Wind turbine fatigue loads as a function of atmospheric conditions offshore

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ABSTRACT

In recent years there has been a growing interest by the wind energy community to assess the impact of atmospheric stability on wind turbine performance, however up to now, typically, stability is considered in several distinct arbitrary stability classes. As a consequence, each stability class considered still covers a wide range of conditions. In this paper wind turbine fatigue loads are studied as a function of atmospheric stability without a classification system, and instead atmospheric conditions are described by a continuous joint probability distribution of wind speed and stability. Simulated fatigue loads based upon this joint probability distribution have been compared to two distinct different cases, one in which 7 stability classes are adopted, and one neglecting atmospheric stability by following IEC standards. It is found that for the offshore site considered in this study fatigue loads of the blade root, rotor and tower loads significantly increase if one follows the IEC standards (by up to 28% for the tower loads), and decrease if one considers several stability classes (by up to 13% for the tower loads). The substantial decrease found for the specific stability classes can be limited by considering one stability class only that coincides with the mean stability of a given hub height wind speed. The difference in simulated fatigue loads by adopting distinct stability classes is primarily caused by neglecting strong unstable conditions for which relatively high fatigue loads occur. Combined, it is found that one has to carefully consider all stability conditions in wind turbine fatigue load simulations. Copyright © 0000 John Wiley & Sons, Ltd.

KEYWORDS

offshore wind energy; wind turbine fatigue loads; fatigue load simulation; atmospheric stability; wind shear; turbulence

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1. INTRODUCTION

Wind turbines are expected to operate typically for about 20 to 25 years, during which the turbine will experience fatigue loads. The fatigue and extreme loads that the turbine experiences are predominantly caused by atmospheric conditions such as wind shear, turbulence and gusts. It is common procedure in wind turbine design to define wind conditions following IEC standards [1, 2]. The fundamental physical processes underlying the dynamics of the atmosphere are only partially incorporated in such guidelines. In reality wind shear and turbulence depend on these dynamics [3] and should be treated in a coupled way in contrary to guidelines which typically treat them one by one separately. Practically this coupling mechanism means that for non-extreme conditions there is either strong wind shear or high turbulence levels, but never both at the same time. To this end it is expected that the individual atmospheric conditions as prescribed in guidelines are not necessarily wrong, but the dynamic coupling of the whole atmosphere is missing. The offshore environment inherently causes an added complexity, since not only processes within the atmosphere are coupled, but also the sea surface and the atmosphere have an interaction [4, 5, 6]. Despite this sea-air interaction, in this study we emphasize purely on the coupling of the dominant atmospheric processes that cause fatigue loads (thus shear and turbulence), and the necessity of including this coupling in wind turbine design.

The coupling of shear and turbulence has been discussed in [7] as well, but in a statistical way in agreement with guidelines. Though this does result in a practical methodology, it does not provide fundamental insight how the underlying physics that govern the atmospheric flow indirectly influence the performance of a wind turbine. As such, the emphasis of this study is to explain how the governing forces couple wind shear and turbulence, and how as a result fatigue loads of a
wind turbine are influenced. Considering the physics of the atmospheric flow, it is commonly accepted that wind shear and turbulence both depend on atmospheric stability [8]. Recent studies have explored the impact of atmospheric stability on wind turbine performance. [9] for example assessed the dependence of power production on atmospheric stability, and [10] assessed the dependence of wind turbine fatigue loads to atmospheric stability. A recurring aspect of such studies is that the stability of the atmosphere is divided into distinct but arbitrary classes. Examples found in literature show differences in the amount of stability classes adopted, for example [11] considered 3 stability classes, [12] considered 5 stability classes and [13] considered 7 stability classes. Any physical based argument for these exact boundaries of the adopted stability classes however is missing. Atmospheric stability in terms of the Obukhov length $L$ [14] is in fact a continuous parameter which can range from $-\infty$ to $+\infty$, and note that in the class definition of [10] extreme stable ($0 < L < 10$) and extreme unstable ($-50 < L < 0$) conditions are neglected. As such one might question if adopting a specific distinct classification system for atmospheric stability is beneficial for wind energy purposes, besides giving general insight in the performance of a wind turbine for stable, neutral and unstable atmospheric conditions.

Although there is a simplification in how guidelines approach the description of the atmosphere, one has to acknowledge the practicality of reducing complexity from defining atmospheric conditions. In scope of the number of load cases that have to be addressed in offshore wind turbine design [2], adding more complexity (and thereby probably adding more required simulations) for each load case can quickly result in a significant computational burden. In terms of the classification system for atmospheric stability discussed previously, it can easily be shown that incorporating stability with 7 classes causes an increase in computation demand by a factor 7. Adding such a computational burden to industry standards can only be justified if there is a significant improvement in the accuracy of lifetime fatigue load estimations compared to simplifying the atmosphere.

In this study the impact of using either IEC standards, specific stability classes or a continuous distribution of stability in wind turbine design is studied for the offshore environment. Atmospheric conditions are prescribed based on either offshore IEC standards [1, 2] or based on offshore observation data [15], and wind turbine fatigue loads are simulated for various turbine components. This should not only result in better understanding how the coupling of wind shear and turbulence influences wind turbine fatigue loads, but also provide insight if adopting specific stability classes influences simulated wind turbine loads. Besides, it serves as an exploration to see if following the guidelines (which are applied to local conditions as much as possible) results in an incorrect estimation of the number of fatigue cycles of turbine components by neglecting the dynamic coupling within the atmosphere. It is also aimed to define a characteristic state of the atmosphere for which fatigue loads are representative as if one would carry out numerous simulations with varying atmospheric conditions but similar hub height wind speeds. This should result in a practical incorporation of advanced atmospheric physics into wind turbine design. It is recognised that the DNV standard for offshore structures does mentioned the relevance of atmospheric stability, but only for wind shear and not for turbulence levels [16, 17]. Since observations show that atmospheric stability influences both wind shear and turbulence conditions offshore [15], it is decided not to follow these specific DNV standards but the IEC standard to define atmospheric conditions for the simulation case where stability is not considered.

