PAPER • OPEN ACCESS

The influence of an unstable turbulent wind spectrum on the loads and motions on floating Offshore Wind Turbines

To cite this article: J M Knight and C Obhrai 2019 IOP Conf. Ser.: Mater. Sci. Eng. 700 012005

View the article online for updates and enhancements.

You may also like

- <u>Similarity Model Development of Spar</u> <u>Floating Wind Turbine for Vibration</u> <u>Experimental Study</u> W.Q. Huang, E.M. He and J.J. Yang
- Data-driven fault detection of a 10 MW floating offshore wind turbine benchmark using kernel canonical variate analysis Xuemei Wang, Ping Wu, Yifei Huo et al.
- <u>Validation of a FAST spar-type floating</u> wind turbine numerical model with basin test data

H B Liu, F Duan, F Yu et al.





DISCOVER how sustainability intersects with electrochemistry & solid state science research



This content was downloaded from IP address 18.218.55.14 on 06/05/2024 at 22:58

IOP Publishing

The influence of an unstable turbulent wind spectrum on the loads and motions on floating Offshore Wind Turbines

J M Knight^{*} and C Obhrai

Department of Mechanical and Structural Engineering and Material Science, University of Stavanger, Norway

*Corresponding author: jamknight333@gmail.com

Abstract. Floating offshore wind turbines (FOWT) are exposed to harsh environmental conditions and often experience unstable atmospheric conditions. Including the effects of atmospheric stability should improve the accuracy of fatigue load calculations, and subsequently, the design of the wind turbine. The current standards recommend two turbulence spectral models that are valid for neutral atmospheric conditions only. The objective of this study is to investigate the influence of Højstrup's 1981 Unstable Spectra Model on the loads and motions on a spar and a semi-submersible FOWT. This study focuses on the effect of unstable atmospheric conditions in the free stream wind and does not include the effect of wakes. The most significant differences observed in this study were for the tower top torsion loads, where very unstable conditions gave 47% larger loads than neutral conditions for OC3-Hywind turbine and 30.4% larger for OC4-DeepCwind turbine. Since very unstable conditions corresponded to the highest turbulence intensities and larger turbulent fluctuations, they also resulted in higher fatigue loads. The blade root flap-wise loads were also observed to be higher under unstable conditions compared to neutral conditions, but the differences were smaller with 7.5% for OC3-Hywind and 23% for OC4-DeepCwind.

1. Introduction

Offshore renewable energy has gained significant momentum throughout the world recently, which strengthens the need for further research of wind fields and load simulation techniques. To develop better designs and maintenance strategies, it is beneficial to look at the influence of atmospheric stability and turbulent wind modelling. Presently, most research studies relating to turbulent wind spectra are often focused on neutral wind conditions. The International Electrotechnical Commission (IEC) standards recommend two turbulence models: the IEC Kaimal Spectra & Exponential Coherence Model and the Mann Spectral Tensor Model [1], neither of which consider the effect of atmospheric stability. The objective of this study is to investigate how turbulent wind fields and the generated wind coherence influence the motions and loads on a floating offshore wind turbine (FOWT), specifically using Højstrup's 1981 Unstable Spectra Model and two FOWT designs, the OC3-Hywind spar-buoy and the OC4-DeepCwind semisubmersible. The Højstrup model takes into account the effect of boundary layer height and buoyancy generated turbulence on the velocity spectra under unstable conditions, which is of particular interest to floating offshore structures, such as wind turbines.

The effect of atmospheric stability on the loads of bottom fixed wind turbines has been studied previously [2], [3] and [4]. In the study by [3], atmospheric stability and its relationship to the fatigue loads of a fixed offshore wind turbine were investigated using measurements from the offshore wind farm, Alpha Ventus. The study specifically looked at the impact of atmospheric stability on the blade root bending and the tower base moments, which were found to be the highest under unstable conditions

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under licence by IOP Publishing Ltd 1

in wind speeds between cut-in speed and approximately 14 m/s. They also noted that fatigue loads on the tower base were primarily influenced by atmospheric turbulence, unlike the fatigue loads on the blade root bending, which were influenced by a combination of wind shear for stable wind conditions and turbulence for neutral and unstable wind conditions. Sathe and Bierbooms [5] calculated fatigue loads at the blade root using non-neutral wind profiles and steady winds. They concluded that fatigue loads increase when using non-neutral wind profiles in comparison with those obtained under neutral conditions, with the highest loads observed for stable conditions. In the study by [4], the wind turbine fatigue loads were studied as a function of atmospheric stability without a classification system, but instead, atmospheric conditions were described by a continuous joint probability distribution of wind speed and stability. This study used the Kaimal neutral spectral model but varied the mean wind profiles and turbulence intensities based on measurements from the offshore meteorological mast Ijmuiden in the North Dutch Sea.

