Diurnal Wind Characteristics and WTG Loading

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SUMMARY

It is well known that some sites have strong diurnal patterns in wind characteristics, in particular wind shear. However, as these are site specific conditions, they are not covered by the generic type conditions of the wind turbine design standard IEC 61400-1 Ed. 3.0. This investigation examines diurnal wind shear characteristics at a site in inland China. These conditions were modelled on a standard multi-megawatt wind turbine design and compared to the fatigue loading from the IEC standard wind conditions. The results showed that, as high shear doesn't generally occur in high winds, structural loads are not as high as would first be supposed. A site specific assessment would be required to determine the high wind shear's effect on a particular turbine model.

INTRODUCTION

The daily cycle of solar radiation on the earth and the associated absorption and radiation of heat from the earth's surface is known to cause changes in wind conditions, in particular wind shear. The diurnal variations in wind speed are often related to atmospheric stability [i]. Wind shear is the variation of wind shear with height. Using the simple power law relationship to describe the variation in wind speed (*V*) with height (*h*), wind shear is described by the shear exponent α as

$$\frac{V_{h1}}{V_{h2}} = \left(\frac{h_1}{h_2}\right)^{\alpha} \quad . \qquad \textbf{Equation 1}$$

In this study we are considering shear values for average 10-minute wind speeds. An examination of short term (≥ 2 s) extreme shear values due to turbulence is given in [ii].

The level of wind shear depends on local geography, diurnal temperature variations and large-scale weather patterns. These are well known phenomena; for example detailed meteorological observations in coastal [iii] and mountainous [iv] terrain have been previously conducted. It should be noted that both these papers mention the formation of low-level jets (at above 100m). Jets have not been confirmed on the site discussed in this paper but this phenomena has been discussed extensively with relation to wind turbines in [v]. Wind shear investigations for potential wind farm development areas in coastal [vi] and inland sites [vii] in the USA have been conducted by NREL. Two of the four coastal sites and all of the inland sites (although it should be noted that the inland sites are in the USA central plain's area known to have high diurnal variations) showed prolonged high shear values above 0.2.

Diurnal patterns are site specific because they are influenced by the surrounding topography, surface cover and seasonal variations experienced at the site which can alter atmospheric mixing and therefore stability. As diurnal patterns are site specific and some sites do not experience strong effects, these conditions are not covered by the standard wind regimes specified in IEC 61400-1 Ed. 3 [viii]. This standard specifies a normal wind shear with the value α of 0.20 for the fatigue strength calculation and an extreme wind shear value for ultimate strength investigation. This standard specifically warns that the design wind conditions are not intended for areas where high shear values are encountered for extended periods of time. Site specific load modelling should be conducted for such sites but this will not occur until an advanced stage in the development of the project when an appropriate turbine is selected. It would be useful to qualitatively assess the likely effects of such diurnal variations on wind turbine loading early in site investigations to determine the importance and timing of risk mitigating measures such as site specific modelling. However, developers lack information on the effect of such conditions on wind turbine fatigue loading and the affect on the longevity of the turbine components.

This paper examines the factors that cause strong wind conditions and measurements of wind speed, shear and turbulence at a site that show strong diurnal variations. Seasonal patterns in the diurnal variations are also examined. From this data an example diurnal wind condition was obtained. These wind conditions were simulated with a standard multi-megawatt wind turbine design and the effect on loading on major components compared to that from the standard IEC 61400-1 wind conditions. The analysis of the effect of diurnal wind shear condition on wind turbine loading provides a basis for assessing the site risk.

The influence of wind shear on turbine loading was investigated in load simulation using the Garrad Hassan program tool BLADED, which is based on the blade element momentum theory and widely used in the industry for load calculation under consideration of the complete structure dynamics and aerodynamics. The use of CFD to calculate the wind field over the rotor plane was investigated by Risø [ix].

METHOD

Site Monitoring

The data discussed in this paper is based on measurements made on 60m, 70m and 80m monitoring masts, using brand-name cup anemometers. For each wind speed, data has been acquired for at least two heights above ground level, with a 20m separation between levels. The shear exponent between the two levels was calculated for each time-step (10 min or hourly). The average shear exponent for each hour of the day has been plotted, for periods of time when the wind speed at the top level exceeds 8m/s.

Turbine Modelling

A generic, pitch controlled wind turbine with 2MW rated output, 77m hub height and a rotor diameter of 90m was considered for the load calculation. The turbine was modelled in BLADED considering the dynamic properties of the structure, the aerodynamic profiles of the blade and the controller parameters. It is assumed that the effect of higher shear value will increase with the size of the rotor and therefore a large rotor diameter was chosen for the investigations.

