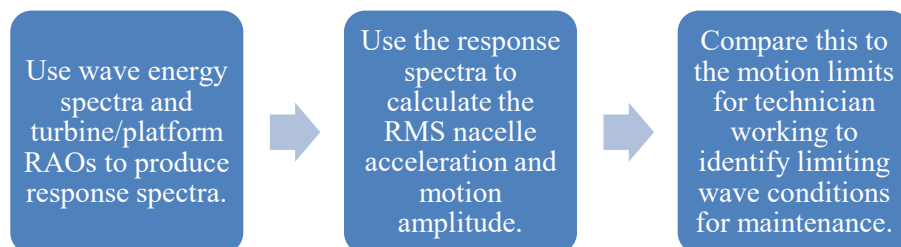

Figure 1. Overview of the steps taken in this paper.

2. Method

This section outlines the approach taken in this work. It describes the turbine and platform assembly and the response amplitude operators used for this analysis, how the nacelle acceleration and motion amplitude was calculated, and how the limiting wave conditions for safe technician working were found.

2.1. Floating Turbine Response Amplitude Operators

When analysing the motion of a floating structure in the frequency-domain, a frequency-dependent transfer function can be used to characterise the structure's motion response to varying wave frequencies, assuming it shows a linear response. This transfer function is called the response amplitude operator (RAO) and, for a floating structure, can be found using Equation 1. Where $\hat{\bar{\xi}}(\omega)$ is a vector of the complex amplitude of structure motion per unit wave amplitude in each of the six degrees of freedom, and $\hat{F}(\omega)$ is the complex amplitude of the wave excitation force acting on the structure per unit wave amplitude. The remaining parameters characterise the structural and hydrodynamic properties of

the structure, where **M** is a matrix of the structure's mass and inertia around the centre of motion in each degree of freedom, **A**(ω) is a matrix of hydrodynamic added mass, **B**(ω) is a matrix of radiation damping, and **C** is a matrix of restoring stiffness which, for a floating wind turbine, includes the hydrostatic stiffness and mooring stiffness [6].

$$\boldsymbol{RAO}(\omega) = \hat{\boldsymbol{\xi}}(\omega) = \frac{\widehat{\boldsymbol{F}}(\omega)}{-\omega^2\big(\boldsymbol{M} + \boldsymbol{A}(\omega)\big) + i\omega \boldsymbol{B}(\omega) + \boldsymbol{C}} \tag{1}$$

The turbine and platform used for this analysis was the IEA 15 MW offshore reference turbine supported by the UMaine VolturnUS-S semi-submersible reference platform published by NREL [7], [8]. The hub height of the turbine is 150m and the semi-submersible platform consists of three outer columns and an inner column, on which the turbine is mounted. The combined mass of the turbine and platform is 20,093t, and the platform is moored through three catenary mooring lines. This assembly is shown in Figure *2* and detailed descriptions can be found in [7], [8].

Figure 2. Image of the IEA 15MW reference turbine supported on the UMaine VolturnUS-S reference platform [8].