2. SIMULATION CONDITIONS

Due to the nature of this study, the simulation conditions are elaborated on before specific atmospheric conditions applied in the simulations are discussed in detail in section 3. In this study wind turbine fatigue loads at three specific locations of the wind turbine are assessed. The corresponding coordinate systems are shown in Figure 1, where for the blade root and rotor a rotating reference frame is considered. The blade root flapwise and edgewise loads correspond to respectively the bending moments $M_{y,B}$ and $M_{x,B}$ assuming the blades are not pitched. Once the blades are pitched both $M_{y,B}$ and $M_{x,B}$ contribute to the flapwise as well as the edgewise loads, and the relative importance of each bending moment depends on the pitch angle. The rotor out of plane loads correspond to $M_{y,R}$ and $M_{z,R}$, depending on the position of the coordinate system (i.e., rotor azimuth angle), while the rotor in plane loads correspond to $M_{x,R}$. For the tower loads we have a simple fixed coordinate system, and the fore-aft loads thus only correspond to $M_{y,T}$, and the side-side loads are caused by $M_{x,T}$.

The simulations are carried out for the SMW NREL reference turbine frequently used in research [18], with main characteristics being summarized in Table I. Although waves cause fatigue as well this study emphasizes purely on the influence of offshore atmospheric conditions on wind turbine fatigue loads, hence hydrodynamic loads are not included in any of the simulations to keep the results as clear as possible. We thus only do not consider the complete IEC standard for offshore conditions, only the sections that describe atmospheric conditions, and compare subsequent fatigue loads. The wind turbine tower below sea level is modelled as a monopile structure with constant diameter and a water depth of 20 m. All simulations are carried out with the wind turbine design software Bladed version 3.85, and fatigue load simulations are carried out for typical operating wind speeds ranging from 4 to 25 m s$^{-1}$ with a 1 m s$^{-1}$ interval. To reduce problems with spin-up during which the wind turbine has to adjust to the ambient conditions, the simulations are run for 630 seconds from which the last 600 seconds are used for the load calculations. Simulations are carried out in such
Figure 1. Coordinate system used in this research for the blades (left, subscript B), rotor (middle, subscript R) and tower (right, subscript T). The bending moments around all three axes are shown as well.

Table I. Overview of primary characteristics of the NREL 5MW machine.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>5.0 MW</td>
</tr>
<tr>
<td>Number of blades</td>
<td>3</td>
</tr>
<tr>
<td>Rotor diameter</td>
<td>126 m</td>
</tr>
<tr>
<td>Hub height</td>
<td>90 m</td>
</tr>
<tr>
<td>Cut-in wind speed</td>
<td>3 m s(^{-1})</td>
</tr>
<tr>
<td>Rated wind speed</td>
<td>11.6 m s(^{-1})</td>
</tr>
<tr>
<td>Cut-Out wind speed</td>
<td>25 m s(^{-1})</td>
</tr>
<tr>
<td>Control</td>
<td>Variable speed, collective pitch</td>
</tr>
</tbody>
</table>

Lifetime fatigue loads are considered in terms of the lifetime equivalent load, which can be calculated as [19]

\[
F_{EQ-TOT} = \int_{\nu_{in}}^{\nu_{out}} \int_{-\infty}^{\infty} F_{EQ} (\nu_h, \zeta_h) \cdot P (\nu_h, \zeta_h) \, d\zeta_h \, d\nu_h
\]  

Here \(F_{EQ-TOT}\) is the total lifetime equivalent load, \(F_{EQ}\) is the equivalent load for a given hub height wind speed \(\nu_h\) and stability \(\zeta_h\) and \(P (\nu_h, \zeta_h)\) is the joint probability of hub height wind speed and stability. The stability parameter \(\zeta\) is related to the Obukhov length \(L\) as \(\zeta = z/L\) where \(z\) is the height above the surface, and similarly \(\zeta_h = h/L\) where \(h\) is the hub height of the wind turbine. The equivalent load \(F_{EQ}\) is calculated similar as [20]

\[
F_{EQ} = \left( \frac{\sum F_{i}^{m} n_{i}}{n_{EQ}} \right)^{1/m}
\]

with \(n_{EQ}\) is the number of equivalent cycles, taken as \(10^7\), \(F_{i}\) and \(n_{i}\) are the fatigue load ranges and fatigue cycles and \(m\) is the Whöler exponent. The fatigue load and fatigue cycles are obtained from a rainflow counting algorithm in Bladed. Since the SMW NREL turbine is a hypothetical reference turbine, there are no S-N curves available to obtain \(m\) for specific turbine components. As such we follow [20] and consider \(m\) to be respectively 4, 8 and 12 for the tower, the hub and the blades. This corresponds to welded steel for the tower, cast iron for the hub and glass fibre for the blades.
To assess the impact of including a physical based representation of the atmosphere in wind turbine design, three separate cases are defined for which all load simulations are carried out (see Table II for a summary). These cases differ only in terms of prescribed environmental atmospheric conditions while turbine characteristics are kept constant. The first simulation case follows the IEC standards version 61400-3 for offshore conditions as closely as possible. With the considered wind speeds and turbulence seeds, one needs to carry out 132 simulations. The second case follows the traditional way of assessing the impact of atmospheric stability on wind turbine performance with arbitrary distinct stability classes. We consider the classification system of [13] with seven stability classes, and for each stability class one characteristic stability condition is adopted for which simulations are carried out. As such, the second case requires seven times more simulations (924). The stability class boundaries and the representative stability for each class is shown in Table III, where the representative stability for each stability class equals the mean of the corresponding class boundaries. The third case aims to approach the distribution of atmospheric stability as closely as possible. In practice it is an extension of case two, but with a significant increase in the amount of stability classes. To keep the computational time required for all simulations manageable, the continuous distribution of stability is approximated by 34 separate classes, which increases the amount of required simulations to 4488.