For the load simulations three dimensional turbulent wind fields were created for wind bins between cut in and cut out wind speed, turbulence intensity values were assumed according IEC 61400-1 Ed. 3. Only one set of turbulent wind fields was used to eliminate influences on the results by differing wind fluctuations in the same wind speed interval.

Forces and moment in the blade coordinate system, the hub coordinate system (rotation and stationary) as well as the tower coordinate system were investigated. Results for the blade pitching moment (Mzs), blade flapwise moment (Mys), blade edgewise bending Moment (Mxs), hub bending moments in the rotation system (Myr and Mzr) and the rotor torque (Mx) and the resulting tower bending moment (Mxy) were found to be affected by prolonging higher wind shear values and will be discussed in the results section on load modelling.

RESULTS

Site Monitoring

Figure 3 shows the wind speeds measured at the inland Chinese site at various heights (note the axis values have been removed and the axis stretched to remove commercially sensitive information). This site shows higher average wind speeds during the day than at night for wind measurements up to about 40m, however, for measurement heights above this the reverse is true. This behaviour is symptomatic and consistent with the development of a strong night-time temperature inversion. In this case it appears this inversion is causing decoupling of the airstream near the surface, resulting in relatively still air close to ground level, with normal wind speed (or slightly higher) at higher levels. This is the cause of the high observed wind shear (or difference in wind speed at different measurement levels).

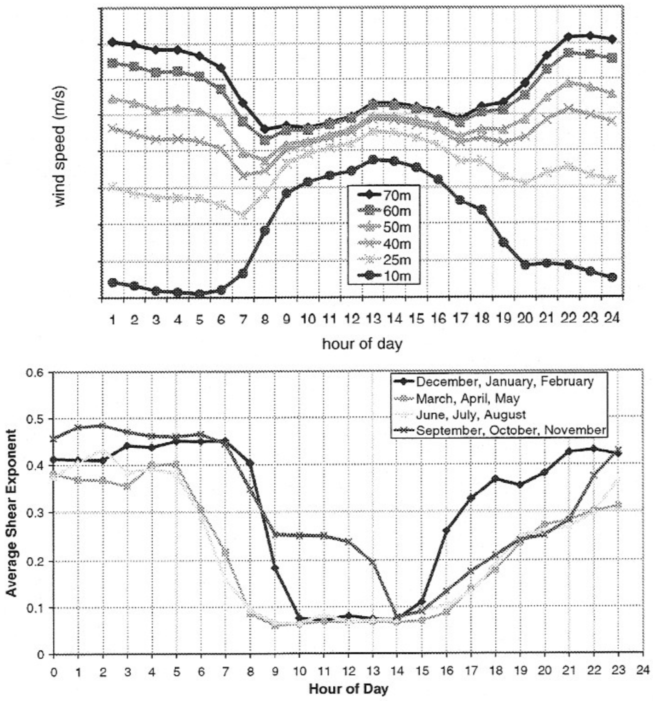

Figure 3 – Diurnal patterns of wind speed by height and wind shear by season at inland Chinese site

There does not appear to be any evidence of a low level jet stream or similar effect, but rather the presence of particularly still air near the surface. Despite having a number of available monitoring levels, no particular "horizon" was identified, indicating that there is not a sharp boundary occurring where decoupling takes place. In the absence of terrain or other features to introduce turbulence, mixing of the air mass does not occur until the temperature change associated with morning occurs.

The effect of this phenomenon during the night is that wind speeds are low close to ground level, but continue as normal at higher levels. Due to conservation of momentum of the air mass, higher level air is probably accelerated to some degree, but not energetically in a way that would be of concern. To confirm this supposition a tower with multiple instruments up until maximum rotor blade tip height has been installed and further investigations will be carried out. Thus the issue becomes the high differential in wind speed (and hence load) across the WTG rotor. During the day, there does not appear to be any particular issue with wind shear.

The effect may be lessened by anything that creates turbulence, or effective mixing/convection of the air mass. Terrain can do this, or possibly changes in surface vegetation. There is a possibility that the wake induced turbulence caused by wind turbines might lessen the shear effect.

The seasonal values are also shown in Figure 3. The autumn (September, October and November average) shows the unusual secondary daytime drop off in shear that affects the yearly average. However, all other profiles are similar to each other and that for inland sites in general. Note the winter (December, January, February) site has a shorter minimum region because the number of daylight hours is reduced at this time of year.

