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Influence of different wind profiles due to varying atmospheric stability on the fatigue life of wind turbines

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Abstract.
Offshore wind energy is being developed on a very large scale in the European seas. The objective of developing wind energy offshore is to capture greater wind speeds than are encountered onshore and as a result more energy. With this also come more challenges in the design of wind turbines due to the hostile offshore environment. Currently the standards for offshore wind turbines prescribe a site specific design for the support structures and the design for the rotor nacelle assembly according to onshore standards. Wind turbines are designed to withstand fatigue and ultimate loads. For the fatigue loading several input conditions have been prescribed, amongst which wind profile is one of them. Wind profile is represented by power law or logarithmic law as given in the standards. A neutral stability of the atmosphere is considered while obtaining the wind profile using the logarithmic law. In this paper the atmospheric stability is varied in order to estimate different wind profiles and simulations are run in Bladed to check its influence on the fatigue damage at the blade root. The variations in the atmospheric stability has been taken into account by using some typical values of Obukhov length. From steady state simulations it has been found that atmospheric stability is important for fatigue damage. The analysis showed that variation in the distribution of atmospheric stability causes large variations in the fatigue damage for different sites. Thus, it is worthwhile to carry out a full scale study using the turbulent winds and real data for wind turbine and environmental conditions.

1. Introduction

Offshore wind energy is on a rapid expansion in Europe and many offshore wind farms are being built. This preludes further development of offshore wind farms all around the world. A wind turbine is subjected to various kinds of loads originating from different sources. Aerodynamic loads is one of the sources of loads on wind turbines. These loads occur due to various input environmental states that a wind turbine has to encounter. Wind shear is one of the environmental state that occurs all the time during the lifetime of a turbine. It is an important parameter which causes cyclic loading in the rotor and hence fatigue damage. Wind shear is extrapolated from measurements done at lower heights to a height z as given by logarithmic law.

$$u_z = \frac{u_*}{k} ln\left(\frac{z}{z_0}\right) \tag{1}$$

where u_* is the friction velocity, k is the von Karman constant and z_0 is the roughness length. Wind shear is also given by the power law as:

$$\frac{u_z}{u_{z_r}} = \left(\frac{z}{z_r}\right)^{\alpha} \tag{2}$$

where α is the power exponent, u_{z_r} is the reference velocity and z_r is the reference height. Equations 1 and 2 assume a neutral stability of the atmosphere while extrapolating to different heights. Offshore wind farms are being planned for wind turbines with large rotor diameters. This poses a particular question on the viability of using neutral stability to obtain wind shear from a reference height. Previous studies [1], [2] and [3] have shown that the energy yield estimates differ when stability is taken into consideration. In this paper the effects of stability classes have been ascertained on the fatigue damage at the blade root. The resulting damage is compared with the fatigue damage obtained from logarithmic and exponential wind shear. The exponential wind shear is obtained using a power law exponent of 0.14 for offshore sites as given in [4].

During the course of the day, cooling and heating of the surface takes place causing different stability conditions and hence different stratifications. According to Monin-Obukhov similarity theory the atmospheric stability can be described in terms of stability parameter z/L, where L is the Obukhov length. Taking stability into account, equation 1 can be written as,

$$u_z = \frac{u_*}{k}\left[ln\left(\frac{z}{z_0}\right) - \psi\left(\frac{z}{L}\right)\right] \tag{3}$$

where $\psi\left(\frac{z}{L}\right)$ is the stability parameter. The stability parameter can be calculated using the Bussinger-Dyer formulation [5]

$$\psi = 2ln\left(\frac{1+\phi_m}{2}\right) + ln\left(\frac{(1+\phi_m^2)}{2}\right) - 2tan^{-1}(x) - \frac{\pi}{2} \quad for\frac{z}{L} < 0 \tag{4}$$

$$\psi = -\beta\frac{z}{L} \quad for\frac{z}{L} > 0 \tag{5}$$

where β and γ are the empirical parameters whose values are taken as 4.8 and 19.3 respectively, [6]. From the wind speed at reference height z_r, the wind speed at height z can be obtained from equation 3,

$$u_z = u_{z_r}\frac{ln(\frac{z}{z_0}) - \psi(\frac{z}{L})}{ln(\frac{z_r}{z_0}) - \psi(\frac{z_r}{L})} \tag{6}$$

In this paper the values of L have been assumed from the classification of stability into five categories given in [7].