Finally, the study by [2] used data from a met mast at Høvsøre to derive parameters for the Mann Spectral Tensor Model [1] for different atmospheric stabilities. This resulted in higher simulated turbulence intensities and higher fatigue loads for neutral conditions. This is thought to be due to the fact that the Mann Spectral Tensor Model [1] is not able to simulate buoyancy generated turbulence, which is present in unstable atmospheric conditions. The Mann Spectral Tensor Model [1] was modified by [6] & [7] to account for non-neutral stability using an additional parameter z/L. The model parameters were obtained by fitting the model to measured one-dimensional velocity spectra, cospectra between horizontal and vertical velocity components, and temperature. However, the model had deficiencies in reproducing spectra and cospectra in unstable regimes at lower wavenumbers for larger lapse rates [7].

In addition to atmospheric stability, wind coherence is an important parameter to consider in turbulent wind modeling for offshore wind turbines. The effect of atmospheric stability on vertical coherence has been studied previously [8]. Using measurements from FINO 1, [8] derived a two-parameter decay function for modeling the coherence of the vertical velocity component in non-neutral conditions. In this study, the simpler Davenport Coherence Model was used with fixed decay coefficients, valid for neutral conditions only. Including the effect of atmospheric stability on vertical and horizontal coherence is a topic for further work. Until now, most studies have focused on the effect of atmospheric stability on the loads and motions of bottom fixed wind turbines and do not include wind spectra suitable for non-neutral conditions. A previous study by the authors [9] involved a short parametric study using the Højstrup Unstable Spectra Model and then used this to simulate the loads and motions of a spar-type FOWT. The present study extends the analysis of this previous work to investigate the effect of unstable conditions on the loads and motions of a spar type and a semi-submersible type floating wind turbine in free wind conditions.

2. Theoretical background

2.1. Atmospheric stability

Atmospheric stability can be characterized as stable, neutral, or unstable based on the "tendency of air particles to move vertically" relative to the temperature of their surroundings [10]. In stable conditions, the air particles are cooler than the surrounding air, causing them to sink or remain where they are. This stratification leads to less mixing and typically results in lower turbulence intensities. In unstable conditions, the air particles are warmer than the surrounding air, which causes them to rise and leads to more vertical mixing. Hence, this is called "buoyancy generated" turbulence. Due to the enhanced vertical mixing, one would expect larger turbulent fluctuations and higher fatigue loads under unstable conditions, which are typically more dominant at offshore sites [2]. However, stability conditions are largely dependent on the site location [11]. Overall, atmospheric stability tends to reduce turbulence in stable conditions and increase turbulence in unstable conditions.

In some cases, atmospheric stability is classified using the Monin-Obukhov length (L), or the length scale of energy-containing eddies. The Monin-Obukhov length is an important part of classifying

COTech

IOP Conf. Series: Materials Science and Engineering 700 (2019) 012005 doi:10.1088/1757-899X/700/1/012005

thermal stratification in the surface layer, and is typically associated with the height above ground (z). The ratio between the height above ground and the Monin-Obukhov length is recognized as an important stability parameter which reflects the impact of varying height and stability conditions [12].

2.2. Turbulent wind spectra

The IEC standards currently recommend two turbulence models: the IEC Kaimal Spectra & Exponential Coherence Model and the Mann Spectral Tensor Model [1]. Since these two models were originally developed for neutral conditions, this paper will focus on the Højstrup 1981 Unstable Spectra Model and use the original Kaimal Spectra model as a comparison for neutral conditions. The Højstrup spectra model is based on a modification of the Kaimal spectral model such that when L tends to infinity (i.e. neutral conditions) the Højstrup model reduces to the Kaimal model. In this study, we compare the Kaimal Spectral model to the Højstrup model to study the influence of unstable conditions on the loads and motions of FOWT's.

