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Atmospheric stability and its influence on wind turbine loads

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Abstract. Simulations of wind turbine loads for the NREL 5 MW reference wind turbine under diabatic wind conditions are performed for mean wind speeds between 3 – 16 m/s at the turbine hub height. The loads are quantified as the cumulative sum of the damage equivalent load for different wind speeds that are weighted according to the wind speed and stability distribution. It is observed that atmospheric stability influences the tower and rotor loads. The difference in the calculated tower loads using diabatic wind conditions and those obtained assuming neutral conditions only is approximately 16%, whereas the difference for the rotor loads is up to 11%. The blade loads are hardly influenced by atmospheric stability, where the difference between the calculated loads using diabatic and neutral input wind conditions is less than 1%. The wind profiles and turbulence under diabatic conditions have contrasting influences on the loads, e.g. under stable conditions, loads induced by the wind profile are larger due to increased wind shear, whereas those induced by turbulence are lower due to less turbulent energy. The tower base loads are mainly influenced by diabatic turbulence, whereas the rotor loads are influenced by diabatic wind profiles. The blade loads are influenced by both, diabatic wind profile and turbulence, that leads to nullifying the contrasting influences on the loads. The importance of using a detailed boundary-layer wind profile model is also demonstrated. The difference in the calculated blade and rotor loads is up to 6% and 8% respectively, when only the surface-layer wind profile model is used in comparison to those obtained using a boundary-layer wind profile model. Finally, a comparison of the calculated loads obtained using site-specific and IEC wind conditions is carried out. It is observed that the IEC loads are up to 75% larger than those obtained using site-specific wind conditions.

1. Introduction

Wind turbines are designed to withstand fatigue and extreme loads during their lifetime of approximately 20 years \cite{1}. Amongst different factors that cause fatigue loading, atmospheric turbulence and wind profile have significant influences. The IEC standards \cite{1} prescribe a range of wind conditions between the cut-in and cut-out wind speeds under which the turbine has to operate. These input conditions are prescribed only for neutral atmospheric stability. For many years it has been a matter of great interest in the wind energy community as to whether atmospheric stability influences wind turbine loads significantly. To this extent several studies have been carried out \cite{2, 3, 4, 5, 6, 7} mainly using statistical techniques with differing conclusions. \cite{8} performed simulations under steady winds, and provided further motivation to perform full-scale load calculations. Recently, \cite{9} performed a detailed simulation study of wind turbine loads under diabatic conditions, where only free stream wind was considered.

Two diabatic wind profile models are investigated, the first is using the standard surface-layer scaling according to Monin-Obukhov theory \cite{10}, and the second is using the more advanced theory developed by \cite{11} that connects the surface layer scaling with the geostrophic drag law.
The main difference between these models is the inclusion of the boundary layer height parameter in [11] that limits the growth of the wind profile length scale above the surface layer. Turbulence is simulated using the Mann model [12] under different atmospheric stabilities. The time-domain aeroelastic code HAWC2 is utilized for the calculation of the loads on various components of the wind turbine. Fatigue loads are quantified using the concept of Damage Equivalent Loads ($D_{EQ}$), which for a given arbitrary number of load cycles would produce the same fatigue damage as that of the sum of the individual load cycles. Simulations are used to compare the load cases.

Section 2 of this article gives a description of the sites and the measurements used. Section 3 describes the wind climate, wind profile models and turbulence. Section 4 briefly explains the aero-elastic simulation tool used in this study. The load calculations are described in section 5. Finally, we conclude our work in section 6.

2. Site Description
Load calculations are performed based on turbulence and mean wind speed data at Høvsøre, which is the Danish National Test Center for Large Wind Turbines. Based on data availability the range of mean wind speeds chosen is 3 – 16 m/s. Under diabatic conditions we do not always have sufficient data until 16 m/s.

A reference meteorological mast (met-mast), which is 116.5 m tall and intensively equipped with cup and sonic anemometers, is located at the coordinates 56°26′26″ N, 08°09′03″ E. The site is about 2 km from the West coast of Denmark. The eastern sector is generally characterized by a flat, homogeneous terrain, and to the South is a lagoon. To the North, there is a row of five wind turbines. The sonics are placed on the North booms of the met-mast, resulting in unusable data when the wind is from the South because of the wake of the mast, and from the North because of the wakes of the wind turbines. In order to bin the wind speeds we use the cup anemometers at 80 and 100 m, since the hub height of the turbine is 90 m (refer table 1). The data is selected between March 2004 – November 2009. To comply with terrain homogeneity and avoid aforementioned wake conditions, we restrict our analysis to a directional sector of 50° – 150°. Atmospheric stability is characterized using the standard surface-layer length scale $L$, commonly known as the Monin-Obukhov length. $L$ is estimated using the eddy covariance method [13] from the sonic measurements at 20 m. The aerodynamic roughness length $z_0 = 0.014$ cm. More details of the site and instrumentation can be found in [14].

