A systematic hub loads model of a horizontal wind turbine

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Abstract: The wind turbine industry has focused offshore on increasing the capacity of a single unit through up-scaling their machines. There is however a lack of systematic studies on how loads vary due to properties of a wind turbine and scaling of wind turbines. The purpose of this paper is to study how applied blade modifications, with similarities such as mass, stiffness and dimensions, influence blade root moments and lifetime damage equivalent loads (DELs) of the rotor blades. In order to produce fatigue load blade root moment trends based on the applied modifications. It was found that a linear trend of lifetime DELs based on the applied modifications of blades, which have effect on the natural frequency of blade of the original or reference model. As the control system was tuned for the specific frequency of the reference model. The linear trend of lifetime DELs was generated as long as the natural frequency of the reference model was preserved. For larger modifications of the wind turbine the controller would need retuning.

1. Introduction

Up-scaling of wind turbines is being driven by the offshore market. Although the specific cost of such turbines in Euro/rated MW may increase with scale, reductions in infrastructure costs and in O&M, with larger offshore units per MW of total installed capacity, appear to justify the use of turbines rated at 5 MW and above. Software for calculating loads of horizontal axis wind turbines is long established as are the rules for defining the relevant load cases and performance of load calculations for turbine certification [5]. However, in spite of extensive load calculations that have been performed throughout the wind industry, there is no given evaluation of load trends to relate turbine scale, wind conditions and structural parameters. In the past several techniques were introduced to obtain a methodical understanding and quantifiable classification of wind turbine load trends.

Linear scaling or scaling with similarities was introduced by Chaviaropoulos [1], where tip speed is constant or unchangeable and any dimensional changes are proportional or linear. The disadvantage of this method is that it neglects any innovation in construction materials. Nevertheless it can provide useful insights.

The second method is to base trends on the commercial data of wind turbines, as done by Jamieson [2]. The drawback of this technique is the diversity among designs of wind turbines in commercial data such as: operational strategies and environmental conditions (terrain, wind class and level of turbulence). As a result there is huge variation in design between small (older) and large (newer) wind turbines. However the data from wind turbines of similar design provides a clear trend, highlighting progress and optimisation of the materials and construction of blades, because linear scaling is realistic for wind turbine blades. Moreover, a systematic hub load trend requires linear scaling modifications to systemise all these changes at the early stages of this area of research.

This paper focuses on the impact of blade self-weight loads on hub fatigue damage at different turbulence levels (two turbulence reference intensities), where the blades of a wind turbine scale with similarity as it provides a clear outlook of systematic load trends. This paper is a continuation of previous work done by the authors [3].

2. Background theory:

2.1. Fatigue:

Extreme and fatigue loads are a major consideration in the design of wind turbines. Fatigue loads become more relevant as wind turbines scale up since gravitational loads increase dramatically. The source of fatigue loads is aerodynamic (wind turbulence) and rotating motions of the hub (self-weight). According to linear scaling, the associated moments are scaled up by a power of four. In this case the fatigue loads become more important in design of large or scaled up wind turbines. Normally there are 10^7 rotor revolutions during twenty years of the nominated design life of wind turbines. Each revolution of the rotor results in fatigue damage which is caused by both deterministic and stochastic loads, where stochastic part loads are from wind turbulence and deterministic loads are a result of gravity, wind shear, tower shadow and yaw error [4].

Lifetime damage equivalent loads (DELs) have been calculated according to the IEC standard [5] where the lifetime DELs is based on 10 minute simulations of mean wind speed associated with a Weibull distribution, which presents the probability of wind speed for an entire year.

3. Method :

The goal of this research is to define hub fatigue load trends associated with blade root bending moments for the two different cases. Each case investigates how different modifications in the blades affect the blade root bending moment. In the first scenario the blade mass per unit length and stiffness were modified by the same factor, while the dimensions of blade were modified as a function of blade mass ($m \approx R^3$) [6]. For example: if blade mass increases by 20 % the blade dimensions increase by 6.3 %. The second case involved a modification where the original natural frequency of the reference model was preserved. In this instance the blade mass unit length and stiffness of the blades were changed by different factors and the dimensions amended in the same way as for the first scenario. Additionally, two different turbulence conditions (turbulence reference intensities) were used for the two cases in order to investigate how fatigue loads depend on turbulence. Moreover, the lifetime DELs

is calculated for a combination of deterministic and stochastic loads and for deterministic part loads. The lifetime DELs of the stochastic part loads is not considered in this paper as it cannot provide any trend since stochastic loads are output from turbulence which is random or chaotic.