2.2.1. Kaimal Spectra Model. The most commonly used equations for the Kaimal spectra in engineering applications are based on the neutral stability Kansas measurements [13] and are adjusted to account for the 4/3 ratio that is expected in the inertial subrange [12]. These equations are as follows [14]:

$$\frac{nS_u}{u_*^2} = \frac{105f}{(1+33f)^{5/3}} \tag{1}$$

$$\frac{nS_{\nu}}{u_*^2} = \frac{17f}{(1+9.5f)^{5/3}} \tag{2}$$

$$\frac{nS_W}{u_*^2} = \frac{2f}{1+5.3f^{5/3}}$$

(3)

IOP Publishing

where *n* is frequency in Hertz, S_u , S_v , S_w are the velocity spectra in the along wind, cross wind, and vertical direction respectively, u_* is friction velocity, and $f = nz/\bar{u}$, a nondimensional reduced frequency.

2.2.2. *Højstrup 1981 Unstable Spectra Model.* The goal of Højstrup's 1981 Unstable Spectra Model was to develop a simple model that could resemble velocity spectra in unstable conditions downwind of a change in surface roughness and heat flux [15]. Since atmospheric turbulence consists of both a buoyancy generated component and a mechanically generated component, Højstrup found it important to create a velocity spectrum that involved both aspects and could be modelled as the sum of two semi-empirical spectra. This can be seen in Equation (4) [15]:

$$S(n) = S_L(n) + S_M(n)$$

with $S_L(n)$ corresponding to the low frequency part of the spectra and $S_M(n)$ corresponding to the Kaimal Spectra Model. The backbone of the model is the addition of a buoyancy-produced part (low frequencies) and a shear-produced part (high frequencies), thus creating the following equations [15]:

$$\frac{nS_u}{u_*^2} = \frac{0.5f_i}{1+2.2f_i^{5/3}} \left(\frac{z_i}{-L}\right)^{2/3} + \frac{105f}{(1+33f)^{5/3}}$$
(5)

$$\frac{nS_{\nu}}{u_*^2} = \frac{0.32f_i}{1+1.1f_i^{5/3}} \left(\frac{z_i}{-L}\right)^{2/3} + \frac{17f}{(1+9.5f)^{5/3}}$$

(6)

(4)

$$\frac{nS_{W}}{u_{*}^{2}} = \frac{32f}{(1+17f)^{5/3}} \left(\frac{z}{-L}\right)^{2/3} + \frac{2f}{1+5.3f^{5/3}}$$
(7)

IOP Publishing

For neutral conditions, when $L=\infty$, Equations (5), (6), and (7) reduce to the Kaimal spectrum. The key variables of the model are the three scaling lengths: height (z), inversion height (z_i), and Monin-Obukhov length (L). The reduced frequency parameters are defined as, $f = nz/\bar{u}$ and $f_i = nz_i/\bar{u}$, which provide knowledge of the spectra's variation with stability [16].

2.3. Davenport Exponential Coherence Model

A suitable model for vertical coherence, when the separation between points are small in comparison to the length scale of turbulence, is the Davenport Exponential Coherence Model. Equation (8) includes both vertical and horizontal cross-flow separations [17]:

$$\gamma_i(d_y, d_z, n) \approx \exp(-\frac{n}{\bar{u}} * \sqrt{\left(C_y^i \, d_y\right)^2 + \left(C_z^i \, d_z\right)^2})$$
(8)

where $i = \{u, v, w\}$, d_y and d_z are the horizontal and vertical separation distances between points, *n* refers to the frequency in Hz, \bar{u} is the horizontal mean velocity, and C_y^i and C_z^i are decay coefficients in the y- and z-direction, respectively.

3. Wind turbine characteristics

The simulations conducted in this study included the spar-buoy type FOWT, a ballast stabilized concept, from Phase IV of the IEA Annex XXIII Offshore Code Comparison Collaboration (OC3) project [18], as well as the semi-submersible design from Phase II of the Offshore Code Comparison Collaboration Continuation (OC4) project [19], an extension of the OC3 project. Both phases make use of the National Renewable Energy Laboratory's (NREL) offshore 5 MW standard wind turbine, with alterations to the foundation type depending on the design concept. Basic parameters of NREL's 5 MW turbine are displayed in Table 1 and further details of the OC3 and OC4 FOWTs can be found in [18] and [19], respectively. Table 2 displays the eigen frequencies for the first 10 modes for the OC3-Hywind [18] and OC4-DeepCwind [19] FOWTs, which are relevant for the platform motion analysis.

Parameter	NREL 5 MW Wind Turbine
Power Production Rating	5 MW
Number of Blades	3
Rotor Orientation	Upwind
Rotor Diameter	126 m
Hub Height	90 m
Cut in, Rated, Cut out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Cut in, Rated Rotor Speed	6.9 rpm, 12.1 rpm

 Table 1. Specifications for NREL 5 MW Offshore Wind Turbine.