In this study the same observation data is used as in [19] and [15], where $L$ is calculated with the bulk Richardson method based on regular observation data of surface conditions and atmospheric conditions at 27m height. A clarification on uncertainty in the determination of $L$, specifically with respect to sea surface temperature observations, is presented in [15]. It is found that the majority of observations for the considered far offshore site have a stability within the range $L \leq -9$ and $L \geq 18$ (this covers at least 90% of all observations for a given hub height wind speed). As will be shown later, conditions within $L \leq -18$ and $L \geq 30$ cause by far most of the fatigue loads, thus those conditions that are not included specifically should not influence the outcome of the results significantly. The 34 classes are defined in terms of $\zeta_h$, ranging from -10 to 5, with a stability class size of 1, and increased density of classes between $-1 \leq \zeta_h \leq 1$ where a class size of 0.1 is adopted. This increased density is adopted since for near neutral conditions atmospheric conditions change rapidly with only a slight change in atmospheric stability.

### 3. PRESCRIBING ATMOSPHERIC CONDITIONS

The atmospheric conditions that are of most importance for the lifetime fatigue loads for non-extreme conditions are wind shear and turbulence, where turbulence is characterized in terms of the turbulence intensity, the turbulence spectrum and the turbulence coherence. The atmosphere is defined following the IEC standards for simulations of case 1, and following [15] for simulations of case 2 and 3. In this section only the primary used equations are shown, for a full derivation one is referred to either of the used references [2] and [15]. For case 1 wind shear and turbulence intensities are defined according to [2], and the turbulence spectra according to [1].

<table>
<thead>
<tr>
<th>Class name</th>
<th>Stability regime ($L$)</th>
<th>Stability regime ($\zeta_h$)</th>
<th>Characteristic $L$</th>
<th>Characteristic $\zeta_h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Unstable</td>
<td>$-100 \leq L \leq -50$</td>
<td>$-1.8 &lt; \zeta_h \leq -0.9$</td>
<td>$L = -75$</td>
<td>$-1.2$</td>
</tr>
<tr>
<td>Unstable</td>
<td>$-200 \leq L &lt; -100$</td>
<td>$-0.9 &lt; \zeta_h \leq -0.45$</td>
<td>$L = -150$</td>
<td>$-0.6$</td>
</tr>
<tr>
<td>Near Neutral Unstable</td>
<td>$-500 \leq L &lt; -200$</td>
<td>$-0.45 &lt; \zeta_h \leq -0.18$</td>
<td>$L = -350$</td>
<td>$-0.28$</td>
</tr>
<tr>
<td>Neutral</td>
<td>$</td>
<td></td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>Near Neutral Stable</td>
<td>$200 \leq L &lt; 500$</td>
<td>$0.18 \leq \zeta_h \leq 0.45$</td>
<td>$L = 350$</td>
<td>0.28</td>
</tr>
<tr>
<td>Stable</td>
<td>$50 \leq L &lt; 200$</td>
<td>$0.45 \leq \zeta_h \leq 1.8$</td>
<td>$L = 125$</td>
<td>0.72</td>
</tr>
<tr>
<td>Very Stable</td>
<td>$10 \leq L &lt; 50$</td>
<td>$1.8 \leq \zeta_h \leq 9$</td>
<td>$L = 30$</td>
<td>3</td>
</tr>
</tbody>
</table>

Table II. Overview of case specifications for the fatigue load assessment. The number of simulations corresponds to the amount of simulations required for each wind turbine component as elaborated upon in section 3.

Table III. Stability classification for simulation case 2, taken from [13].
For wind shear it is common procedure to use either a power law (used for case 1) or a logarithmic shear profile (used for case 2 and 3), which can be written as

\[
\frac{U(z)}{U_h} = \left( \frac{z}{h} \right)^{\alpha}
\]

and

\[
\frac{U(z)}{U_h} = \ln \left( \frac{z}{z_0} \right) - \Psi \left[ \frac{z}{h} \right]
\]

to define the wind speed at a given height as a function of a reference wind speed. Here \( h \) is a reference height (here the hub height), \( \alpha \) is the power exponent of the power law (here 0.14), \( z_0 \) is the aerodynamic roughness length (here calculated with Charnock’s relation, see [21]) and \( \Psi \) is a stability correction function. The stability correction function differs for stable and unstable conditions, and here the correction function following the free convection limit [22] is used for unstable condition, and the correction function of Holtslag [23] is used for stable condition (see [24] and [15] for validation of these correction functions offshore).

The turbulence intensity is determined at the hub height. For the turbulence intensity, the IEC offshore standards propose that the standard deviation of the wind is a function of the surface roughness and wind speed, and the lateral and vertical turbulence intensity equal respectively 0.7 and 0.5 times the longitudinal turbulence intensity. The turbulence intensity proposed by the IEC corresponds approximately to the 90% percentile [25], which is typical used in wind turbine design. Combined, this corresponds to the following equations:

\[
TI_x = \frac{1}{\ln \left( \frac{h}{z_0} \right)} + 1.84 \frac{I_{ref}}{U_h}
\]

\[
TI_y = 0.7TI_x
\]

\[
TI_z = 0.5TI_x
\]

Here \( I_{ref} \) is the reference turbulence intensity, which equals the mean turbulence intensity observed at wind speed of 15 \( m \) \( s^{-1} \) (here found to be 5.66% for the site considered) and the subscripts \( x, y, z \) denote the longitudinal, lateral and vertical direction. For the simulation cases that incorporate atmospheric stability, the \( \sigma_x \) equations of [15] are combined with the logarithmic shear profile to determine the turbulence intensity at a given height. As is shown in [19], the mean turbulence intensity can be corrected to determine the equivalent turbulence intensity (see Appendix C.4 of [20] for details on the equivalent turbulence), which agrees well with the 90% percentile used in the IEC standards. Combined, the following set of relations is used to define the longitudinal turbulence intensity for case 2 and case 3:

\[
TI_x (\zeta_h < 0) = \frac{A_x \kappa \left( 1 - B_x \zeta_h \right)^{1/3}}{\ln \left( \frac{h}{z_0} \right) - \Psi \left[ \frac{z}{h} \right]} \left[ \epsilon_x^2 + 1 \right]^{0.5m - 0.5}
\]

\[
TI_x (\zeta_h > 0) = \frac{A_x \kappa \left( 1 + C_x \zeta_h \right)^{-1/2}}{\ln \left( \frac{h}{z_0} \right) - \Psi \left[ \frac{z}{h} \right]} \left[ \epsilon_x^2 + 1 \right]^{0.5m - 0.5}
\]

