Influence of atmospheric stability on the load spectra of wind turbines at alpha ventus

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Abstract. Dependence between fatigue loads on a wind turbine located in an offshore wind farm and atmospheric stability was analysed by using measurement data of alpha ventus. An investigation of the fatigue load spectra of the wind turbines was performed enabling a detailed evaluation besides the damage equivalent load. Therefore, load spectra of a turbine in free-stream and a turbine experiencing wake inflow conditions were compared. Atmospheric stability was taken into account by means of the Bulk Richardson number. It was shown, how atmospheric stability affects load spectra of tower base and blade root bending moment. Hereby, it was found that few events of high fatigue loading increase the damage equivalent load (DEL) substantially, especially in unstable conditions.

1. Introduction

Aerodynamically induced fatigue loads on a wind turbine structure are dependent on the inflow conditions; these mainly consist of the wind speed, turbulence intensity and wind shear. An additional factor is thermal atmospheric stability which is related to the wind shear and turbulence intensity. Furthermore, in a wind farm the turbine inter-spacing influences the fatigue loads on wind turbines located in the wake of other turbines.

The relation between atmospheric stratification and fatigue loads on wind turbines has been investigated in the past; for the case of a single wind turbine Sathe et al. [1] [2] and Holtslag et al. [3] performed numerical studies. The authors showed that the inclusion of atmospheric stability increases the accuracy of the load calculation which potentially leads to more accurate design calculations. Wharton et al. [4] analysed the dependence between the power production of a single wind turbine and the atmospheric stratification. An influence of the atmospheric stability on the power production due to the different wind shear profiles and turbulence intensities was shown. Hansen et al. [5] and Barthelmie et al. [6] extended this to a wind farm scenario in which the power production data of utility scale wind farms was analysed and the influence of atmospheric stability on the wake losses was emphasised. In further research, the fatigue loads and their correlation with the atmospheric stability in a wind farm were examined numerically by Lee et al. [7], as well as experimentally using measurement data by Hansen et al. [8]. It was demonstrated that the influence of atmospheric stability on fatigue loads also varies strongly with type of inflow conditions (single wake, multiple wakes).

Studies related to fatigue load assessment of wind turbines often utilise the damage equivalent load (DEL) as an indicator for the strength of fatigue loading. The advantage of this method lies in its simplicity in terms of visualisation and comparability. The fatigue load information of a 10-min time series is entered in one number which is the DEL. However, information about the actual load spectrum
is missing in that kind of analysis and assumptions such as the Stress-cycle (S-N) curve must be made. Consequently, in the presented study a direct comparison of the load spectra of two turbines in line was made using full-scale measurement data of 5 MW turbines located at the German research wind plant alpha ventus. Hereby, the wind direction sector was chosen in a way that the first turbine is in free-stream and the second turbine is affected by the wake of other turbines. This allowed a comparison of the fatigue load spectra for the same global wind conditions whereby the uncertainties are reduced in the evaluation of the loads on a wind turbine in wake. Furthermore, the atmospheric stability was analysed in order to allow conclusions of its influence on the load spectrum.

2. Wind farm database

2.1. General information
A measurement campaign was carried out at the wind farm test site alpha ventus focusing on two of the Adwen AD 5-116 wind turbines named AV7 and AV8 (see Figure 1). The turbines have a rated power of 5 MW at a wind speed of 12.5 m/s, a rotor diameter of 116 m and a hub height of 90 m. The wind direction of main interest is about 270° where the AV7 is in free-stream and the AV8 is in the wake of the AV7. The inter-spacing of the two turbines is approximately 7.3 times the rotor diameter. Meteorological measurements were taken from the Fino 1 met mast (see Figure 1) and contain 10-min statistics of the provided sensor signals.

![Figure 1. Wind farm layout: alpha ventus; north is at the top](image)

2.2. Meteorological measurements
For binning purposes wind speed measurements at hub height (90 m) were used from Fino 1 in the undisturbed sector 190-350°. They were complemented by wind speed measurements of the calibrated nacelle anemometer of turbine AV12 in the sector 350-190°. The same splitting of sectors was also undertaken for the measurement of the wind direction, which is also measured at 90 m at Fino 1.

2.3. Wind turbine structural measurements
The AV7 and AV8 turbines are equipped with strain gauges at the tower base and the blade root. In particular, the following number of sensor signals passed quality checks and could be considered in the investigation:

- a) 5 (AV7) and 3 (AV8) sensors, located at the blade root (radius = 3 m) and distributed over three blades, measuring loads in flap-wise direction
- b) 3 (AV7) and 2 (AV8) sensors, located at the blade root (radius = 3 m) and distributed over three blades, measuring loads in edge-wise direction
c) 4 (AV7) and 3 (AV8) sensors, located at the tower bottom (33.1 m above mean sea level distributed equally over the cross section, measuring tower fore-aft and side-side strains

Due to a failure of one strain gauge at the tower base of turbine AV8, the temperature compensation for the calculations of the resulting fore-aft and side-side bending moments was out of function; therefore, the uncertainty of the load signal was increased.