Table 1. Classification of stability according to Obukhov lengths

very stable	0<L<200 m
stable	200<L<1000 m
near-neutral	$\mid L \mid$ >1000 m
unstable	-1000<L<-200 m
very unstable	-200<L<0 m

The sea surface roughness z_0 is also not constant and varies with time. Previous studies [1] and [2] have shown that the effect of sea surface roughness is not significant and hence in this paper, for the analysis, its value is taken as constant. Nevertheless, two extreme values of z_0 are assumed and its influence on fatigue damage estimated to verify its influence.

2. Description of the work

The design software used for the fatigue analysis is 'Bladed' developed by Garrad Hassan and Partners Ltd. It is a complete design software and an industry standard, which has been validated by Germanischer Llyod. The wind turbine used is a reference turbine which was prepared for a research project at DUWIND. The characteristics of the turbine are summarized in table 2.

Table 2. Turbine properties

Class I turbine, Mean wind speed = 10 m/s
Power = 5.5MW
Rotor Diameter = 129m
Hub Height = 95m
Number of Blades = 3
Rotational speed = Variable speed
cut in wind speed, v_{cut-in} = 4 m/s
cut out wind speed, $v_{cut-out}$ = 25 m/s

As given in table 2, the turbine has a large rotor diameter and is suited for the analysis of stability influence. The fatigue analysis is carried out for the blade root section. Blade root is selected as the section because it experiences maximum bending moments due to cyclic loading as compared to any other section on the blade. The blade root is modeled as a thin annular cylinder with an outer diameter of $3.5m$ and inner diameter of $3.42m$. The material for the blade is assumed as Glass Epoxy with an inverse slope on the log-log S-N curve as 9 and an intercept of $70Mpa$. The reference height is taken as hub height based on which wind shear across the rotor plane is determined. A wind turbine's life has been assumed as 20 years [8] and fatigue damage has been estimated for different stability classes and compared with the fatigue damage obtained using exponential and logarithmic wind shear assuming a neutral profile. The simulations have been run for steady conditions. The choice of the steady wind conditions for the simulation may not represent the real situation but the analysis would nevertheless give a primary insight into the importance of atmospheric stability. Also, if the steady conditions would not have a significant effect on the fatigue damage then it may not be worthwhile to go for a full scale study using turbulent winds. Apart from the wind conditions, tower shadow effects, gravity and inertia loads have also been taken into account. This allows for the simulation time to be reduced from the standard specified 600s [8] to a value representing a minimum of one complete cycle of loading. Considering that the turbine is a variable speed turbine the minimum simulation time should at least be greater than the time required for one revolution of the rotor at minimum wind speed, i. e. $4m/s$. The rotor speed at $4m/s$ was found to be $4rpm$ and hence the simulation time should be more than $15s$. Nevertheless, the simulation time has been chosen as $90s$ covering 6 cycles of revolution. Thus it is sufficient to cover even the slowest revolution of the rotor. A pre-analysis of the effect of varying z_0 on the fatigue life was carried out to ascertain if its variability would be important. According to DNV offshore standards [9], z_0 can vary from 0.0001 for calm sea to 0.003 for coastal waters with the wind blowing from land to sea. With time, z_0 would at most vary in the two extreme values. Table 3 shows the influence of varying z_0 on the fatigue damage at blade root.

As seen from table 3 there is some influence of z_0 on the fatigue damage. In reality z_0 would not attain a fixed value on either side of extremes but would at most hover from one extreme to the other depending on the wind and site conditions. This would reduce the difference in

Table 3. Fatigue Damage for different sea surface roughness

Roughness	Fatigue Damage
0.003	0.37
0.0001	0.13

the fatigue damage obtained for two extreme z_0 values as shown in table 3. Hence its variation is not accounted for in this paper but could be worthwhile to study using real data. For this paper z_0 is taken as 0.001 assuming that the site would be a coastal site. The combinations for simulations are made using the wind speed bins of $1m/s$ from v_{cut-in} to $v_{cut-out}$ for a z_0 value of 0.001 and various values of L as given in table 1. Table 4 summarizes the combination of simulations.