The constants \( A_x, B_x, C_x \) are taken from [15], \( \epsilon_x \) is a constant that equals respectively 0.23, 0.25 and 0.20 for the longitudinal, lateral and vertical wind components, \( \kappa \) is the von Karman constant assumed to be 0.4 and \( m \) is the Wohler exponent. For the turbulence intensity of the lateral and vertical wind component only the constants \( A_x, B_x, C_x \) and \( \epsilon_x \) change, the remainder of Equations 8 and 9 are kept constant. Note that it is assumed that the turbulence intensity is constant with height, which in practice is not true, but the simulation environment considered here does not allow for prescribing the turbulence intensity as a function of height. Also, because the turbulence intensity is a function of \( m \), and \( m \) differs for the three turbine components considered in this study, simulations cases 2 and 3 mentioned in Table II require additional simulations for each wind turbine component considered. As such, whereas the 132 simulations of case 1 suffice for all three wind turbine components, for case 2 and 3 we need respectively 2772 and 13464 simulations to cover the three wind components.

For the turbulence spectrum, the three dimensional Kaimal spectrum is considered [26], which is one of the suggested spectra of the IEC standard. The general form for the spectrum is given as

\[
\frac{f S_x (f)}{\sigma_x^2} = \frac{4f L_x / U(h)}{[1 + 6f L_x / U(h)]^{5/3}}
\]

With \( f \) is the frequency in Hz, \( S_x \) is the x-component spectral energy and \( L_x \) is a turbulent length scale. The IEC standards propose that the turbulent length scale above 60m height equals respectively 340.2m, 113.4m and 27.7m for the longitudinal, lateral and vertical direction. In [15] the spectra is slightly rewritten and it is shown that the length scale depends on stability. After rewriting to confirm to the notation of the Kaimal spectrum as shown in Equation 10, the length
Figure 2. Weibull distribution (upper left panel), stability class distribution (upper right panel) and the joint probability distribution of wind speed and stability (lower panel).

scale $L_x$ equals

$$L_x (L < 0) = 0.041 \frac{h}{D_x [1 - E_x \zeta_h]^{-1/2}} \tag{11}$$

$$L_x (L > 0) = 0.041 \frac{h}{D_x + F_x \zeta_h} \tag{12}$$

where the constants $D_x$, $E_x$ and $F_x$ are taken from [15].

As shown in Equation 1, the lifetime fatigue loads depend on the joint probability distribution of wind speed and stability, which is given by

$$P(U_h, \zeta_h) = P(U_h) P(\zeta_h | U_h) \tag{13}$$

where $P(U_h)$ is the distribution of the hub height wind speed and $P(\zeta_h | U_h)$ is the distribution of stability conditioned by hub height wind speed. If stability is neglected as is done for case 1, one does not consider the probability distribution of stability and hence the distribution of $P(U_h)$ suffices. The wind speed and stability distributions considered in this
study are based on one year of observations data taken in 2012 from the far offshore meteorological mast IJmuiden, located 85 km offshore at N 52°50.89′ E 3°26.14′ in the Dutch North Sea area (see [15] for details of the observation site). The resulting Weibull distribution has a scale parameter of 10.52 and a shape parameter of 2.18. For case 2 the joint probability distribution equals the multiplication of the probability distribution of the wind speed and the relative occurrence of each stability class. Figure 2 shows in the upper panels the distribution of the wind speed and the occurrence of stability conditions, which are used to determine $P(\overline{U}_{h}, \zeta_{h})$ for case 1 and 2. The wind speed and stability distributions are plotted as a function of the 85 m height wind speed (not the hub height wind speed of the 5MW NREL wind turbine) since only at this height sonic anemometers are installed which allow for assessing turbulence characteristics of three wind components. For case 3 the continuous PDF of stability conditionalised by wind speed is approximated with 34 stability classes. Based on [19] it is recognised that $P(\zeta_{h} | \overline{U})$ is approximately Gaussian distributed for each hub height wind speed with distribution parameters depending on wind speed. In recent work Kelly & Gryning [27] modelled the distribution of $L$ by separating the distribution into two tails, one for stable conditions and one for unstable conditions with distinct different characteristics. By definition their model has a peak in the PDF of $L$ at neutral conditions. Although this is appropriate for various observation datasets (as shown in their validation), it is recognised that in this study the conditionalised distribution of $L$ is required which not necessarily has a maximum in the distribution at neutral stratification (i.e. see Figure 1a of [19]). With the distribution parameters taken from [19], the joint probability distribution of wind speed and stability can be obtained as shown in Figure 2, which will be used in assessing the fatigue loads for case 3.

Comparing the stability class distribution and the joint probability distribution of stability and wind speed, note that adopting the stability classification of Table III results in the classification of many stable and very stable conditions for wind speeds ranging from 1 to 10 m s$^{-1}$. In contrary, the joint probability distribution shows there are predominantly unstable conditions for these wind speeds. This difference is caused by the choice of class boundaries in Table III, and conditions with $-50 \leq L \leq 0$ are neglected in the classification. It can be seen that such conditions (which equal $\zeta_{h} \leq -1.8$) in fact occur very frequently. It is expected that neglecting these unstable conditions in the classification system of simulation case 2 will have a significant impact on the simulated lifetime fatigue loads.