3. Input wind conditions
Fig. 1 shows the distribution of atmospheric stability with respect to the mean wind speed and the wind speed histogram at Høvsøre. We observe that low wind speeds are dominated by diabatic conditions, whereas high wind speeds are dominated by neutral conditions. It would thus seem that assuming neutral conditions for load calculations at high wind speeds is probably alright, but for low wind speeds stability can influence the results. On the other hand, fatigue damage is mainly caused by loads induced at high wind speeds (approximately greater than 12 m/s) [15]. Considering that there are less number of observations of high wind speeds (Fig. 1b), the relation between atmospheric stability and loads seem quite complex, and detailed load simulations are necessary.

3.1. Wind profile
Two wind profile models are studied. The first is the diabatic wind profile in the surface layer [16] and the second is the model by [11] that is valid for the entire boundary layer. The theoretical details of the corresponding models can be found in [17, 9].

The comparison between the measured and modelled wind profile is shown in Fig. 2. The $x$-axis is normalized by the friction velocity ($u_*$) in order to include the comparison for all mean wind speeds. We observe that there is considerable wind shear under stable conditions
Figure 1: Distribution of atmospheric stability and mean wind speed at Høvsøre

(a) Stability distribution

(b) Histogram

Figure 2: Measured and modelled surface-layer and boundary-layer wind profiles for different stability classes. The markers indicate measurements and the lines indicate the models. The unstable, neutral and stable wind profiles from the models are represented by dashed, solid and dash-dot lines respectively.

(a) surface-layer theory

(b) Boundary-Layer model by [11]

as compared to the unstable and neutral conditions, which is captured in the model by [11] reasonably well (Fig. 2b). In the surface-layer theory, the length scale increases with height without bounds, but in [11] it is limited by the boundary layer height. The differences between the two models are most pronounced under very stable conditions, where [11] fits the measurements slightly better (Fig. 2b). For unstable conditions, both models agree well with the measurements, which indicates that limiting the length scale with boundary layer height may not be necessary. [17] gives a more detailed comparison between the two models.
3.2. Atmospheric turbulence

We quantify atmospheric turbulence using the Mann model [12]. This model is described by the three model parameters, $\alpha \epsilon^{2/3}$, which is a product of the spectral Kolmogorov constant $\alpha$ and the rate of viscous dissipation of specific turbulent kinetic energy to the two-thirds power $\epsilon^{2/3}$, a length scale (wavelength of the eddy corresponding roughly to the maximum spectral energy) $L_M$ and an anisotropy parameter $\Gamma$. Thus any variation of turbulence with respect to specific site conditions means variation of $\alpha \epsilon^{2/3}$, $L_M$ and $\Gamma$. The quite complicated equations of the spectral tensor model may be found in [12].

The Mann model [12] is a semi empirical model that is strictly valid only for neutral conditions in the surface layer. Nevertheless, in this study we perform a $\chi^2$-fit of the Mann model [12] with the measurements to obtain $\alpha \epsilon^{2/3}$, $L_M$ and $\Gamma$ (using Eq. 4.1 from [12]) under different atmospheric stabilities at 80 and 100 m for mean wind speeds between 3 – 16 m/s. Ideally, we would like to fit the model with the measurements at 90 m, which is the hub height of the turbine (refer table 1). Unfortunately, at Høvsøre we do not have sonic measurements at 90
m, and hence, $\alpha \epsilon^{2/3}$, $L_M$ and $\Gamma$ are linearly interpolated between 80 and 100 m to obtain the same at 90 m. We assume that since the difference between the measurement heights is only 20 m, the model parameters are locally linear (refer Fig. 4 in [18]) and the errors introduced in the two-point turbulence statistics by linear interpolation of the parameters would be negligible. It should also be noted that the performance of the Mann model [12] has not been tested in predicting coherences, i.e. two-point statistics under diabatic conditions, but in this study we assume that the coherences can be predicted under all conditions using this model.