Table 4. Simulation parameters

Obukhov Length, L					Wind speeds	Roughness, z_0
-300	-100	∞	100	300	v_{cut-in} - $v_{cut-out}$	0.001

The wind shears for a wind speed of $10m/s$ is given in figure 1 as an example.

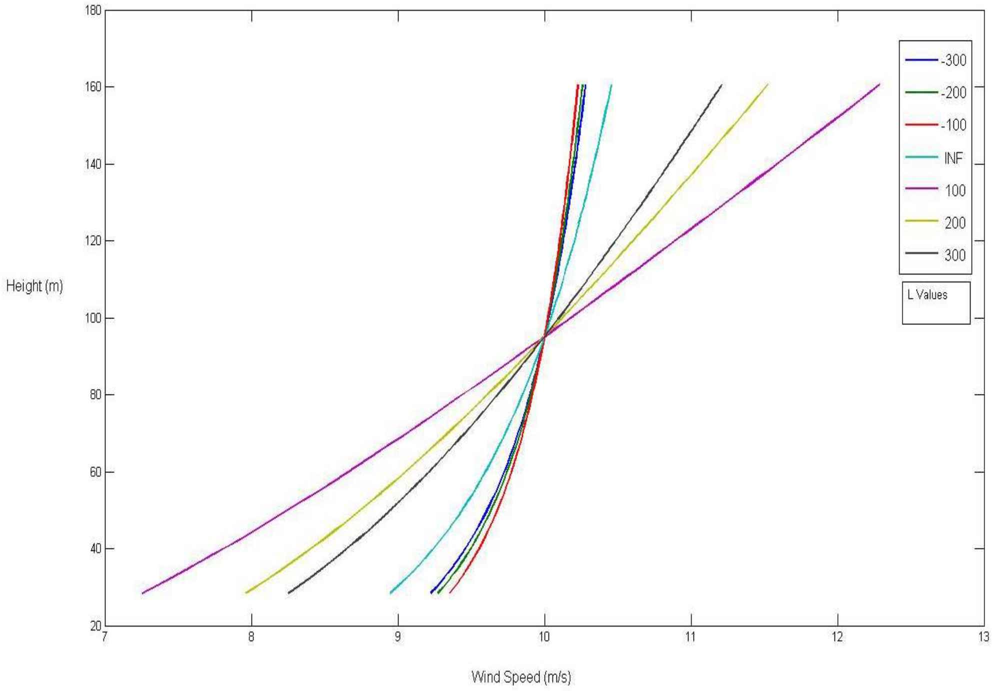

Figure 1. Wind shear for different stability conditions at $10m/s$

To check the influence of stability, it is important to assume a distribution to be able to assess its effect. Hence, distribution of a particular stability condition sampled by wind speeds is taken into consideration. [2] gives stability distributions found for various Danish sites. In this paper the distributions are taken from [2] for Rodsand and Vindeby sites and fatigue damage ascertained. Figures 2 and 3 show the distribution of stability conditions sampled by wind speed.

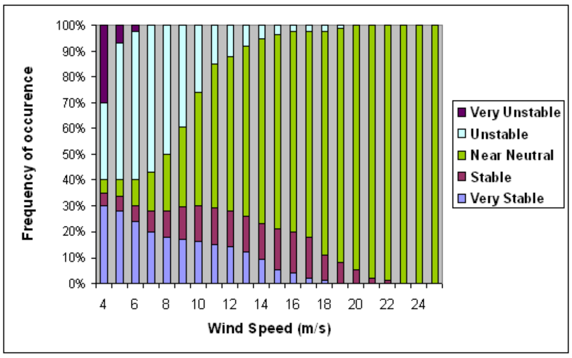

Figure 2. Frequency of occurrence of stability conditions sampled by wind speed for Rodsand site[2]