A cross analysis with air temperature did not reveal a connection with wind shear; however a comparison with the rate of change of temperature reveals a clear correlation with a change in wind shear. This property is show in Figure 4 for the winter results. Specifically, the high wind shear period begins with a minimum and ends with a maximum in the rate of change of temperature.

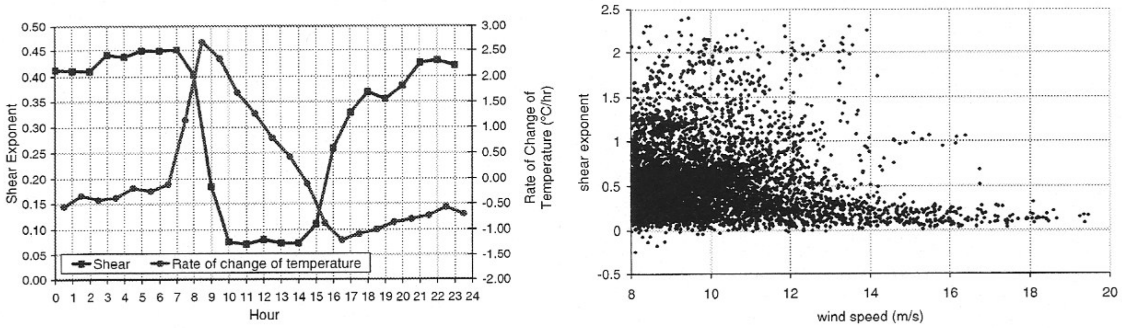

Figure 4 – Winter shear and rate of change temperature and shear exponents based on 10min average wind speed inland Chinese site

Figure 4 also shows the wind shear as a function of wind speed. As can clearly be seen the wind shear is not strong for high mean wind speeds. Note wind shear in the previous plots was only calculated when the wind speed was greater than 8m/s. The frequency of occurrence of various wind shears at this site was used to create some simplified load cases for modelling which is discussed in the next section. High wind shear events were not observed at the site during high wind speeds presumably due to increased mixing of the atmosphere. However, at the site modelled high wind events were rare. Therefore for simplicity for all but one case wind speed was considered independently of wind shear.

Wind Field and Turbine Modelling

Table 3 – Description of modelled scenarios

Case A	**Case B**	**Case C**	**Case D**
Constant	Simple	Complex	Simple plus constant shear high winds
Constant α = 0.4	20% of time α=0.07 50% of time α=0.2 30% of time α=0.4	24% of time α=0.0 26% of time α=0.2 21% of time α=0.4 13% of time α=0.6 7% of time α=0.8 9% of time α=1.0	As for CASE B except α=0.2 if v >14m/s

The scenarios modelled are shown in Table 3. Load simulations were carried out using the sets of turbulent wind fields, different wind shear values, and considering the control system of the turbine. The load simulations were accumulated and weighted for the life time of 20 years using a Rayleigh distribution of the wind speed for an average wind speed value of 7.5m/s, 8.5m/s and 10m/s, according to the IEC Classes III A, II A and I A respectively. Different weighting for the different average wind speed values are assumed to reflect different behaviour for high wind speed sites and low wind speed sites. A simulation with a constant shear value of 0.2 was considered as the base case.

Constant range load spectra (damage equivalent loads) for the four scenarios and the base case were calculated for the different IEC classes (I,II,III) and than the scenarios were compared to the base case (constant shear value of α=0.2). The IEC I A scenarios result in the most adverse case, as larger wind shear will have more influence with higher wind speeds, therefore the deviation between base case and scenario A-D are higher in the IEC IA comparison and therefore only those for the IEC Class I A case weighting for the 20 year life time are shown in Figure 5.

Considering blade root moments, the shear increases the equivalent flapwise moment and the pitching moment but has little effect on the edgewise moment, as shown in Figure 5. The constant range flapwise moment increase up to 35% for a Woehler slope (m) of 10 for Case C, however, considering a wind shear of α=0.2 for wind speeds > 14m/s the increase in the fatigue loads for the flapwise bending moment at blade root is negligible. The pitching moment increases up to 10% for the constant range load spectra for m=10 in Case C, but shows little influence in case D where the shear is set to 0.2 for wind speed above 14m/s.

Figure 5 also shows, for IEC Class IA, the bending moments in the hub (Myr and Mzr in a rotating reference frame), the rotor torque and the resulting tower bending moment which are representative of the other significantly different load components. The hub bending moment was the most increased moment on the turbine with up to 45% for the worst scenario and the increase in loads from the 0.2 case was relatively constant for the various IEC classes. Interestingly, the rotor torque constant range load spectra in the scenarios A-D resulted in lower values than the reference case. Note the constant load spectra are dependent on load ranges, the load ranges for the rotor torques decrease for high shear case. This is not the case for the energy output. The energy is dependent on the mean value and is discussed later in this section. The tower bending moment depends on the modes of vibration of the tower so is very case dependent. The tower bending moment shown is the highest seen on this tower design (about 15m below tower top). Tower bending is resulting moment out of tilting (towards and away from rotor) and rolling (sideways in plane of rotor). Given a high shear field it is unsurprising that high tilting moment would be observed.