Fig. 3 shows variation of $\alpha \epsilon^{2/3}$, $L$ and $\Gamma$ with the mean wind speed under diabatic conditions. In Fig. 3a it is observed that under all stabilities the energy dissipation rate increases with the increase in the mean wind speed. This is mainly because the turbulent energy production increases with increasing mean wind speeds. For a fixed height $z$, neutral surface-layer scaling dictates that $\epsilon^{2/3} \propto \bar{u}^2$, which is reflected in Fig. 3a. The neutral conditions have the largest dissipation rates followed by the unstable conditions. The stable conditions have the smallest rate of dissipation because there is hardly any turbulent energy production. In Fig. 3b a systematic trend is observed with increasing mean wind speeds such that under unstable and neutral conditions the length scales increase, whereas under stable conditions they decrease. The increase in length scales under neutral conditions is in agreement with [18], however the magnitude of increase is much lower than that observed by [18]. More detailed explanation can be found in [9].

4. Description of the simulation environment
The simulations are carried out for mean wind speeds between 3 – 16 m/s with a bin size of 1 m/s. In this way, we can compare the cumulative fatigue loads, and also those varying with the mean wind speed. For the chosen eastern sector we do not have any wind observations above 16 m/s. For each wind speed bin we fit the Mann model [12] with the turbulence measurements from the sonic anemometers and obtain the three model parameters $\alpha \epsilon^{2/3}$, $L_M$ and $\Gamma$. We obtain the wind profile over the entire turbine using the wind profile models described in section 3.1. The three-dimensional wind is then simulated over the entire rotor following [19]. The simulated loads are the blade root flap-wise and edge-wise bending moments, tower base fore-aft bending moments, and the rotor bending moments at the hub.

Fig. 4 shows the coordinate system for the blades, hub, and the tower used in the load calculations. For each blade, the $z$-axis is along the blade, $y$-axis is in the mean wind direction and $x$-axis is in the lateral direction to the blade tip. The blade loads are obtained in the rotating blade coordinate system (subscript B) attached to the blade root. The rotor loads at the hub are obtained in the rotating coordinate system attached to the hub (subscript H). If we consider the initial position of the rotor such that the blade points upwards then the orientation of the axes are the same as that for the blade coordinate system, and rotates with this particular blade. The tower loads are obtained in a fixed coordinate system attached to tower base (subscript T), where the $y$-axis is along the mean wind direction, $x$-axis is in the lateral direction and the $z$-axis is in the vertical direction.

We use the NREL 5 MW reference wind turbine for simulating the turbine loads, which is a fictional representative utility-scale multi-MW wind turbine, used by research teams worldwide to standardize baseline offshore wind turbine specifications, and to quantify the benefits of advanced land- and sea-based wind energy technologies. The details of the turbine are given by [20]. The main characteristics of the turbine are given in table 1. The details of the aeroelastic time-domain code HAWC2 can be found in [21, 22].

5. Load calculations
If we denote $P(L|\bar{u})$ as the distribution of atmospheric stability at given mean wind speed $\bar{u}$ and $P(\bar{u})$ as the distribution of the mean wind speeds, then the cumulative Damage Equivalent
Table 1: Main properties of the wind turbine

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power</td>
<td>5 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</td>
</tr>
<tr>
<td>Rated wind speed</td>
<td>11.4 m/s</td>
</tr>
<tr>
<td>Cut-out wind speed</td>
<td>25 m/s</td>
</tr>
<tr>
<td>Control</td>
<td>Variable speed, collective pitch</td>
</tr>
</tbody>
</table>

Load $D_{EQC}$ is estimated as,

$$D_{EQC} = \sum_{u=3}^{16} \left( \sum_{L=\text{vu}}^{\text{vs}} D_{EQ} \times P(L|\bar{u}) \right) \times P(\bar{u}),$$  

where $D_{EQ}$ is the fatigue damage at each mean wind speed and the limits of $L$ indicate the corresponding probability of atmospheric stability at a given mean wind speed, such that $\text{vu}$ denotes very unstable conditions, and $\text{vs}$ denotes very stable condition. The operating conditions considered are normal power production for the chosen wind speed range. Variations in the load cases are given in table 2. Table 3 gives the normalized $D_{EQC}$ for different cases. The loads are normalized with those from the reference case I. The blade flap-wise and edge-wise loads are defined as the bending moments at the root of the blade along the x and y axis respectively, in the blade coordinate system (Fig. 4). The fore-aft loading of the tower is defined as the bending moment at the base of the tower along the x-axis in the tower coordinate system (Fig. 4). $M_x$, $M_y$ and $M_z$ denote the rotor loads at the hub defined along the x, y and z axis respectively.
Table 2: Load cases