The scaling modifications have been done in a restricted way to prevent any significant changes in the dynamics of wind turbine, allowing the use of the same control system. Consequently, the original control system of the base model can be used as there are no significant changes in the dynamics of the machine due to the applied modifications.

3.1. Base line model:

The reference turbine model was created for this study. It is a three-bladed upwind machine operating with variable speed and pitch control. The design of the blades is based on NACA 634xx aerofoil sections.

- Rated power – 3 MW
- Nominal rotor diameter – 100 m
- Cut-in wind speed - 4 m/s
- Rated wind speed - 11.5 m/s
- Cut-out wind speed - 25 m/s
- Transmission - Gearbox
- Tower height - 79 m
- Tip Speed Ratio - 9

3.2. Simulation set up:

Bladed software [8] was used for performing simulations. The modification characteristics of each case are given below:

- 1st case – blade mass and stiffness adjusted by the same factor; dimensions are based on a mass factor ($m \approx R^3$).
- 2nd case - blade mass and stiffness adjusted by different factors to keep the natural frequency of the blade unchanged; the dimensions are modified in the same way as the 1st case.

Each case was split into nine sub-cases which characterised the blade modifications in a range from 20% to +20% with a 5% step compared to the original blade.

The two different wind conditions were applied for each case. The first wind conditions were wind class I A with 0.16 turbulence reference intensity [5]. For the second wind conditions the turbulence reference intensity was increased from 0.16 and 0.2 with other parameters kept unchanged.

4. Results:

In this section the obtained data is presented in graphical and tabular formats. The following sections cover edgewise bending moment (Mx) of the blade root, lifetime DEL, and deterministic lifetime DEL.

4.1. *Auto spectral density of blade root bending moments*

Analysis of the blade root bending moment is not performed in the time domain as it cannot provide clear results because the blades are in motion and are under wind flow which varies randomly with time. As a result, bending moment measurements over a specific time interval are dissimilar. Thus the bending moment was transferred to the frequency domain using Fourier transform, which is called auto spectral density or power spectral density.

There is no investigation of flap-wise bending moment (My) of the blade root in this research as there is no significant effect from the applied blade modifications (see figure 1). However, there are minor changes in structural mode frequencies among the two cases and the original model. These are not visible especially for the 1st, 2nd and 3rd structural mode. The visible difference appears at the 5th structural mode, but the 1st, 2nd and 3rd modes are used in the design of wind turbine as these modes are located in the low frequency range which is significant for fatigue design because large machines operate in the low frequency range which is in the vicinity of the turbulent peak frequency [7].
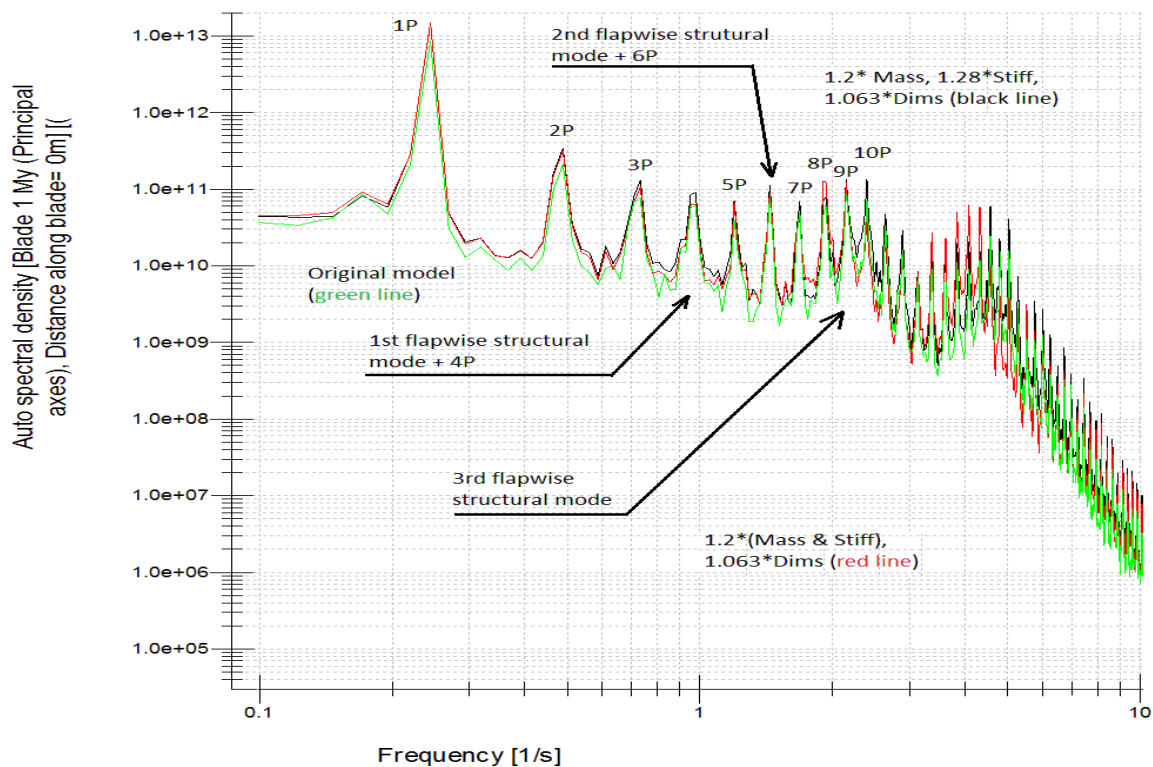