Several response amplitude operators for the wave-induced motion of this assembly are provided in [8], this includes the RAO for the turbine nacelle fore-aft motion, the platform heave motion, and the platform pitch motion at zero degrees wave heading. The values of these RAOs were extracted from these figures over the frequency range given using the Engauge Digitizer software [9]. The extracted RAOs are shown in Figures 3-5. For this analysis it is assumed that the platform heave response is equal to the nacelle heave response and therefore represents the vertical response at the nacelle, and the platform pitch response is equal to the nacelle pitch response. This approach assumes that the tower is a rigid structure. As the tower is generally considered to be flexible, higher accelerations are expected when considering this as a rigid body, therefore making this present approach conservative. Within this paper, the nacelle fore-aft motion is also referred to as the lateral motion.
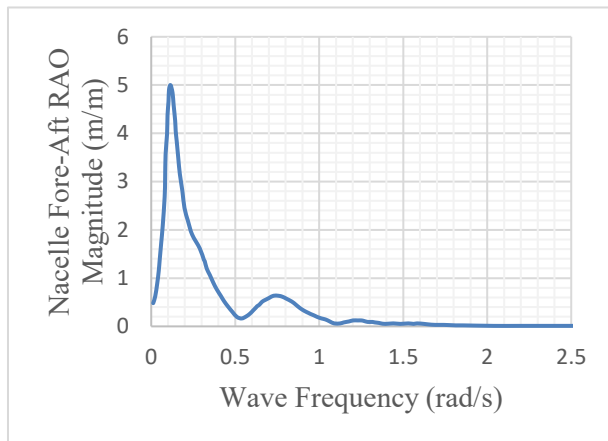
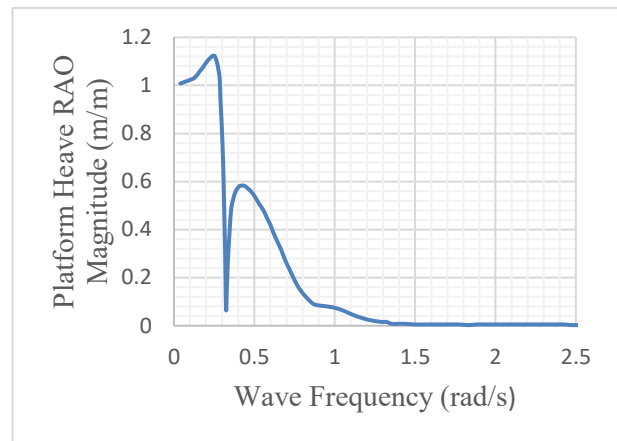Figure 3. Nacelle fore-aft response amplitude operator extracted from [8].

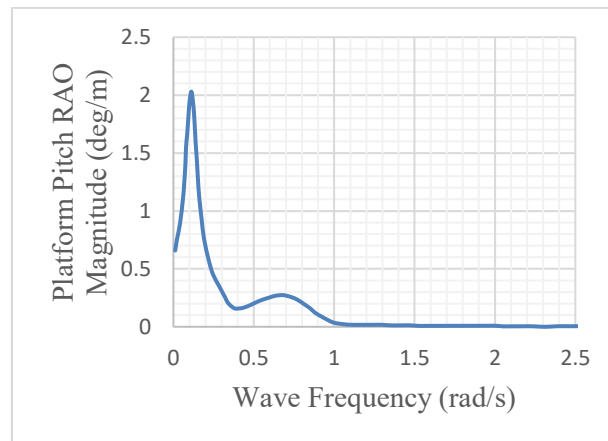Figure 4. Platform heave response amplitude operator extracted from [8].

Figure 5. Platform pitch response amplitude operator extracted from [8].

2.2. Determining the Nacelle Motions

Using wave energy spectra and response amplitude operators, response spectra can be found which characterise the platform motion under a range of wave conditions. For this analysis, two different theoretical wave spectra were used, JONSWAP spectra, representative of North Sea conditions [10], and Bretschneider spectra representative of conditions seen in the Atlantic Ocean [11]. These spectra can be characterised through two parameters - the significant wave height (H_s), and the peak wave period (T_p) [12]. The response spectrum, S_R, can be calculated using Equation 2, where $S_w(\omega)$ is the wave energy spectrum [13].

$$S_R(\omega) = |RAO(\omega)|^2 * S_w(\omega) \tag{2}$$

The moments of the response spectra can be calculated using Equation 3, where i = 0 defines the amplitude of motion, i = 2 defines the velocity, and i = 4 defines the acceleration [14].

$$m_{R,i} = \int_0^\infty |\omega|^i . S_R(\omega) . d\omega \tag{3}$$

The moment of the response spectrum is equal to the variance, $\sigma_{R,i}^2$, and the square root of this is the root mean square (RMS) value. Therefore, the RMS value of the nacelle pitch amplitude was found using Equation 4 and the RMS values of the nacelle lateral acceleration and vertical acceleration were found using Equation 5.

$$Amplitude_{RMS} = \sqrt{m_{R,0}} = \sqrt{\int_0^\infty S_R(\omega) . d\omega} \tag{4}$$

$$Acceleration_{RMS} = \sqrt{m_{R,4}} = \sqrt{\int_0^\infty |\omega|^4 . S_R(\omega) . d\omega} \tag{5}$$

Using this approach, the RMS values of nacelle lateral acceleration, vertical acceleration and pitch amplitude were found over a range significant wave height, H_s, values from $0.1m - 3m$ and a range of peak wave period, T_p, values from 4.75s to 15.75s using JONSWAP spectra and 6.25s to 15.75s using Bretschneider spectra. This range was chosen to capture a likely range of significant wave height values in which turbine maintenance tasks would be considered due to vessel accessibility, and to capture the majority of peak wave period conditions expected at a floating wind site.