Table 2. Eigen	frequencies	for first 1	0 modes of the	OC3-Hywind &	OC4-Dee	pCwind FOWTs.
0				2		

Mode	Platform Motion	Spar (Hz)	Semisubmersible (Hz)
1	Surge	0.008	0.01
2	Sway	0.008	0.01
3	Heave	0.032	0.058
4	Roll	0.034	0.04
5	Pitch	0.034	0.04

IOP Publishing

6	Yaw	0.11	0.012
7	1 st Tower fore-aft	0.43	0.43
8	1 st Tower side-side	0.44	0.43
9	Drivetrain torsion	0.63	0.63
10	Blade flap-wise	0.64	0.64

3.1. Wind Simulation Model

To generate the velocity spectra of the Højstrup model, a MATLAB script was used to determine the spectra for the u, v, and w components based on Equations (5), (6), and (7). The spectral representation approach was then used to simulate turbulent wind fields using the method from [20]. A function called WindSimFast [21], available on MathWorks File Exchange, was used to simulate the random wind fields from the Højstrup spectra model. To allow for the simulations to closely resemble the stochastic nature of wind and waves and to minimize uncertainty, six random seeds were defined within the script to generate the velocity histories. The necessary input parameters are displayed in Tables 3, 4, and 5. Within this study, atmospheric stability was classified using Monin-Obukhov length, as presented in Table 5, which coincides with the atmospheric stability classes as suggested by [22]. The logarithmic wind speed profile corrected for unstable conditions was chosen to represent the mean wind speed profile for the simulations as given in the DNV standards [23]:

$$U(z) = U_{ref} \frac{\ln(z/z_0) - \psi_m(z/L)}{\ln(z_{ref}/z_0) - \psi_m(z_{ref}/L)}$$

$$\psi_m(z/L) = 2\ln[1+x] + \ln[1+x^2] - 2\tan^{-1}(x)$$

$$x = (1 - 19.3(z/L))^{\frac{1}{4}}$$
(9)

where z_{ref} is a reference height, U_{ref} is the mean wind velocity at z_{ref} , z_o is sea surface roughness length, and ψ_m is the stability function (shown specifically for unstable conditions). In this study z_o was fixed and did not vary with wind speed this could be done in future work

Table 3. Input parameters.						
Sampling Frequency	Duration	XYZ grid	u_{*0}	Zi	Z ₀	К
9.1 Hz	1hr	32768 x 32 x 32	0.4 m/s	1000 m	0.00014	0.4

Coefficient	c_y^u	c_y^v	c_y^w	C_z^u	c_z^v	C_Z^W
Value	7	7	6.5	10	10	7

Table 4. Decay coefficients used for Davenport Coherence Model

Table 5	5. Atmos	pheric	stability	classes.
I apic .	• 1 tunos	phene	stability	classes.

Atmospheric Stability Class	Monin-Obukhov Length (m)
Very Unstable	-90
Unstable	-180
Neutral	∞

Figure 1 shows the target spectra for the Højstrup spectra model for varying values of L, at hub height, where L = -90 m represents very unstable conditions, L = -180 m represents unstable conditions, and $L = \infty$ is the Kaimal neutral wind spectra. Given that the high frequency part of the Højstrup model is identical to the Kaimal model, it makes sense that the resulting spectra would converge at high frequencies, as can be seen in Figure 1.



Figure 1: The target spectra for the Højstrup spectra model with varying L at hub height (90 m).

3.2. SIMO-RIFLEX AeroDyn

A FOWT with the characteristics in Table 1 was implemented into SIMA, a simulation and analysis tool developed by SINTEF Ocean [24]. Within SIMA, there is a SIMO-RIFLEX coupling tool that allows for the simulation of multi-body hydrodynamics. For this study, the OC3 spar-buoy FOWT [18] stored within SIMO-RIFLEX was used and adjusted to model wind fields using the Højstrup spectra model. The OC4 semisubmersible type FOWT [19], supported by the NREL 5 MW baseline wind turbine [25], was provided by SINTEF. The turbine tower and blades were modelled with nonlinear beam elements, and the mooring lines were modelled with nonlinear bar elements, which allowed for the rotation of each element [26].

The environmental loads implemented in this study include both wind and wave loads. The waves were defined using irregular airy waves based on the Joint North Sea Wave Project (JONSWAP) wave spectrum [27], with a peak parameter (γ) = 3.3, significant wave height (H_s) = 6 m, and a peak period (T_p) = 12 s. The peak period corresponds to a peak wave frequency (f_p) of 0.083 Hz.