Plausibility checks and calibration of the sensor signals were done by using specific events such as a nacelle rotation or a rotor rotation during low wind conditions. Several of those events were found distributed over the analysed period. Approximately two years (10/2010 – 11/2012) of 50 Hz high resolution measurement data as well as the data of supervisory control and data acquisition (SCADA) are available. However, because of failures of the measurement system and after filtering the usable data base was reduced to approximately 4300-7000 hours; the actual number depends on the sensor. Additionally, 10-min statistics of the sensor signals were available and used for efficient filtering of the high resolution data.

DELs were calculated for the considered sensor signals based on 10-min time periods by applying Miner’s rule. Hereby the material performance is given by the log-log S-N-curve, also known as the Wöhler curve. The following equation was used to calculate the DEL,

$$ S_{r, eq} = \left( \sum_{i=1}^{n} \frac{S_{m, i}}{N_{eq}} \right)^{1/m} $$

where $S_r$ is the range of a load cycle and $1/m$ is the slope of the S-N line, $N_{eq}$ is the number of equivalent cycles. Different Wöhler exponents for tower $(m = 4)$ and blades $(m = 10)$ were taken into account. The DEL-values were normalised by using the mean DEL which is recorded for the free-stream direction at the wind speed of interest.

For the analysis of load spectra, rainflow counts were conducted following the rules defined in [9]. Subsequently, rainflow counts were carried out for each 10-min event. The load range bins were fixed, implying that they were the same for each 10-min time series. Lastly, a mean value of the number of load cycles was calculated over all 10-min events; this takes into account that a different number of events likely exist for multiple atmospheric stability classes.

### 3. Meteorological data analysis

#### 3.1. Classification of atmospheric stability

Atmospheric stability can be classified by applying the Monin-Obhukov similarity theory. Based on the dimensionless height $\zeta = z/L$, where $L$ is the Obhukov length, distinct classes of the atmospheric stability can be introduced. In order to derive $\zeta$, the Bulk Richardson number approach by Barker and Baxter [10] was used in this study, whereby the Bulk Richardson number is computed as follows:

$$ Ri_b = \frac{g}{\Theta_0} \frac{\Delta \Theta \Delta z}{u^2} \tag{1} $$

$g$ is the gravitational constant, $\Theta$ is the potential temperature, $\Delta z$ is the height between the temperature measurements and $u$ is the wind speed. Rodrigo et al. [11] evaluated various methodologies for stability characterisation and found the Bulk Richardson number to be a robust approach within offshore conditions using a minimum of instrumentation. In contrast to this work, they used a mean height $\Delta z$ of lower and upper temperature measurement.

In offshore conditions the Bulk Richardson number can be related to the dimensionless height via equation (2) which is given by Grachev et al. [12] implying a critical $Ri_b$ of 0.2:

$$ \zeta = \begin{cases} 10 Ri_b & \zeta > 0 \\ \frac{1}{1 - 5 Ri_b} & \zeta \leq 0 \end{cases} \tag{2} $$
\( R_{ib} \) was calculated by using the information at sea surface level via buoy temperature measurements; atmospheric temperature and wind speed measurements were used at 70 m height of the Fino 1 met mast, because temperature measurements were sufficiently available. The limits of the atmospheric stability categories are presented in Table 1.

**Table 1. Classification of atmospheric stability**

| Category     | Range     |
|--------------|-----------|
| Very stable  | 1000 > \( \zeta > 2 \) |
| Stable       | 2 > \( \zeta > 0,2 \) |
| Neutral      | 0,2 > \( \zeta > -0,2 \) |
| Unstable     | -0,2 > \( \zeta > -2 \) |
| Very unstable| -2 > \( \zeta > -1000 \) |

The distribution of the different stability classes in the analysed period is shown in Figure 2. While the stable and unstable classes dominate in low wind speed ranges, the share of the neutral stability class increases with higher wind speeds. Very stable and very unstable conditions occur mainly at wind speeds less than 10 m/s. For the assessment of loads, the very stable and stable cases were united into one stable category to increase the number of overall stable events. Consequently, the very unstable and unstable categories were also merged.