4. FATIGUE LOAD ASSESSMENT

To understand the importance of the dynamic coupling of wind shear and turbulence for fatigue load assessment, first the dependence of the fatigue load of various turbine parts on atmospheric stability is assessed. As will be shown, the fatigue load of the various turbine components depend differently on atmospheric stability since the sensitivity of these components to respectively wind shear and turbulence differs. Next the bending moment spectra of the specific turbine components considered in this study are shown to assess if the variation of the bending moments occur primarily at multiples of the rotational frequency, at eigenfrequencies of the turbine components or at other frequencies. Since fatigue is caused by varying loads, the spectra can be used to reason if wind shear or turbulence is expected to cause the majority of turbine fatigue loads (although clearly the spectra cannot be substituted for fatigue loads directly, it serves as an indication). In the last section the lifetime fatigue loads are compared for the three cases specified earlier, and a methodology is proposed how to incorporate stability in fatigue load assessment in a computationally efficient way.

4.1. Sensitivity of fatigue loads to atmospheric stability

The results of case 3, including the continuous distribution of stability, are used for the sensitivity analyses to consider as much stability conditions as possible. Only the equivalent loads of the blade root flapwise, the rotor out of plane and tower base fore-aft bending moment are shown in detail since the remaining loads are predominantly caused by gravitational forces and turbulence. The coupling between wind shear and turbulence is thus far less relevant for the loads not shown in detail in this section. Figure 3 shows in the left panels the equivalent load as a function of hub height wind speed and atmospheric stability for the blade root, the rotor and the tower base. The right panels show the equivalent load multiplied with the joint probability distribution of hub height wind speed and atmospheric stability, indicating which combination of hub height wind speed and atmospheric stability contributes most to the lifetime fatigue loads of the specific wind turbine components.

For the blade root flapwise equivalent load it is found that the highest loads occur for a combination of very strong wind speeds and strong unstable conditions. There is a clear tendency that for a given atmospheric stability the blade root equivalent load increases with increasing wind speeds. The effect of atmospheric stability however is less straight forward, and for a given hub height wind speed there is typically a minimum in the blade root equivalent load for near neutral conditions. When the atmosphere changes from neutral to unstable conditions the equivalent loads increase. For a changing atmosphere from neutral to stable conditions a similar result is found (see mainly for the contour of 2600 kNm), though for low wind speeds the increase in equivalent load is limited. Note as well that for very strong stable conditions (where $\zeta_{h} > 3$) equivalent loads actually decrease slightly with increasing stability (this is best seen for $\overline{U}_{h} > 20$ m.
Figure 3. Equivalent load of the blade root (upper panels), rotor (middle panels) and tower base (lower panels) as a function of hub height wind speed and atmospheric stability (left panels, $F_{EQ}$) and the same equivalent load multiplied with the joint probability distribution of wind speed and stability (right panels, $F_{EQ}P(U_h, \zeta_h)$).
s$^{-1})$. The included contour line of 2600 kNm also shows that the blade root equivalent loads obtained for strong unstable conditions (with $\zeta_h = -10$) and $U_h = 12$ m s$^{-1}$ are equal to the equivalent loads experienced for stable conditions (with $\zeta_h = 5$) and a hub height wind speed of 21 m s$^{-1}$. This serves as an indication of the substantial influence of atmospheric stability on the equivalent loads experienced by the blade root, at least in flapwise direction. After multiplication of the equivalent load distribution with the joint probability distribution of wind speed and atmospheric stability it is found that those situations that result in the highest equivalent load hardly contribute to the lifetime equivalent loads experience at the blade root since such conditions do not occur frequently. Instead, those conditions that occur frequently (near neutral conditions with $10 < U_h < 15$) contribute most to the lifetime equivalent loads. This is also shown by the similarity between the lower panel of Figure 2 and the upper right panel of Figure 3. It is expected based on these results that both wind shear and turbulence are significant for the blade root flapwise loads, since the equivalent loads tend to increase if the atmosphere changes from neutral to stable (here wind shear increases) and the equivalent loads also increase if the atmosphere changes from neutral to unstable (here turbulence levels increase).

For the rotor out of plane equivalent loads it is found, similarly as for the blade root flapwise loads, that highest loads occur for high wind speeds in combination with very strong unstable conditions, and the rotor loads also increase with increasing hub height wind speeds. It is also found, similar as was found for the blade root loads, that for a given hub height wind speed a minimum equivalent load is found for near neutral conditions, and loads increase if the atmosphere becomes either unstable or stable stratified. This increase in rotor equivalent loads for increasing stability is also found for low wind speeds (i.e. see the contour of 800 kNm), and it is found again that if the atmosphere becomes very stable stratified with $\zeta_h > 0$ equivalent loads decrease with increasing stability, though the decrease is minimal. After multiplication of the rotor equivalent loads with $P(U_h, \zeta_h)$ similar results are found as where shown for the blade root loads, and those conditions that occur most frequently also contribute most to the lifetime loads. For the rotor loads however there is a small increase in the contribution of stable conditions to the lifetime equivalent loads compared to the blade root loads. Based on these results there clearly is similarity between the dependence of blade root and rotor loads on atmospheric stability and hub height wind speed.

The tower fore-aft equivalent loads show a similar dependence on hub height wind speed, and an increase in hub height wind speeds tend to result in higher tower loads. It is also found in agreement with the previous results that for a given hub height wind speed the highest tower loads occur when the atmosphere is very unstable stratified, however the lowest loads do not occur for neutral conditions but for stable conditions. The decrease in loads is in fact so substantial that similar equivalent loads occur for strong unstable ($\zeta_h = -10$) and stable ($\zeta_h = 5$) conditions at hub height winds speeds of respectively 7 and 24 m s$^{-1}$. Based on this severe decrease in tower loads for increasing stable stratifications, and recognizing that for stable conditions wind shear increases substantially, it is concluded that wind shear has little impact on tower loads. This is in line with the hypothesis of [10], which states wind shear does not cause a dynamic moment at the tower base. Incorporating the joint probability distribution of wind speed and stability shows similar results as found for the blade root and rotor loads with the exception that stable conditions with $\zeta_h > 1$ hardly contribute to the lifetime tower base equivalent loads.