The synthetic/generated turbulent wind fields, determined by the wind simulation model described previously, were stored in binary format and then used to create the wind loads applied within the coupled SIMO-RIFLEX simulations. Below rated (8 m/s), rated (11.4 m/s), and above rated (15 m/s) wind speed scenarios at hub height were defined. The logarithmic wind speed profile corrected for unstable conditions was chosen to represent the mean wind speed profile for the simulations as given in the DNV standards [23]. An example of the mean wind profile across the rotor at rated wind speed in very unstable conditions is shown in Figure 2.



Figure 2: Corrected Logarithmic Wind Profile for very unstable conditions (L = -90 m) for rated wind speed (11.4 m/s) at the 90 m hub height.

Each scenario was simulated for a 1-hour time series, with a 0.02 s time step. The properties of the wind input also included an air density (ρ) = 1.225 kg/m³, tip loss correction defined through the Prandtl tip loss method, drag force on the turbine tower using the Potential flow tower shadow method, and transient aerodynamics developed through Beddoes-Leishmann dynamic stall method [28].

4. Results and discussion

The results of this study are presented as damage equivalent loads and motion responses using the Højstrup 1981 Unstable Spectra Model under varying atmospheric stability, for both the OC3-Hywind and OC4-DeepCwind FOWT.

4.1. Damage equivalent loads

For a FOWT, it is particularly important to investigate the fatigue damages caused by repetitive loading. Based on the material of the component, the stress level, and the number of load cycles, the corresponding deterioration will vary and has the potential to continue until failure. To quantify the level of deterioration, it is common to consider the accumulated damage for each cycle based on Palmgren-Miner linear damage rule (Miner's rule) [29], which assumes that the damage accumulated from each load range can be added linearly [2]. In order to determine the load ranges (σ_i) and the subsequent number of cycles (n_i), the rain-flow counting method was used in conjunction with Miner's rule and applied to calculate fatigue damage for each load range using Equation (10) [30]:

$$D = \sum_{i} \frac{n_i}{N_i} = \sum_{i} \frac{n_i}{C} \sigma_i^b$$
(10)

where n_i is the subsequent number of cycles, N_i is the total number of cycles until failure at the load range, σ_i , $C = N_i \sigma_i^b$, and b is the characteristic parameter of the S-N curve or the Wöhler exponent. For this analysis, b was set as 3 for the tower, tower top, and mooring lines, since they are all made from steel, and 12 for the blades, since they are made from fiberglass [25].

Using the relationship in Equation (10), an expression for the equivalent alternating stress, σ_{eq} , can be derived, corresponding to the same fatigue damage if the loading were applied for the duration of N_{eq} (equivalent number of load cycles), which was assumed as 10⁷ for this study, or approximately 20 years of operation [2]. To quantify the DEL from the load time series, the relation between the occurring stress and its number of cycles is required. This relation is commonly known as S-N curve and is usually obtained by experiments for different materials. However, since it is difficult to define the S-N curve for a particular component, fatigue damage can instead be quantified using the concept of damage equivalent load (DEL), which can be found with Equation (11) [30]:

$$\sigma_{eq} = \left(\sum_{i} \frac{n_i \sigma_i^b}{N_{eq}}\right)^{1/b}$$

where N_{eq} is the equivalent number of load cycles.

4.1.1. OC3-Hywind spar-buoy FOWT. The normalized DELs (average from 6 simulations) for the blade root flap-wise moment and tower top torsion are displayed in Figure 3.



Figure 3. Normalized DELs for blade root flap-wise bending (left) and tower top torsion moment (right), normalized by the Kaimal model at 8 m/s, with the spar-buoy foundation.

Theoretically, unstable atmospheric stability conditions correlate to higher turbulence intensity and larger turbulent fluctuations than in neutral and stable conditions. Figure 3 shows that the highest DELs corresponded to very unstable conditions, followed by unstable and neutral conditions, although the differences appears to be minor for the blade root flap-wise bending moment. The maximum difference for the blade root flap-wise bending moment when considering the same wind speed was approximately 7.5%. In a study by [28], it was also found that the blade root flap-wise loads were not significantly influenced by atmospheric stability, with only a 6.5% difference. However, this previous study showed that neutral conditions gave the largest DEL, since the simulations were based on the fitted Mann model. In the study by [2], results showed that atmospheric stability had little influence on the blade root flap-wise bending moment, with only a 3% difference in dynamic loads between non-neutral and neutral wind conditions. Similar to [28], the simulations in [2] incorporated the fitted Mann model, and neutral conditions resulted in the largest DEL.