![Figure 2. Atmospheric stability classification (number of samples per bin is given on top of each bin). Left: wind direction 200-290°; Right: wind speed 7-9 m/s](image)

4. **Analysis of statistical loads**
At the beginning of this study, an analysis of DELs was carried out for the turbines AV7 and AV8 to draw a clearer picture of the overall loading situation. Moreover, with this investigation redundancy of the sensor signals was checked. This increases the validity of this study, although the overall amount of events was limited.

In Figure 3 a polar plot of the DEL, compiled for the blade root moment in flap-wise direction, is shown; the wind speed range was set from 7 to 9 m/s and no distinction of atmospheric stability classes was made. It can clearly be seen that loads change with wind direction and are dependent on single or
multiple wake scenarios as well as the distance between the turbines. For example, the overall highest loads occur when the wind comes from the north. In that case wake emitted from 2 turbines hits the AV7 and the AV8. The highest discrepancies in terms of loading for both turbines are detected in the sector 190-350°. While the AV7 experiences free stream conditions, the AV8 is influenced by the wakes of the turbines AV10 (222°, distance 9.9 D), AV7 (272°, distance 7.3 D) and AV4 (313°, distance 10 D). Similar behaviour can be observed for the tower base loads, which are not shown for brevity.

The signal redundancy of the blade root strain gauges in flap-wise direction was verified. Since each blade of both turbines was equipped with strain gauges (at some blades even doubled) a comparison of the signals could be undertaken. According to the statistics the sensor signals of different blades on the same turbine should deliver similar outputs. This holds true even for another turbine (assuming same type) under the same inflow conditions. Therefore, the redundancy of the blade signals for the same turbine was verified as can be seen in Figure 3. For small sectors of approximately free-stream conditions for both turbines (200-210°, 240-258°, 288-296°), similar DELs were detected again (error < 3%).

![Figure 3. DEL of blade root moment in flap-wise direction normalised by mean DEL of free-stream conditions; wind speed range is 7-9 m/s; Bx refers to the blade number.](image)

The following investigation concentrates on the wind direction sector 210-290° for a wind speed range of 7-9 m/s; simultaneously, atmospheric stability was taken into account. DELs of the blade root moment sensors in flap-wise direction are plotted for turbines AV7 and AV8 in Figure 4. First, there is a dependency between the DEL and the wind direction; this is predominant in the case of unstable atmospheric stratification and is likely due to different mean wave heights, which were not studied explicitly. However, according to Westerhellweg et al. [13] mean wave height increases with direction in the range of 210-290°, thus increasing turbulence intensity. This effect was also observed for the tower base moment in fore-aft direction (see Figure 5). The scatter is less for turbine AV7 compared to the blade signals, which is a result of the better quality of the tower base sensors. Unfortunately, this is incorrect for turbine AV8 and a result of the mentioned sensor failure at tower base. In general, the DELs slightly tend to be the highest for unstable atmospheric stability conditions in the considered sector. Additionally, unstable conditions lead to a broader spread in the load data for wake inflow conditions because of stronger wake meandering, which is in agreement with the findings of Hansen et
Similarly, it was noticed that the peak in the load data is more pronounced for stable conditions, in which wake meandering is considered to be moderate [14].

![Figure 4](image1.png)

**Figure 4.** DEL of blade root moment in flap-wise direction normalised by mean DEL of free-stream conditions for different atmospheric stabilities; wind speed range is 7-9 m/s; vertical bars show 0.5x standard deviation. Left AV7, right AV8

![Figure 5](image2.png)

**Figure 5.** DEL of tower base bending moment in fore-aft direction, normalised by mean DEL of free-stream conditions for different atmospheric stabilities; wind speed range is 7-9 m/s; vertical bars show 0.5x standard deviation. Left AV7, right AV8

In order to finalise the statistical load assessment, the relation of DELs with varying wind speeds was examined. In Figure 6 the DEL of the blade root moment in flap-wise direction is plotted over wind speed for wind directions ranging from 210 to 290°. It was found that for lower wind speeds, from 4 m/s to approximately 12 m/s, loads are the highest when unstable stratification is present. Conversely, for
wind speeds above approximately 12 m/s, loads in stable conditions are highest. Nevertheless, it must be mentioned that diabatic atmospheric conditions appeared less often at higher wind speeds, hence reducing the amount of events (see Figure 2). Overall, the results of this examination are in general compliance with the findings in [2], in which the authors conducted numerical simulations.