Overall it is found that highest loads for all turbine components considered in this study occur for strong wind speeds and very unstable conditions, however since such conditions hardly ever occur the relative contribution of these conditions to the lifetime fatigue loads is limited. Wind shear is expected to be important for the blade root and rotor loads, whereas turbulence is expected to be important for all three components considered, seeing that for all three components loads increase substantially if the atmosphere changes from neutral to unstable stratification. The site specific joint probability distribution of wind speed and stability has a significant impact on the estimated lifetime equivalent loads, and if one would consider a different site with more stable conditions results would likely also differ substantially. Results are in line with those presented in [10], who found qualitatively similar results using other turbulence and wind shear models. During resource assessment it is thus of importance that an accurate joint probability distribution of wind speed and atmospheric stability is obtained to estimate the lifetime loads experienced by various wind turbine components.

<table>
<thead>
<tr>
<th>Period/frequency type</th>
<th>Frequency [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1P rotational frequency</td>
<td>0.13</td>
</tr>
<tr>
<td>2P rotational frequency</td>
<td>0.26</td>
</tr>
<tr>
<td>3P rotational frequency</td>
<td>0.40</td>
</tr>
<tr>
<td>First flapwise blade eigenfrequency</td>
<td>1.10</td>
</tr>
<tr>
<td>Second flapwise blade eigenfrequency</td>
<td>4.07</td>
</tr>
<tr>
<td>First fore-aft tower eigenfrequency</td>
<td>0.28</td>
</tr>
<tr>
<td>Second fore-aft tower eigenfrequency</td>
<td>1.88</td>
</tr>
</tbody>
</table>

Table IV. Rotational frequencies and eigenfrequencies of the turbine for $U_h = 7$ m s$^{-1}$. 

<table>
<thead>
<tr>
<th>Rotational frequencies and eigenfrequencies of the turbine for $U_h = 7$ m s$^{-1}$.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotational frequencies and eigenfrequencies of the turbine for $U_h = 7$ m s$^{-1}$.</td>
</tr>
</tbody>
</table>
Figure 4. Spectra of the blade root flapwise bending moment (upper panel), the rotor out of plane bending moment (middle panel) and tower fore-aft bending moment (lower panel) determined for a hub height wind speed of 7 m s$^{-1}$. Stable corresponds to $\zeta_h = 2$, unstable to $\zeta_h = -5$. 
4.2. Spectral analyses of bending moments

With the previous assessment it is clear for which conditions, in terms of hub height wind speed and atmospheric stability, highest equivalent loads occur for various components, and which conditions contribute most to the lifetime equivalent loads experienced by these turbine components. Although one can consider previous results as an indication of the importance of wind shear and turbulence for the loads of these components, it is decided to perform a spectral analyses of the bending moments experienced by the turbine components as well. Although the spectra of the bending moments do not translate directly into equivalent loads, fatigue is caused by variation of the bending moment, and changes in the spectra can be used as an indication which physical processes (i.e. shear or turbulence) contribute to the fatigue of turbine components. An overview of relevant frequencies is shown in Table IV. In the following analyses the same three components are considered as previously discussed, and spectral analyses are carried out for a hub height wind speed of 7 m s$^{-1}$ with an atmospheric stability of $C_{\tau_h} = 2$ for stable conditions and $C_{\tau_h} = -5$ for unstable conditions.

For the interpretation of the turbulence spectra we consider the following reasoning. It is expected that spectral peaks will be found at rotational frequencies (1P in a rotational frame, 3P in a fixed frame) as well as at eigenfrequencies of turbine components. If we would only change the turbulence intensity, we would expect as a result that the spectra of the bending moment will shift upward (for increasing turbulence levels) or downward (for decreasing turbulence levels), since turbulence acts on all frequencies. A change in wind shear however not necessarily influences the spectrum considered. If wind shear is of importance for the bending moment considered, then an increase in wind shear and decrease in turbulence levels (thus from unstable to stable conditions) will cause the spectral peak at rotational frequencies to become narrow and sharp defined. For such conditions the majority of variation in the bending moment occurs at the exact rotational frequency where a peak is observed. If however wind shear is not of importance for the component consider, then the variation in the bending moment will occur at all frequencies, not only at the rotational frequencies. This is expected to be valid even if there is high wind shear and little turbulence. The spectra can thus be used to make an interpretation of the importance of wind shear for the components considered. The turbulence spectra obtained from the simulations are shown in Figure 4.

For the blade root flapwise bending moment the spectra of stable and unstable conditions show distinct peaks at the 1P and 2P frequencies. The small peaks that occur at higher frequencies in fact correspond to two eigenfrequencies of the blade. For the rotor out of plane bending moment similar results are found, though the peaks at higher frequencies are limited. For both components the 1P and 2P peaks differ in shape (width and height) for the spectra corresponding to stable and unstable conditions. At the same time the spectra obtained for the unstable atmosphere are shifted vertically since the turbulence intensity increases for unstable conditions. The combined interpretation is that the blade root flapwise bending moment and the rotor out of plane bending moment are influenced substantially by both wind shear and turbulence.

The spectra of the tower fore-aft bending moment has a relatively broad peak at the 3P frequency. The majority of this 3P spectral peak does not differ substantially in shape for the stable and unstable spectra, in contrary to the pronounced 1P and 2P peaks of the blade root flapwise and rotor out of plane bending moments. There is however for stable conditions a slight narrow peak at the exact 3P frequency. This distinct small peak might be an indication of a minor shear effect, however the far majority of the tower fore-aft bending moment spectra is simply a vertical shift, which is caused by a substantial increase in turbulence intensity for unstable conditions. As such, while wind shear is of importance for blade root and rotor loads, it does not appear to be of significant influence for tower loads. This corresponds to previous results, where it was found that tower fore-aft equivalent loads significantly decrease if the atmosphere changes from unstable to stable stratification. Since turbulence is of importance for the tower fore-aft loads, it is surprising that there is no distinct peak visible at the first tower fore-aft eigenfrequency. In contrary, at approximately 1.1 Hz there is a spectral peak not related to any of the multiples of the rotational frequency. In scope of the presented eigenfrequencies in Table IV, it is unclear what causes the spectral peak specifically at 1.1 Hz, which should be studied in future research. Still it is clear that turbulence is the driving cause of the tower fore-aft loads.