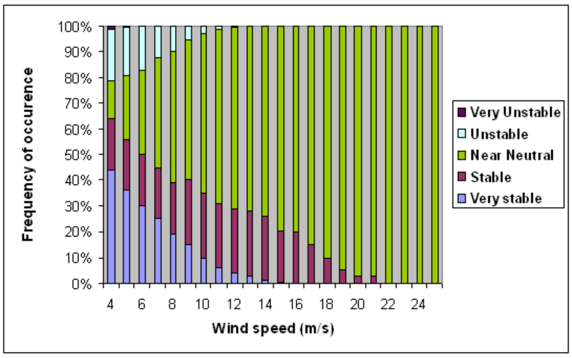

Figure 3. Frequency of occurrence of stability conditions sampled by wind speed for Vindeby site[2]

These sites are chosen without any special preference as any other offshore site could also have been chosen for the analysis. As given in table 4, several simulations were run to calculate the bending moments at the blade root. The time histories of bending moments were converted into stress histories using the following relation:

$$\sigma = \frac{M.y}{I} \tag{7}$$

where σ is the stress at the blade root at a particular time, M is the bending moment, y is the distance at which the moment acts, which is the radius of the outer diameter and I is the moment of inertia of annular cylinder.

3. Results

Figure 4 shows different stress histories for different stability cases for a wind speed of $10m/s$. The figure is just an illustration of various stress histories obtained for various wind speeds and stability classes. The number of cycles to failure and subsequently the fractional damage is calculated using the following log-log relationship:

$$log(S) = log(K) - \frac{1}{m} log(N) \tag{8}$$

where S is the stress amplitude in Mpa, $log(K)$ is the intercept, $\frac{1}{m}$ is the inverse slope and N is the number of cycles to failure. The fatigue damage using different stability classes is calculated using following relation:

$$D = \frac{20 \times 365 \times 24 \times 3600}{90} \sum_{U=4}^{25} \sum_{L=1}^{5} P(U)_L \times d(U)_L \times P(U) \tag{9}$$

where D is the fatigue damage at the blade root, U is the bin average wind speed, $\sum_{L=1}^{5}$ represents five stability classes given in table 1, $P(U)_L$ is the probability of occurrence of a stability class