A similar trend was found for tower top torsion, with very unstable conditions giving the largest DELs. However, in this case, atmospheric stability, and its relationship to turbulence intensity, seems to have a significant influence on the resulting DELs. For the tower top torsion, the maximum difference between very unstable conditions and neutral conditions, considering the same wind speed, was approximately 47%. Figure 4 shows the simulated turbulence intensity at hub height for each of the wind speed scenarios defined in this study. The Højstrup spectra model resulted in the highest turbulence intensities for very unstable conditions, as expected.

(11)



Figure 4: Simulated turbulence intensities at hub height (90 m) for each wind speed scenario.

In previous studies where the Mann Spectral Tensor Model was fitted to measurements, the highest turbulence intensities were simulated for neutral atmospheric conditions [2], [28] and [31]. As a result, these studies found that neutral atmospheric conditions resulted in the highest fatigue loads, followed by unstable and stable conditions. This is most likely because unstable conditions were not fully represented when using this method. In contrast, this study found that the highest turbulence intensities corresponded to very unstable conditions due to the inclusion of vertical mixing associated with buoyancy generated turbulence in the Højstrup spectra model. These results show the importance of including the low frequency energy present in unstable conditions on the resulting tower top torsion fatigue loads.

4.1.2. OC4-DeepCwind semisubmersible FOWT. The average normalized DELs for the blade root flap-wise bending moment and tower top torsion, normalized with the Kaimal model below rated scenario, are displayed in Figure 5.



Figure 5. DELs for blade root flap-wise bending (left) and tower top torsion (right), normalized by the Kaimal model at 8 m/s, with the semisubmersible foundation.

IOP Publishing

The Højstrup wind spectra model under very unstable conditions resulted in the largest fatigue DELs for each wind speed for the semisubmersible foundation, similar to the results for the spar-buoy FOWT shown previously. The maximum difference between very unstable conditions and neutral conditions, considering the same wind speed, was approximately 23% for the blade root flap-wise moment and 30.4% for tower top torsion.

4.2. Platform Motions

In order to fully analyze the response of a FOWT, it is important to evaluate the motions in six degrees of freedom that the structure will experience due to both wind and wave loadings. In this study, the pitch and yaw rotations were highlighted.

4.2.1. OC3-Hywind spar-buoy FOWT. The spectral density for platform pitch and yaw rotation are displayed in Figure 6. The other platform motions were found to be relatively unaffected.



Figure 6. Spectral density of pitch rotation (left) and yaw rotation (right) for varying stability at rated wind speed (11.4 m/s) with the spar-buoy foundation.

Continuous and excessive platform motion may lead to fatigue damage if the frequency of the platform coincides with the frequency of the turbulent wind input. By looking at Figure 6, the platform pitch rotation appears to have been excited by the wave peak frequency, as well as frequencies just below the pitch natural frequency (0.034 Hz). Often, the platform pitch motion is related to negative damping associated with the blade pitch control system, which stems from the reduction in rotor thrust as the wind speed increases above rated [32]. However, modifications were made to the original control system for the NREL 5-MW turbine for the OC3-Hywind and OC4-DeepCwind projects by [19] in an effort to avoid the negative damping issue. These modifications included a reduction of gains in the blade-pitch-to-feather control system and a change in the generator torque control strategy when operating above rated power. This modified controller has been used in all simulations in this study, which seemingly reduced the impact of negative damping.

The differences between the turbulence models were noticeable in the results for the yaw rotation. Significant energy can be seen at low frequencies, around the wave peak frequency, at the OC3-Hywind yaw natural frequency (~0.11 Hz), and a very small response at the 1P natural frequency (0.2 Hz) (Figure 6). Since the spar-buoy foundation is characterized by high mooring stiffness and a low moment of inertia in yaw about the center of mass, it makes sense to see a "quasi-static" yaw response at low frequencies [26]. Additionally, results seen in [28] revealed that unstable conditions gave the largest yaw rotation for rated wind speed, followed by neutral and stable conditions. In this study, it is clear that very unstable conditions resulted in the largest excitation response in yaw, followed by unstable and neutral conditions.

4.2.2. OC4-DeepCwind semisubmersible FOWT. The spectral density for platform pitch and yaw rotation using the semisubmersible foundation are displayed in Figure 7.



Figure 7. Spectral density of pitch rotation (left) and yaw rotation (right) for varying stability at rated wind speed (11.4 m/s) with the semisubmersible foundation.