2.3. Wave Limits for Technician Working
To determine the limiting wave conditions for safe and effective technician working, limiting motion values were then applied when analysing the turbine motions over the range of wave conditions. Using the RMS values of lateral and vertical acceleration, and RMS roll amplitude at the turbine nacelle based on the Nordforsk limits given in Scheu et al. [5], the wave conditions at which these values were exceeded were found. These limiting motion values are summarised in Table 1. The limit for RMS roll amplitude is also considered to be applicable to the RMS amplitude of the motion in the pitch degree of freedom. The wave conditions (H_s and T_p) at which these values are exceeded are then taken as the limiting wave conditions for technician working.

Table 1. Summary of the Nordforsk motion limits discussed in Scheu et al [5] for acceptable technician working.

Limiting Criteria	RMS Lateral Acceleration	RMS Vertical Acceleration	RMS Roll Amplitude
Limiting Value	0.04g (0.39m/s^2)	0.05g (0.49m/s^2)	2.5°

3. Results
The results of the analysis outlined in Section 2 are presented within this section. The calculated RMS values of turbine nacelle motion are presented and compared to the respective motion limits given in Table *1* to determine if and when these are exceeded. This is followed by a comparison between the nacelle motions under different wave characteristics by comparing the results using JONSWAP wave energy spectra and Bretschneider wave energy spectra.

3.1. Limiting Wave Conditions for Technician Working

This section is focussed on the limiting wave conditions (significant wave height and peak wave period) under which maintenance activities can be completed by wind turbine technicians. The calculated RMS values of the turbine nacelle motion with varying peak wave period and significant wave height using JONSWAP wave energy spectra are shown in Figures 6-8. Figure 6 shows how the RMS value of nacelle lateral acceleration varies with peak wave period at three different significant wave height values of 1m, 2m and 3m. It can be seen that the acceleration increases with increasing significant wave height and that there is also a clear influence of peak wave period on the acceleration value. As the wave period increases, the RMS lateral acceleration increases until a peak of around 8s and then decreases. This shape is greatly influenced by the secondary peak seen in the nacelle fore-aft RAO from around 0.5rad/s – 1rad/s.

When comparing the acceleration values in Figure 6 to the limiting value of $0.39m/s^2$ given in Table *1*, it can be seen that this limiting value for technician working is not exceeded over the range of wave conditions analysed. The maximum value seen is around $0.22m/s^2$.
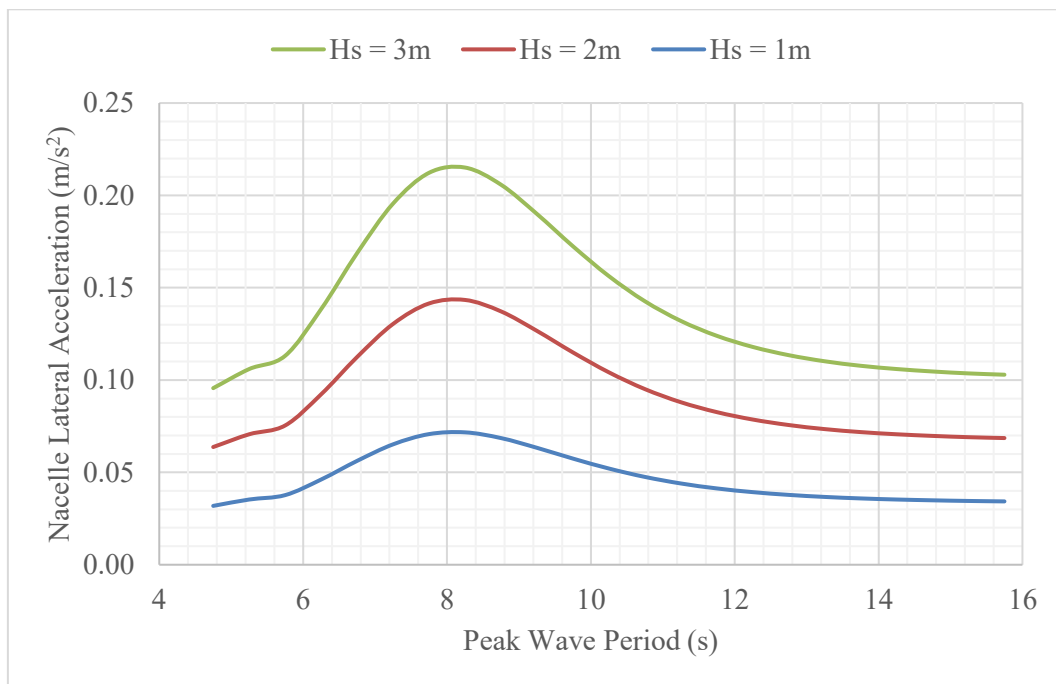