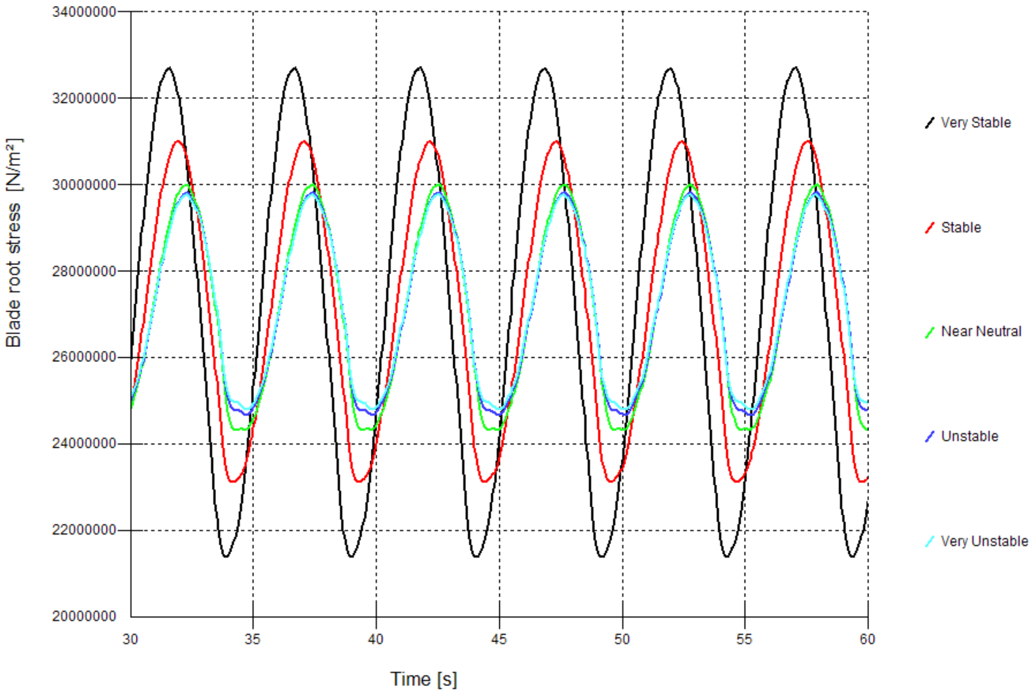

Figure 4. Stress histories for different stability conditions at $10m/s$

sampled by wind speeds, $d(U)_L$ is the fractional damage for the simulation time for respective stability class at a particular wind speed and $P(U)$ is the probability of occurrence of a particular wind speed. Since the simulations have been performed for $90s$ the resulting fatigue damage has been divided by this simulation time. Table 5 summarizes the results obtained from the simulations.

Table 5. Lifetime fatigue damage using different wind shear models

Method used	Fatigue Damage
Wind shear considering stability classes for Rodsand site	6.12
Wind shear considering stability classes for Vindeby site	1.68
Wind shear modeled by logarithmic law and neutral stability	0.25
Wind shear modeled by exponential law	1.91

As seen in table 5, the lifetime fatigue is considerably affected by using different models of wind shear. The distribution of stability shows a significant change in the fatigue damage. For Rodsand site the fatigue damage is considerably higher than for Vindeby site. The wind shear modeled using logarithmic law gives the lowest fatigue damage.

4. Conclusions

As seen in table 5, considering stability classes while modeling wind shear is an important factor in assessing the fatigue damage more accurately. The importance of distribution of stability classes is clearly emphasized in the results. It can be concluded from the above results that logarithmic wind shear with neutral stability underpredicts the fatigue damage depicting a non-conservative approach. It could have been contested that the occurrence of different stability conditions would tend to average out the effects over time but the results do not show this behavior. Two factors are dependent on it:

- Differences in the wind shears for various stability conditions.
- Frequency of occurrence of a particular stability condition.

Figure 1 shows that the difference in the wind velocities at the lowermost part of the rotor and the uppermost part for a very stable condition can be up to $5m/s$ for a hub height velocity of $10m/s$. This difference increases for a greater hub height velocity and with the increase in rotor diameter. This is a significant difference in the wind speed as compared to that obtained from the logarithmic law considering only neutral stability. The importance of a stability is certainly evident in the difference between the fatigue damage obtained at two sites.
Although the results have been obtained for steady state simulations, it provides an impetus to carry out a full scale fatigue damage study by using turbulent winds and real data for wind turbines and environmental conditions.

References

[1] Bernhard Lange, Søren Larsen, Jørgen Højstrup, and Rebecca Barthelmie. Importance of thermal effects and sea surface roughness for offshore wind resource assessment. *Journal of Wind Engineering and Industrial aerodynamics*, pages 959–988, May 2004.

[2] M.Motta and R.J.Barthelmie. The influence of non-logarithmic wind speed profiles on potential power output at danish offshore sites. *Wind Energy*, pages 219–236, 2005.

[3] Jonathan Summer and Christian Masson. Influence of atmospheric stability on wind turbine power performance curves. *Journal of Solar Energy Engineering*, 128:531–538, November 2006.

[4] IEC 61400-3. Offshore wind turbines-part 1: Design requirements. 2005.

[5] Roland B. Stull. *An Introduction to Boundary Layer Meteorology.* Kluwer Academic Publishers, 1988.

[6] U.Högstrom. Nondimensional wind and temperature profiles in the atmospheric surface layer. *Boundary-Layer Meteorology*, pages 55–78, 1988.

[7] Van Wijk AJM, Beljaars ACM, Holtslag AAM, and Turkenburg WC. Evaluation of stability corrections in wind speed profiles over the north sea. *Journal of Wind Engineering and Industrial Aerodynamics*, pages 551–566, 1990.

[8] IEC 61400-1. Wind turbines-part 1: Design requirements. 2005.

[9] DNV Det Norske Veritas. Design of offshore wind turbine structures. June 2004.

[10] Bernhard Lange, Søren Larsen, Jørgen Højstrup, and Rebecca Barthelmie. The influence of thermal effects on the wind speed profile of the coastal marine boundary layer. *Boundary-Layer Meteorology*, pages 587–617, 2004.