The spectral energy plot of the platform pitch motion showed peaks in energy at the pitch motion natural frequency (0.04 Hz) and the wave peak frequency (0.083 Hz). Whereas, the platform yaw motion spectral energy plot showed significant energy at the yaw motion natural frequency (0.012 Hz), but very little energy at the wave peak frequency. Since a semisubmersible foundation is typically characterized by a soft mooring tension and a large moment of inertia in yaw [26], it seems likely that the yaw response would primarily occur at the yaw natural frequency. For each platform motion, the Højstrup model under very unstable conditions maintained the largest spectral energy. Since each degree of freedom for the OC4-DeepCwind FOWT has a fairly low natural frequency, there was no significant excitation response at frequencies higher than the wave peak frequency.

5. Conclusion

In this study, the influence of unstable turbulent wind fields on the loads and motions of floating offshore wind turbines was studied using the Højstrup 1981 Unstable Spectra Model and the Davenport Exponential Coherence function. The most significant difference between the turbulent wind cases was observed for the tower top torsion moment DEL's. Very unstable conditions resulted in fatigue loads for the tower top torsion that were 47% larger than neutral conditions for OC3-Hywind and 30.4% larger for OC4-DeepCwind. As expected, very unstable conditions corresponded to the highest turbulence intensities and the largest turbulent fluctuations due to the inclusion of buoyancy generated turbulence. In previous studies, the fitted Mann model was unable to fully simulate unstable conditions, which may explain why the results from both [2] and [28] found that the highest DEL's corresponded to neutral conditions when using this approach.

The purpose of using the Højstrup spectra model is to include the low-frequency energy that is present in unstable atmospheric conditions, and determine its influence on the resulting loads and platform motions. However, the Højstrup model was developed using onshore wind measurements and has not currently been validated for offshore conditions. A composite spectral model developed by [8], which uses local similarity theory and a combination of a pointed and a blunt model to describe the wind turbulence spectra for different atmospheric stabilities, could be used in further studies. The resulting spectra incorporated measurements collected from the FINO 1 platform and would most likely result in a better depiction of unstable conditions for an offshore environment. However, care needs to be taken when applying wind spectra at different offshore sites to ensure that they are correctly normalized and site specific turbulence intensities are used. Jonkman and Veers [11] concluded that

specific turbulence intensity levels are needed to accurately represent offshore sites, which can be dominated by different atmospheric stability conditions. Therefore, implementation of the Pointed-blunt model would be best suited for a location with similar site conditions to those found at the FINO 1 platform.

Acknowledgments

The authors would like to express their sincere gratitude to Rieska Putri and Dr. Etienne Cheynet for their key insights, collaboration, and abundant knowledge that was needed in completing the objectives of this paper.