The results obtained from the spectral analyses are in line with the preliminary interpretation discussed before: all three wind turbine components are substantially influenced by turbulence, but wind shear is only relevant for the blade root flapwise bending moment and the rotor out of plane bending moment.

4.3. Lifetime fatigue loads

The lifetime fatigue loads that a 5MW NREL wind turbine would experience for the wind speed and stability distribution is determined for the three specified cases. The left panel of Figure 5 shows the relative lifetime fatigue loads of all components considered in this study, and the percentages are also shown in Table V. The absolute numbers are not relevant since we consider a hypothetical wind turbine, and fatigue loads are converted to equivalent loads for comparison purposes. For each component the determined lifetime equivalent load is normalised with those obtained in case 3. It is found that lifetime equivalent loads of the blade root (both in flapwise and edgewise direction) are comparable for case 1 (IEC standards) and case 3 (continuous stability distribution). Using the distinct stability classes results in an underestimation of the flapwise fatigue loads by 6%, while edgewise loads are similar as for both other cases. The similarity between the three cases for determining the lifetime blade root edgewise equivalent loads is caused by the dominant contribution of
Fatigue loads offshore

Figure 5. Relative lifetime equivalent loads of various wind turbine sections (left panel) based on the specified cases, and the sensitivity of the lifetime fatigue loads to the distribution of stability.

<table>
<thead>
<tr>
<th>Case</th>
<th>Blade root flap</th>
<th>Blade root edge</th>
<th>Rotor out of plane</th>
<th>Rotor in plane</th>
<th>Tower fore-aft</th>
<th>Tower side-side</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100.8</td>
<td>100.6</td>
<td>106.3</td>
<td>113.7</td>
<td>127.5</td>
<td>111.3</td>
</tr>
<tr>
<td>2</td>
<td>93.8</td>
<td>99.5</td>
<td>90.2</td>
<td>88.4</td>
<td>87.4</td>
<td>94.8</td>
</tr>
<tr>
<td>3</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

\[ \zeta_h = \zeta_h \]

\[ \zeta_h = 0 \]

\[-0.5 \mu \]

\[ 0.5 \sigma \]

Table V. Equivalent load for various wind turbine components for the cases considered, relative to the loads obtained for case 3.

The lifetime equivalent loads depend strongly on the relative occurrence of stable and unstable conditions and as such the sensitivity of lifetime fatigue loads to the distribution of atmospheric stability is assessed briefly. For this assessment the distribution of stability for each hub height wind speed is adjusted artificially by either imposing pure neutral conditions or by changing the mean or standard deviation of stability for each hub height wind speed. Results are shown in the right panel of Figure 5 and in Table V. The bar in the right panel corresponding to the mean stability will be elaborated upon in the next paragraph. Here it is shown that if one would consider a site with purely neutral conditions the rotor out of plane loads decrease by 4 to 8% for most turbine components besides the rotor out of plane loads. This decrease is caused by a typical reduction in turbulence levels compared to the conditions observed in reality, where unstable conditions occur most frequently (see the lower panel of Figure 2). If the mean stability for each hub height wind speed is multiplied by a factor -0.5 (thus from strong unstable to slight stable, indicated by -0.5 x \( \mu \) in the legend of Figure 5) loads decrease substantially for the rotor in plane and tower fore-aft loads. When the standard deviation of the stability distribution is multiplied by a factor 0.5 (indicated by 0.5 x \( \sigma \) in the legend) loads differ by about 2-7% from those determined with the original observation data. Combined this shows that it is important to recognise the offshore atmosphere is not neutral stratified by default, and it is important to accurately determine probability distribution parameters of atmospheric stability.

gravitational loads, and shows shear and turbulence have little effect on the lifetime blade root edgewise loads. The out of plane and in plane rotor loads are overestimated by the IEC by respectively 6% and 14%, while using the seven stability classes results in an underestimation of respectively 10% and 112%. The fore-aft tower loads are overestimated by 28% by the IEC, and underestimated by 112% following the stability classes, while the side-side tower loads are overestimated by 11% by the IEC, and underestimated by 5% following the stability classes. It is recognised that if hydrodynamic loads would be included differences in tower loads would likely be smaller between the three cases.
Figure 6. Equivalent stability as a function of hub height wind speed for the blade root loads (left panel), rotor loads (middle panel) and tower loads (right panel).

In [19] a methodology is proposed to define an equivalent stability. The equivalent stability is defined as the stability for which one computes the exact same equivalent load as if one would perform a full set of load simulations, represented in this study with the 34 stability classes of case 3. The equivalent stability is thus a function of hub height wind speed. It is suggested in [19] that the mean observed stability for each wind speed resembles a good approximation of the equivalent stability for the blade root loads. Figure 6 shows the equivalent stability for the wind turbine components considered in this study. As can be seen, the mean stability corresponds quite well to the equivalent stability for the blade root flapwise loads and the tower side-side loads, but not for the other components. For the rotor out of plane loads results deviate significantly, and the equivalent stability is much more unstable compared to the mean stability, even for very strong wind speeds. For the remaining components the equivalent stability for wind speeds above 15 m s$^{-1}$ corresponds well to the mean stability, with deviations of $\zeta_h = \pm 0.2$ at most. For wind speeds below rated the equivalent stability differs significantly more from the mean stability. As such, it is concluded that for each component assessed in a fatigue study one should consider a specific equivalent stability. For comparison purposes, the lifetime fatigue loads that one would obtain using the mean stability as a representative substitute for the equivalent stability is included in the right panel of Figure 5. As can be seen, for most components it would be an improvement to consider the mean stability instead of 7 distinct stability classes,
and only for the rotor out of plane loads the results are worse. It therefore appears that for fatigue load assessment, one might be able to neglect the specification of stability classes and incorporate only the mean stability in the load assessment. This significantly reduces the computational demand of fatigue load assessment if one wants to incorporate atmospheric stability.

It is assumed in this study that since the representation of the atmosphere is most elaborate when considering a continuous distribution of stability, the resulting simulated equivalent loads of case 3 correspond best to equivalent loads experienced by a wind turbine in reality. It clearly is of importance to validate if this is indeed true, however this falls outside the scope of this research.