<table>
<thead>
<tr>
<th>Cases</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Diabatic boundary-layer wind profile and turbulence</td>
</tr>
<tr>
<td>II</td>
<td>Neutral boundary-layer wind profile and turbulence</td>
</tr>
<tr>
<td>III</td>
<td>Diabatic surface-layer wind profile and turbulence</td>
</tr>
<tr>
<td>IV</td>
<td>IEC load case, power law exponent = 0.2</td>
</tr>
</tbody>
</table>

Table 3: Normalized $D_{EQC}$ of bending moments

<table>
<thead>
<tr>
<th>Cases</th>
<th>Blade root flap edge</th>
<th>Tower base fore-alt</th>
<th>Rotor loads $M_x$</th>
<th>$M_y$</th>
<th>$M_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>II</td>
<td>0.994</td>
<td>0.996</td>
<td>1.160</td>
<td>0.885</td>
<td>0.996</td>
</tr>
<tr>
<td>III</td>
<td>1.060</td>
<td>1.004</td>
<td>0.987</td>
<td>1.079</td>
<td>1.005</td>
</tr>
<tr>
<td>IV</td>
<td>1.378</td>
<td>1.018</td>
<td>1.749</td>
<td>1.277</td>
<td>1.013</td>
</tr>
</tbody>
</table>

respectively, in the rotating hub coordinate system (Fig. 4). Cases I and II compare the influence of the diabatic boundary-layer wind profile and turbulence on the loads with those obtained by assuming neutral conditions only. Cases I and III compare the differences in the loads obtained by using boundary-layer and surface-layer wind profile models (section 3.1). The turbulence used is the same for both cases. Cases I and IV shows the corresponding comparison with the IEC load case.

The variation of tower loads with respect to mean wind speeds and atmospheric stability is plotted in Fig. 5a. The loads are largest for unstable and neutral conditions, whereas they are significantly smaller under stable conditions (of the order of 2). From our turbulence analysis we observed that for the turbulent energy in the low wavenumber range there is a relatively small difference between the unstable and neutral conditions but a large difference under stable conditions. At smaller length scales the difference in the turbulent energy is relatively small. Hence, the length scales under unstable and neutral conditions that contain larger turbulent energy at low wavenumbers cause more fatigue damage than under stable conditions. Variation of the loads with respect to wind speed is highly non-linear. At about 5 m/s we observe a peak in the loads because at that wind speed the natural frequency of the tower ($\approx 0.33$ Hz) correspond to three times the rotational frequency. At 11 m/s the rated power is reached, and above that wind speed the pitching of the rotor blades causes a decrease of the loads. From table 3 we observe a reduction in calculated tower loads of approximately 16% under diabatic conditions in comparison to those assuming only neutral conditions. By comparing cases I and III, where under diabatic conditions two different wind profile models are used we observe that the tower loads are not influenced significantly ($< 2\%$). The calculated IEC tower loads are significantly larger ($\approx 75\%$) than those obtained by using diabatic turbulence and wind shear, which means that the IEC standard [1] is very conservative in the definition of wind shear and turbulence.

The variation of blade root flap-wise loads with respect to mean wind speeds and atmospheric stability is plotted in Fig. 5b. We observe that the flap-wise loads are increased only slightly (of the order of 1.2) from unstable to stable conditions. It shows that contrasting influence of wind profiles and turbulence under diabatic conditions tend to cancel out the loads. The loads increase with the mean wind speed (Fig. 5b) even after the rated wind speed has reached. This is because wind speed standard deviation increases with the mean wind speed causing greater number of large load range cycles to occur at high wind speeds (refer Fig. 3d). From table 3 we observe that there is a negligible influence on the cumulative flap-wise loads using diabatic wind conditions.
Figure 5: Variation of tower base fore-aft, blade root flapwise and rotor $M_x$ loads with respect to the mean wind speed and atmospheric stability.