Figure 6. Nacelle RMS lateral acceleration with varying peak wave period at significant wave height values of 1m, 2m and 3m.

Figure 7 shows the nacelle RMS vertical acceleration values with varying peak wave period. Similar to the nacelle lateral acceleration, this shows increasing acceleration with increasing significant wave height and that vertical acceleration also varies significantly with peak wave period. When comparing these values to the motion limit of $0.49m/s^2$, it is seen that this value is not exceeded for the range of wave conditions considered.

Higher RMS acceleration values, and therefore exceedance of these acceleration limits, would be expected at higher significant wave height values. For example, at peak wave period values of 8.25s the lateral acceleration limit would be exceeded at significant wave heights above 5.5m. However, it is not expected that maintenance tasks would be attempted in these conditions.
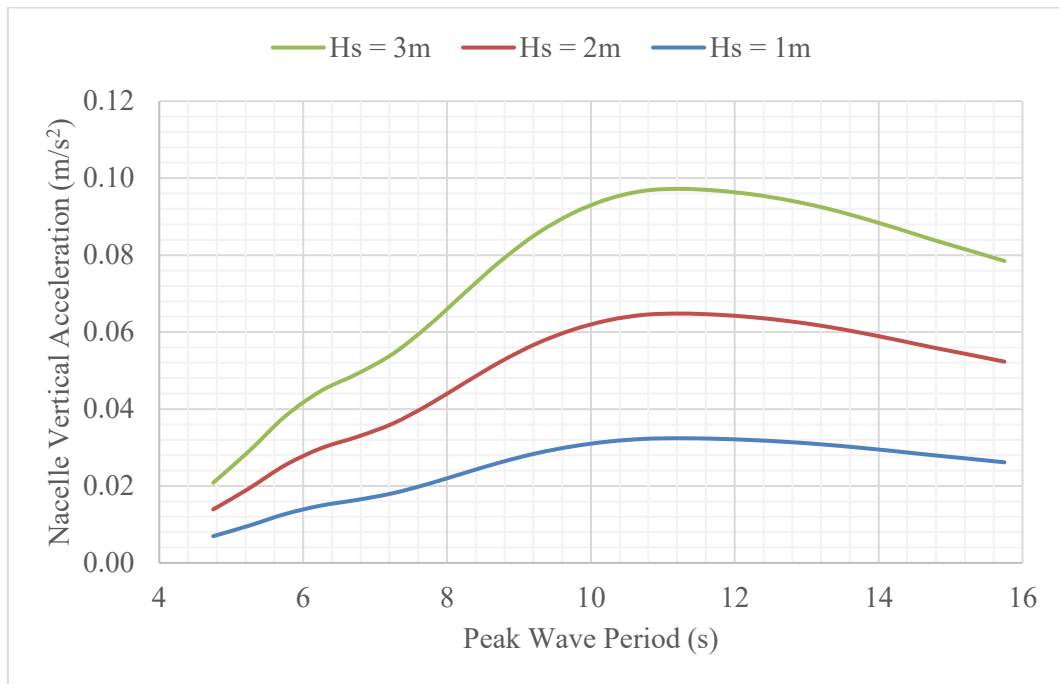
Figure 7. Nacelle RMS vertical acceleration with varying peak wave period at significant wave height values of 1m, 2m and 3m.