References

- [1] International Electrotechnical Commission 2005 IEC 61400-1 Wind Turbines- Part 1: Design Requirements. Geneva: International Electrotechnical Commission, IEC.
- [2] Sathe A, Mann J, Barlas T, Bierbooms W A A M and van Bussel G J W 2013 Influence of atmospheric stability on wind turbine loads. *Wind Energy*, **16** 1013-32.
- [3] Kretschmer M, Shwede F, Guzmán R F, Lott S, and Cheng P W 2018 Influence of atmospheric stability on the load spectra on wind turbines at alpha ventus. *J. Phys.* Conf. Ser. **1037** 05200.
- [4] Holtslag M C, Bierboom WA A M and van Bussel GJW 2016 Wind turbine fatigue loads as a function of atmospheric conditions offshore. *Wind Energy*, **19** 1917-32.
- [5] Sathe A and Bierbooms W 2007 The influence of different wind profiles due to varying atmospheric stability on the fatigue life of wind turbines. *Journal of Physics: Conference Series*, **75** 12056–62.
- [6] Chougule A 2017 Modelling atmospheric turbulence via rapid distortion theory: Spectral tensor of velocity and buoyancy. *J. Atmos. Sci.* **74** 949-74.
- [7] Chougule A, Mann J, Kelly M and Larsen G 2018 Simplification and validation of a spectraltensor model for turbulence including atmospheric. *Boundary Layer Meteorol.* **167** 371-97.
- [8] Cheynet E, Jakobsen J and Reuder J 2018 Velocity spectra and coherence estimates in the marine atmospheric boundary layer. *Boundary-Layer Meteorol.* **169**(3) 429 60.
- [9] Putri, R M, Obhrai, C, & Knight, J M (2019, October). Offshore Wind Turbine Loads and Motions in Unstable Atmospheric Conditions. In Journal of Physics: Conference Series (Vol. 1356, No. 1, p. 012016). IOP Publishing.
- [10] Atmospheric Stability: Stability of Dry Air. [online]. PowerPoint PPT Presentation. Available at: https://www.slideserve.com/Jimmy/atmosphericstability [Accessed January 2019]
- [11] Jonkman J and Veers P 2019 DNV GL joint industry project on validation of turbulence models. *Cooperative Research and Development Final Report*, CRD-17-673. NREL/TP-5000-73167.
- [12] Kaimal J C and Finnigan J J 1994 Atmospheric boundary layer flows: Their structure and *measurement*. Oxford University Press, Inc.
- [13] Haugen, D A, Kaimal, J C and Bradley, E F 1971 An experimental study of Reynolds stress and heat flux in the atmospheric surface layer. *Quart. J. R. Met. Soc.*, **97** 168-80.
- [14] Kaimal J C, Wyngaard J C, Izumi Y and Coté O R 1972 Spectral characteristics of surface-layer turbulence. *Quart. J. R. Met. Soc.*, 98 563-89.
- [15] Højstrup, J 1981 A simple model for the adjustment of velocity spectra in unstable conditions downstream of an abrupt change in roughness and heat flux. *Boundary-Layer Meteorol.* 21 341-56.
- [16] Olesen H R, Larsen S E and Højstrup J 1984 Modelling velocity spectra in the lower part of the planetary boundary layer. *Boundary-Layer Meteorol.* **29** 285-312.
- [17] Davenport A G 1961 The Spectrum of Horizontal Gustiness near the Ground in High Winds. *Quart. J. R. Met. Soc.*, **87** 194-211.
- [18] Jonkman J, Larsen T et al. 2010 Offshore Code Comparison Collaboration within IEA Wind Task 23: Phase IV Results Regarding Floating Wind Turbine Modeling. Conference Paper. NREL/CP-500-47534.

- [19] Robertson A, Jonkman J, Masciola M, Song H, Goupee A, Coulling A and Luan C 2014 Definition of the Semisubmersible Floating System for Phase II of OC4. National Renewable Energy Laboratory. Technical Report. NREL/TP-5000-60601.
- [20] Shinozuka M and Deodatis G 1991 Simulation of stochastic processes by spectral representation. *Appl. Mech. Review*, **44**(4) 191-204.
- [21] Cheynet E 2018 Wind field simulation (the fast version). MathWorks file exchange. Available at: https://se.mathworks.com/matlabcentral/fileexchange/68632-wind-field-simulation-thefast-version [Accessed September 2018]
- [22] Gryning S, Batchvarova E, Brümmer B, Jørgensen H and Larsen S 2007 On the extension of the Wind Profile over Homogeneous Terrain beyond the Surface Boundary Layer. *Boundary Layer Meteorol.* 124 251 – 68.
- [23] Det Norske Veritas AS 2010 DNV-RP-C205: Environmental conditions and environmental loads. Oslo: Veritas Offshore Technology and Service AS, DNV.
- [24] Karimirad, M. MARINTEK Numerical Tools for Coupled Aero-Hydro-Servo-Elastic Simulations of Offshore Wind Turbines. SINTEF. MARINTEK. [Accessed 2019].
- [25] Jonkman J, Butterfield S, Musial W and Scott G 2009 Definition of a 5-MW Reference Wind Turbine for Offshore System Development. NREL/TP-500-38060.
- [26] Bachynski E and Eliassen L 2019 The effects of coherent structures on the global response of floating offshore wind turbines. *Wind Energy*, **22** 219-38.
- [27] Hasselman K, Barnett T P, et al, 1973 Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP). Deutsche Hydro. Zeitschr. Riehe, A8
- [28] Putri R 2016 A study of the coherences of turbulent wind on a floating Offshore Wind Turbine. Master Thesis, University of Stavanger,.
- [29] Driscoll F, Jonkman J, Robertson A, Sirnivas S, Skaare B and Nielsen F 2016 Validation of a FAST model of the Statoil-Hywind Demo Floating Wind Turbine. *Energy Procedia*, **94** 3-19.
- [30] Lalanne C 2009 Fatigue Damage. Mechanical Vibration and Shock Analysis, Second Edition, 4.
- [31] Pena A, Gryning S E and Mann J 2010 On the length scale of the wind profile. *Quart. J. R. Met. Soc.*, **136** (653) 2119–31.
- [32] Lackner M 2013 An investigation of variable power collective pitch control for load mitigation of floating offshore wind turbines. *Wind Energy*, **16** 519-28.