(cases I and II). We observe a slightly larger influence of using a different wind shear model, where the loads vary by up to 6% (cases I and III). Using the surface-layer wind profile (case III) we get a large wind gradient under stable conditions thus resulting in large asymmetrical loading as compared to the model by [11] (case I). This effect is more pronounced because at Høvsøre stable conditions dominate over unstable conditions. As observed for the tower base fore-aft loads, the blade root flap-wise loads are significantly larger for the IEC load case (up to 38%) in comparison with those obtained under diabatic conditions (cases I and IV). The blade root edge-wise loads are the least influenced by atmospheric stability, where the difference with neutral conditions is less than 1%. This is mainly because the gravity forces resulting from the mass of the blades are more dominant in producing edge-wise loads as compared to the wind loads. For the same reason we also do not see any influence of using a different wind profile model (cases I and III). Even with the very conservative IEC standard we observe that the variation in the loads is up to 2% only.

The difference between the rotor and blade loads is that the rotor loads are experienced at
the hub due to the combined loading by all three blades, whereas the blade loads are experienced at the respective blade root for each blade. The rotor yaw and tilt loads can be calculated if the azimuth angle is fixed, but in this study the rotor loads are obtained in a rotating coordinate system. Thus, the rotor $M_x$ and $M_z$ loads along $x$ and $z$ axis respectively experience alternating yaw and tilting loads depending on the azimuth position. From table 3 we see that the rotor loads along the $x$ axis ($M_x$) obtained under diabatic conditions are up to 11% larger (cases I and II) than those obtained assuming neutral conditions. The variation of the rotor $M_x$ loads with respect to atmospheric stability and mean wind speeds is plotted in Fig. 5c. We observe that the loads increase significantly with increasing wind speeds when the conditions change from unstable to stable (by a factor of 2). By comparing cases I and III in table 3 it seems that only wind profiles influence rotor $M_x$ loads. The surface-layer wind profile model with a much larger wind gradient in comparison to the wind profile model by [11] induces larger rotor $M_z$ loads. At stable site such as Høvsøre we observe that using the surface layer wind profile model the rotor $M_x$ loads are approximately 8% larger than those obtained using the boundary layer wind profile model [11]. The conservative IEC standards calculate much larger $M_x$ loads (up to 28%) in comparison to the measured wind conditions. The rotor loads along the $z$ axis ($M_z$) are not influenced by atmospheric stability. Taking a closer look at the coordinate system defined for rotor loads (refer Fig. 4) we observe that the moment along the $z$-axis will be induced only due to those blades through which the hub coordinate system does not pass. In Fig. 4 it is then due to the two blades at angle of 120° and pointing downwards. The resulting moment $M_z$ will then be a summation of a positive moment due to one blade and a negative moment due to the other blade. If, say, we had no turbulence and the wind was completely uniform, then $M_z$ would be zero and in principle we would have no rotor loads along the $z$-axis. However, in reality wind profile and turbulence exist, and $M_z$ varies non-linearly with respect to the wind speed. Hence, it will create a differential loading of the two blades as they sweep the rotor area. The magnitude of this differential loading seems to be small. Hence, we get approximately the same $M_z$ under diabatic and neutral conditions (cases I and II). The rotor loads along the $y$ axis ($M_y$) are not influenced by atmospheric stability. This is because the gravity will have a more dominating influence instead of the wind loads, in a similar manner as compared to the blade root edge-wise loads. The difference in the loads in comparison with the IEC standard is up to 1% only (cases I and IV).

6. Conclusions

The influence of atmospheric stability can be considered significant (up to 16%) depending on the component of interest. Wind turbine loads are influenced by wind profile models to a limited extent (up to 8%), and mainly depend on a particular component that we are interested in investigating. The influence of wind profiles and turbulence have contrasting effect on wind turbine loads under diabatic conditions, i.e. under stable conditions the wind gradient is large, which induces larger fatigue loads (as observed in [8]), whereas turbulent energy is small, which induces smaller fatigue loads. It is important to note that a different site with a different stability and wind speed distribution will have different influence on the loads. The IEC standards are extremely conservative in its definition of wind shear and turbulence. The calculated loads using the IEC standard are much larger (up to 75%) in comparison to those obtained using the site specific wind conditions. This presents a case for performing detailed calculations of the loads for all IEC load cases defined in [1]. The goal is to eventually reduce wind turbine costs, and such a study can provide valuable comparisons with the current design standard.

As to whether to include atmospheric stability in load calculations depends on the influence of overestimating the loads on wind turbine costs. A detailed cost analysis is required to make any conclusions about how important atmospheric stability is for wind turbine loads. Also, a detailed investigation is necessary to verify whether the differences in the calculated loads under
diabatic conditions are larger compared to the uncertainties in the load calculations.

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