Figure 8 shows the nacelle pitch amplitude with varying wave conditions and again it can be seen that these values increase with increasing significant wave height and vary with peak wave period. It can also be seen that these values in Figure 8 are significantly lower than the motion limit of 2.5° and therefore this limit is also not exceeded.
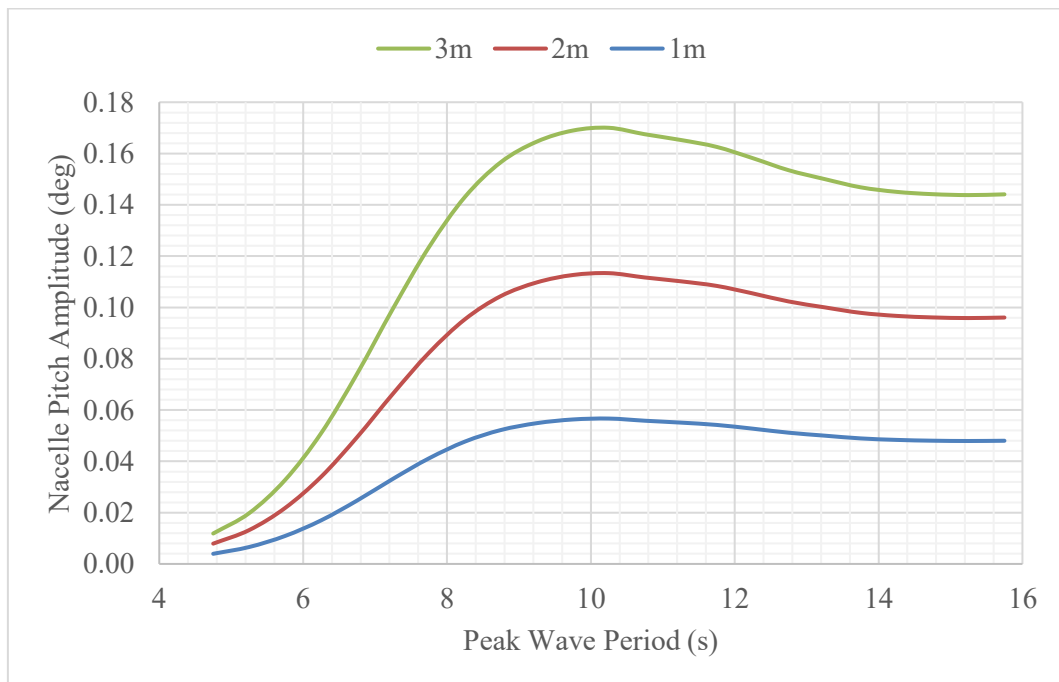

Figure 8. Nacelle RMS pitch amplitude with varying peak wave period at significant wave height values of 1m, 2m and 3m.

Higher RMS pitch amplitude values, and therefore exceedance of this limit, would be expected at significantly higher wave period values than those considered in this analysis. The maximum peak wave period considered here is equivalent to a wave frequency of around 0.4rad/s, and it can be seen in Figure 5 that the peak of the pitch motion RAO is at a significantly lower wave frequency, and therefore higher wave period, than this value. However, these higher wave period values are not considered to be within the range of typical conditions expected at a floating wind site.