5. DISCUSSION

From the previous results it is found that if one follows the IEC standards one will overestimate the fatigue loads for all wind turbine components considered in this study. Based on the used equations for wind shear and the longitudinal turbulence intensity one can find that the relations that incorporate stability (Equations 4, 8 and 9) frequently result in higher wind shear or turbulence intensity compared to the relations prescribed by the IEC (Equations 3 and 5). As such one cannot conclude that the IEC standards simply overestimate wind shear or turbulence levels. As a clarification, Figure 7 shows wind shear from observation data taken from [15]. One can see here that indeed the determined shear and turbulence levels following the IEC are not by default too strong compared to either the observation data or the stability dependant relations. For stable conditions shear is frequently higher compared to IEC standards, and for unstable conditions turbulence is frequently higher compared to the IEC standards. For neutral conditions however (the intersection of the blue and red line in Figure 7), both wind shear and the turbulence intensity are less than the conditions prescribed by the IEC standards. Besides, whenever wind shear is high turbulence is low (upper left corner of Figure 7) and vice versa when turbulence levels are high wind shear is limited (lower right corner of Figure 7). There is never an occurrence of both high wind shear and high turbulence levels (upper right corner of Figure 7). This shows that indeed wind shear and turbulence are coupled, and by considering atmospheric stability this coupling can be included in wind turbine load assessment.

When adopting the stability classes the dynamic coupling is included, however for the majority of wind turbine components fatigue loads are underestimated compared to considering a continuous distribution of stability. This is primarily caused by the choice of class boundaries, since stable conditions up to $\zeta_h = 9$ and unstable conditions up to $\zeta_h = -1.8$ are chosen as the stability limits.

From the load figures shown in this research it is evident that unstable conditions of $-10 < \zeta_h < -1.8$ contribute significantly to the lifetime fatigue loads, while for very stable conditions with $\zeta_h > 2$ fatigue loads are limited. As
such incorporating the arbitrary choice of class boundary limits causes an underestimation of lifetime fatigue loads, and it is recommended to include more significant unstable conditions in fatigue load assessment as well.

It is recognised that the results obtained in this study are wind turbine specific, and results might differ if the wind turbine design is changed. Especially the material considered for the various wind turbine components are of crucial importance since the results are certainly dependant on the choice of the Wöhler exponent \( m \). The equivalent load \( F_{EQ} \) obviously depends on \( m \) (see Equation 2), but the equivalent turbulence for cases 2 and 3 (i.e. the stability dependant cases) is a function of \( m \) as well (see Equations 8 and 9). If one would consider materials that correspond to a lower Wöhler exponent, for example welded steel instead of cast iron for the hub, then the equivalent turbulence would decrease. Since the equivalent load ranges are in first approximation linearly proportional to the standard deviation of the wind [20], the equivalent load would also decrease (besides the obvious change based on Equation 2). It would therefore be valuable to assess the sensitivity of the results presented in this study to the Wöhler exponent and specific wind turbine designs, however this falls outside the scope of the current research.

6. CONCLUSION

Wind turbine fatigue loads are predominantly caused by wind shear and turbulence levels, which both are influenced by atmospheric stability. It is shown that the offshore site considered is not neutral stratified by default, especially for low wind speeds. The impact of atmospheric stability on wind turbine fatigue loads is assessed for the 5MW NREL wind turbine for three wind turbine components. For all three components highest loads occur when the atmosphere is unstable stratified since for such conditions turbulence levels are high. Fatigue loads decrease when the atmosphere changes from an unstable to a neutral stratification since turbulence levels decrease and wind shear does not increase substantially. When the atmosphere becomes stable stratified, wind shear rapidly increases while turbulence levels rapidly diminish. The impact on fatigue loads differs for the three components considered. The tower loads decrease strongly when the atmosphere becomes stable stratified, which indicates shear is not contributing substantially to the tower loads. The blade root flapwise loads and rotor loads increase if the atmosphere becomes stable stratified, but if the atmosphere becomes very stable this increases in simulated fatigue loads stops.

The lifetime fatigue loads experienced by a wind turbine depend strongly on the joint probability distribution of hub height wind speed and atmospheric stability, and typically IEC standards are followed in which atmospheric stability is neglected, which has significant benefits in terms of computational demands for the load simulation. One can also decide to adopt a limited set of stability classes with arbitrary class boundaries. In this study both approaches are compared to a computational heavy set of simulations where the continuous distribution of stability is approximated. Here it is assumed that fatigue loads simulated with the continuous distribution of stability are most comparable to reality, however there clearly is a need for validation with fatigue load observations. It is found that if one neglects atmospheric stability following the IEC standards lifetime fatigue loads are overestimated, while adopting several stability classes results in an underestimation of lifetime fatigue loads. The overestimation by the IEC standards is not caused by conservatism in wind shear or turbulence levels. Instead, the coupling of wind shear and turbulence by atmospheric stability is missing. By incorporating atmospheric stability in the fatigue load assessment one prevents simulating an atmosphere with both high levels of wind shear and turbulence. This coupling is included in the load assessment when stability is considered in several stability classes, however the classification system used in this study neglected strong unstable conditions with \( \zeta_h < -1.8 \). Such conditions were found to occur frequently at the site considered here, and for such conditions typically highest fatigue loads occur. As such, neglecting strong unstable conditions in fatigue load assessment results in an underestimation of the lifetime fatigue loads experienced by a wind turbine.

If one approaches the continuous distribution of atmospheric stability with many small stability classes one approaches reality at the cost of heavy computational expenses. It is found that one can significantly reduce computational expenses by adopting one mean stability for each hub height wind speed. The error in lifetime fatigue loads does not increase substantially compared to using several stability classes. This approach has the same computational expenses as if one follows the IEC standards, but the error in lifetime fatigue loads is significantly reduced, especially for the tower loads. Combined, there are significant benefits in considering atmospheric stability in a smart and computational effective way in wind turbine fatigue load assessment.

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