Except for tower bending moment which is highest for Case A (constant high shear) the other moments are highest for Case C which has the highest shear values, but for short periods of time. Case D has the lowest damage equivalent loads so clearly the combination of high shear and high winds has affects loading more than the usual case of high shear in relatively low wind speed conditions.

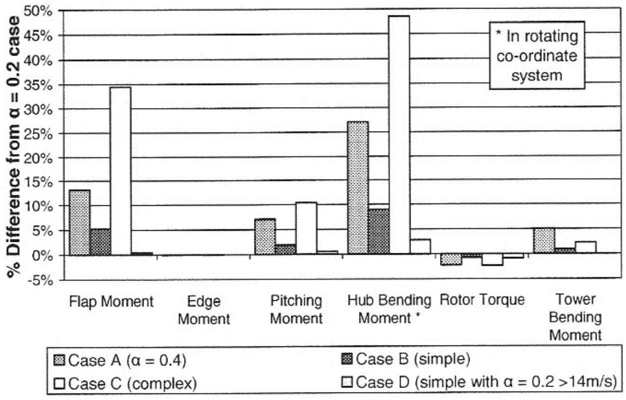

Figure 5 - Damage Equivalent Loads Blade Root, Hub and Tower (IEC Class IA)

CONCLUSIONS

The large variation in the loading for the different scenarios of high shear values showed an high sensitivities in load increase depending on the frequency of occurrence for high shear values at high wind speeds. Especially for the blade flap wise moment and the hub bending moments increased loads were seen. Assessing the site condition has to be conducted with care and special caution has to be paid when wind shear values α> 0.2 occurred at wind speeds above rated wind speed as this scenarios shows the highest load increases for the load components presented. These results show that diurnal shear effects can be significant. However, as high shear doesn't generally occur in high winds structural fatigue loads might not been as high as would first be supposed. Nevertheless, individual investigation depending on turbine model and site specific conditions are recommended. A site specific assessment will be required to determine the high wind shear's effect on a particular turbine model and for a particular site. Load measurements on wind turbines in high wind shear sites would be of great interest to the wind power industry.

REFERENCES

1. van den Berg GP. Wind Turbine Power and Sound in Relation to Atmospheric Stability. *Wind Energy* 2008; **11**:151-169.
2. Hansen KS, Larsen GC & Pedersen BJ. *Analysis of Extreme Wind Shear Events*, in Larsen GC & Hansen KS (eds.), *Database on Wind Characteristics - Analyses of Wind Turbine Design Loads*; Risø-R-1473(EN), 2004; 58-66.
3. Hahn CJ. A Study of the Diurnal Behaviour of Boundary-Layer Winds at the Boulder Atmospheric Observatory. *Boundary-Layer Meteorology* 1981; **21**:231-245.
4. Haeger-Eugensson M. Vertical Interactions in a Nocturnal Multi-Scale Wind System Influenced by Atmospheric Stability in a Coastal Area. *Theoretical and Applied Climatology* 1999; **65**:69-82.
5. Kelley N, Shirazi M, Jager D, Wilde S, Adams J, Buhl M, Sullivan P & Patton E. *Lamar Low-Level Jet Project Interim Report.* National Renewable Energy Laboratory; NREL/TP-500-34593; January 2004.
6. Schwartz M & Elliot D. *Coastal and Marine Tall-Tower Data Analysis.* Preprint to be presented at the American Wind Energy Association WindPower 2007 Conference and Exhibition, Los Angeles, California, June 3-6; NREL/CP-500-41858; 2007.
7. Schwartz M & Elliot D. *Wind Shear Characteristics at Central Plains Tall Towers.* Preprint to be presented at the American Wind Energy Association WindPower 2006 Conference, Pittsburgh, Pennsylvania, June 4-7; NREL/CP-500-40019; 2006.
8. International Electrotechnical Commission, International Standard Wind Turbines – Part 1: Design Requirements. IEC 61400-1 Ed 3.0, 2005.
9. Sørensen NN & Johansen J. UPWIND, Aerodynamics and aero-elasticity. Rotor aerodynamics in atmospheric shear flow. EWEC, 2006.