Figure 1: Auto spectral density of My (flap-wise) blade root of the two cases and original model at 14 m/s mean wind flow

Figure 2 depicts the auto spectral density of Mx (edgewise) blade root of the 1st case, where the blade mass and stiffness was increased by twenty percent and the dimensions were increased by 6.3% compared with the auto spectral density of Mx blade root of the original model. The first structural mode frequency of the 1st case is reduced in comparison with the original model. In this case there is a shift between the structural modes of two curves which is highlighted by the green ellipse. As a result the 6P peak is amplified by the 1st structural mode. This situation can possibly lead to a negative effect on lifetime DELs calculations as the control system has been tuned for the specific natural frequency.

The natural frequency of the blade changed due to the applied modifications (see equation 1). In this case there is a shift between the structural modes of two curves which is presented in figure 1.

$$w_{Beam} = \propto \sqrt{\frac{E\,I}{m\,L^4}}; \qquad (1)$$

Where, $\propto$ is coefficient, EI is bending stiffness, m is mass and L is length.
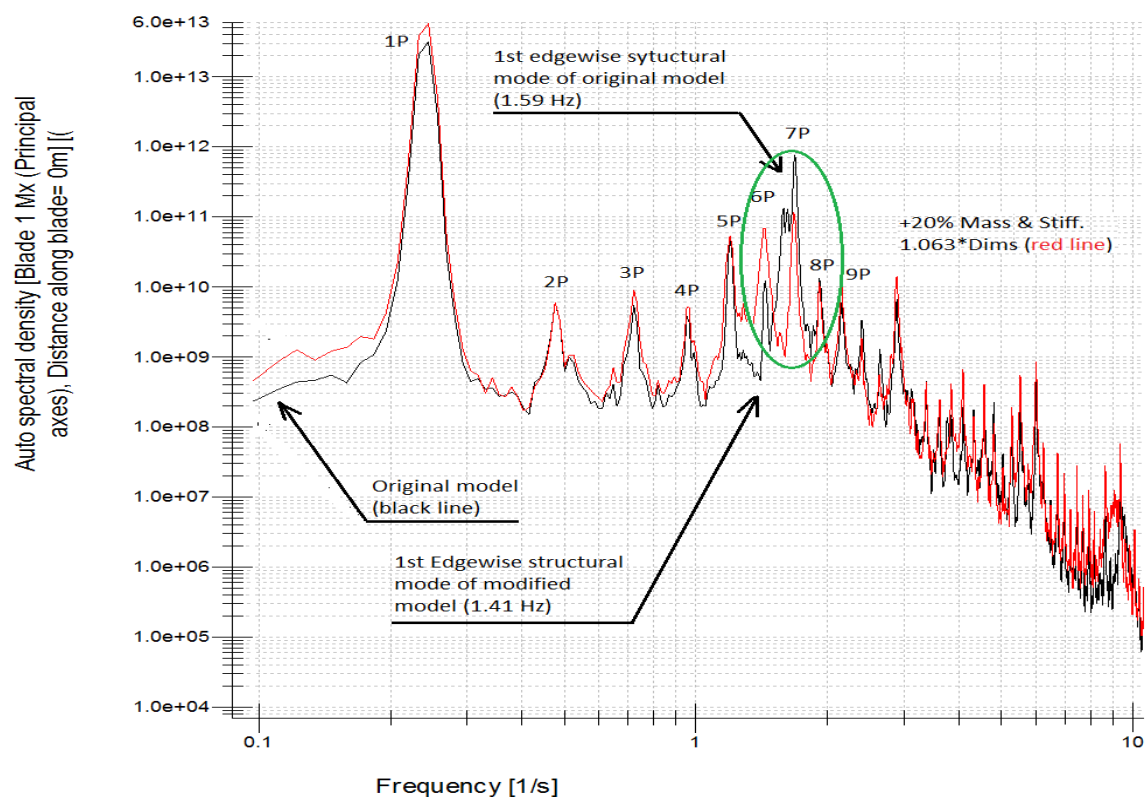
Figure 2: Auto spectral density of Mx blade root of the 1st case and original model at 14 m/s mean wind flow