Figure 6. DEL of blade root moment in flap-wise direction, normalised by mean DEL of free-stream conditions at wind speed 7-9 m/s for different atmospheric stabilities; wind direction sector is 210-290°; vertical bars show 0.5x standard deviation. Left AV7, right AV8

5. Load spectra
Based on the statistical data evaluation in the previous chapter, specific events were picked in order to look at the loading situation in more detail. Rainflow counts were conducted according to the rules

Figure 7. Load spectrum of blade root bending moment in flap-wise direction, normalised by the load range at $10^3$ cycles in neutral conditions at AV7; (-) lines belong to AV7, (:) lines belong to AV8. Left: wind direction 202-208°, wind speed 7-9 m/s. Right: wind direction 202-208°, wind speed 13-16 m/s
defined in section 2.2. Firstly, a plausibility check of the procedure was carried out. Therefore, the wind direction sector 202-208° was chosen, to have free stream conditions for both turbines AV7 and AV8. The related plots are shown in Figure 7. It can be seen, that there is an acceptable agreement between the sensor signals of the turbines AV7 and AV8 in different atmospheric conditions. On the other hand, it must be mentioned that the amount of events was limited in that sector, leading to a jagged curve in the higher load ranges. Load cycles below 0.5 resulted from the averaging procedure. For wind speeds, ranging from 13 to 16 m/s, hardly no events with unstable conditions were found, so they were excluded from investigation.

The blade root bending moments (flap-wise) and tower base moments (fore-aft) were investigated for free-stream conditions in Figure 8 and Figure 9 respectively. For the blade loads it can be seen, that load spectra at lower load ranges (<0.75) are similar in neutral and unstable conditions. However, few events with high load ranges during unstable conditions increased the loading which eventually lead to significantly higher DELs. Similar behaviour was observed for the tower base bending moment in fore-aft direction (Figure 9) for neutral and unstable conditions. Conversely, for the tower base moment the number of load cycles in stable conditions is less over the entire load range compared to neutral and unstable conditions. It was therefore concluded, that the tower base loads are predominantly influenced by turbulence and less by wind shear. On the other hand, the blade loads are affected by both turbulence and wind shear, which is stronger in stable conditions. This agrees with the findings presented by Sathe et al. [2] in a numerical study.

![Figure 8](image.jpg)  
**Figure 8.** Load spectrum of blade root bending moment in flap-wise direction at AV7, normalised by the load range at 10^3 cycles in neutral conditions; wind direction 210-290°, wind speed 7-9 m/s.  

![Figure 9](image.jpg)  
**Figure 9.** Load spectrum of tower base bending moment in fore-aft direction at AV7, normalised by the load range at 10^1 cycles in neutral conditions; wind direction 210-290°, wind speed 7-9 m/s.

Figure 10 shows the load spectra of the blade root bending moments in flap-wise direction for the turbines AV7 and AV8 at wind speeds 7-9 m/s and 13-16 m/s. Since the wind direction range was set to 250-290°, the AV7 faced only free stream conditions, while the AV8 experienced single wake conditions. In general, it was observed, that higher load ranges (> 0.4) occur more often for the turbine AV8, thus resulting in higher DELs. In addition, homogenisation of the load spectra for stable und neutral conditions was noticed for the turbine in wake, especially for wind speeds between 13 and 16 m/s. In other words, the initial load spectra in free stream conditions vary substantially, whereas the load...
spectra seem to converge for the turbine in wake. Mechanically added turbulence from the first turbine is most likely the reason for this observation.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{load_spectra}
\caption{Load spectrum of blade root bending moment in flap-wise direction, normalised by the load range at $10^4$ cycles in neutral conditions for AV7. (-) lines belong to AV7, (:) lines belong to AV8. Left: wind direction 250°-290°, wind speed 7-9 m/s. Right: wind direction 250°-290°, wind speed 13-16 m/s.}
\end{figure}

6. Conclusion

Full-scale measurement data of two 5 MW wind turbines located at the alpha ventus wind farm was investigated. In particular, the influence of different atmospheric stability classes (stable, neutral, unstable) on the fatigue load spectra of blade root and tower base loads was studied. Hereby, the Bulk Richardson number was used to classify atmospheric stratification.

In general, fatigue loads at tower base and blade root are the highest in unstable conditions for wind speed ranges from cut-in to approximately 14 m/s. This is mainly caused by a few events of high fatigue loading, hence leading to a high DEL. Additionally, a higher number of load cycles was observed for the turbine in wake over the entire load range of the load spectrum. It was shown, that the fatigue loads at tower base are mainly driven by atmospheric turbulence, whereas the loads at blade root are influenced by a combination of wind shear in stable conditions and turbulence in neutral or unstable conditions.

The analysis of load spectra leads to a better understanding of the dependency between fatigue loads and atmospheric stability. This knowledge can be used to validate computer models, consequently increasing the reliability of calculations, for instance in terms of life time extension.
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