3.1.1. Nacelle Motion with Differing Wave Characteristics. The nacelle lateral acceleration was then calculated at 0 degrees wave heading and 2m significant wave height using Bretschneider wave energy spectra, representative of conditions seen in the Atlantic Ocean. The results were compared to those found using JONSWAP spectra, representing North Sea conditions, and a comparison is shown in Figure 9. It was found that there are similarities in the trend when comparing both over the range of peak wave period values considered, with the RMS acceleration increasing up to a peak before decreasing. However, there are also differences. The RMS acceleration values found using JONSWAP spectra are larger than those calculated using Bretschneider spectra up until a peak wave period of around 9.6s. After this point the RMS acceleration values found using the Bretschneider spectra are larger. This difference is due to how the energy is distributed over the wave frequencies in the different spectra, with the wave energy being more concentrated around the peak wave period in the JONSWAP spectrum. Therefore, greater motion is seen around the wave frequencies which coincide with higher values in the platform RAOs.
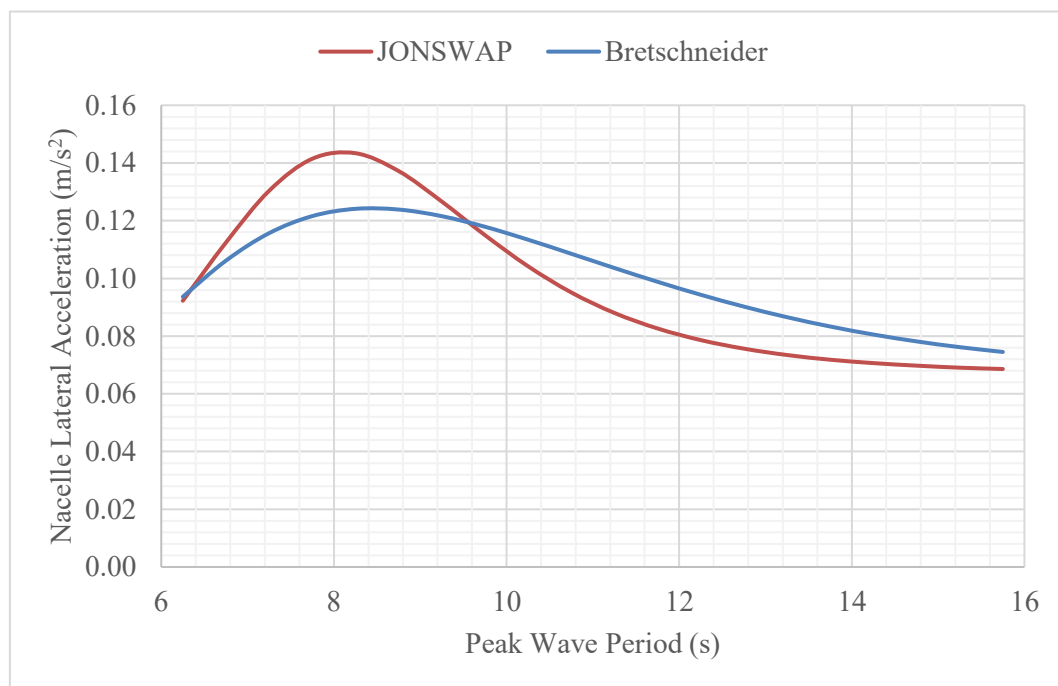

Figure 9. Nacelle lateral acceleration with varying peak wave period using JONSWAP wave energy spectra and Bretschneider wave energy spectra at 2m significant wave height.

4. Conclusion

In conclusion, the objective of this work was to estimate the range of wave conditions in which offshore wind turbine technicians can safely and effectively carry out maintenance tasks on a 15MW floating turbine. Through calculating the turbine nacelle motion using a statistical frequency domain analysis, it was found that the motion limits for technician working were not exceeded over the range of wave

conditions analysed for the semi-submersible reference turbine described in Section 2.1. It was also shown that the turbine motion increased with increasing significant wave height and was also highly influenced by the peak wave period during this analysis. These results suggest that, for this floating platform and turbine assembly, the ability of turbine technicians to complete maintenance tasks within the turbine nacelle will not be significantly impacted by the wave-induced dynamics. It should be noted that these results are highly dependent on the platform RAOs, as can be seen in Equation 2, thus highlighting the impact of platform type and hydrodynamic design in determining turbine accessibility for floating turbines. Current O&M planning and costing tools for offshore wind generally consider only significant wave height as a limiting factor, and therefore the impacts of the peak wave period of the wave spectrum should also be considered when applying these models to floating wind.

The influence of differing wave characteristics on turbine nacelle motion, represented here by the use of different wave energy spectra (JONSWAP and Bretschneider), was also investigated. It was found that the distribution of energy over the wave frequencies also had an impact on the motion seen at different wave periods and wave heights.

It should however be noted that this analysis is focused on identifying the wave conditions for acceptable turbine nacelle motions for technician working, it does not consider other limitations to completing maintenance operations, for example vessel accessibility. In reality these will place significant limitations on turbine accessibility for maintenance operations.

5. References

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