The comparison between Mx blade root of 2nd case (where blade mass, stiffness and dimensions were modified by factor 1.2, 1.28 and 1.063 respectively) and the unmodified original model is depicted in figure 3. In this case there is no shift between the first structural mode frequencies of curves in the highlighted region by the green ellipse in figure 3.
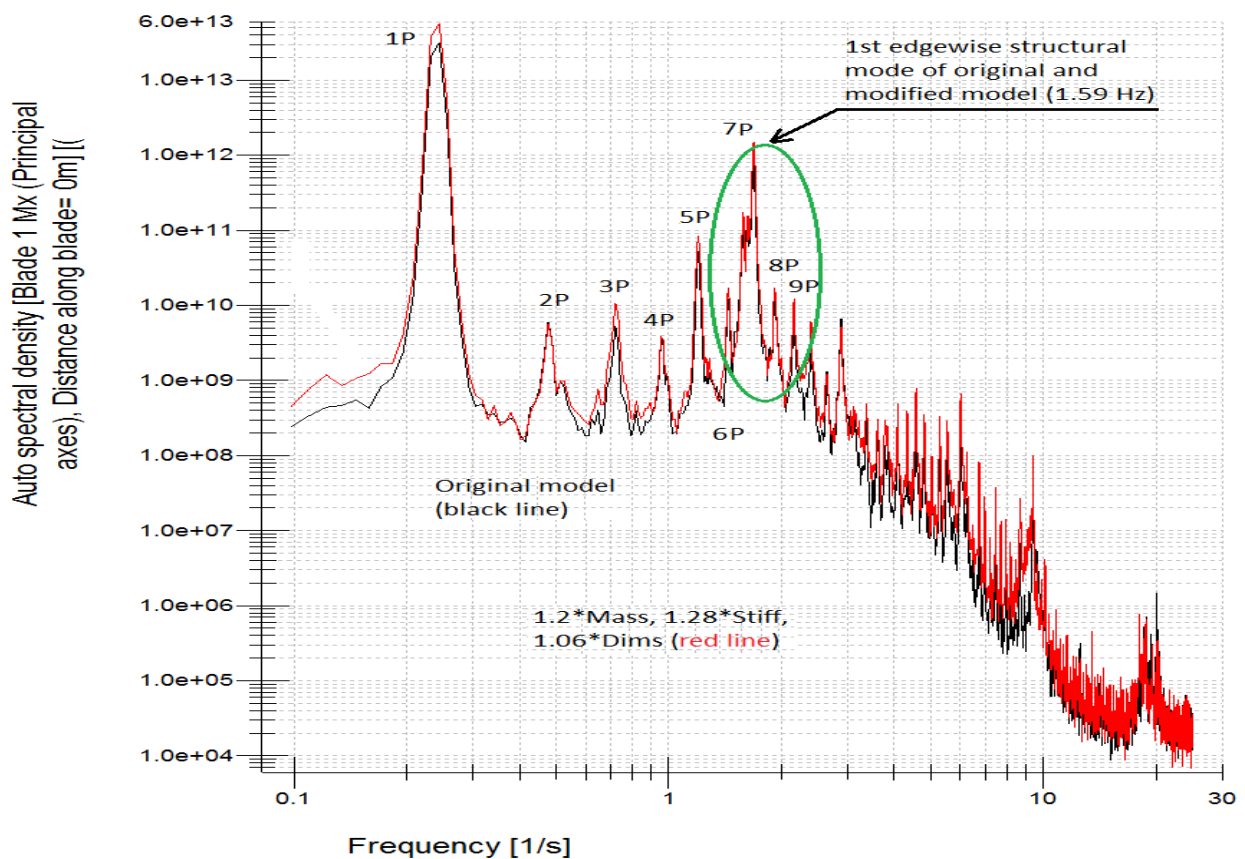
**Figure 3:** Auto spectral density of Mx blade root of the 2nd case and original model at 14 m/s mean wind flow

4.2. *Lifetime damage equivalent loads (DEL)*:

The two following figures depict Mx blade root lifetime DEL for the two above mentioned cases. Figure 4 displays lifetime DELs value of the 1st case against Wohler coefficient (the Wohler coefficient is the fatigue ductility exponent, which is the gradient of an S-N curve for a specific material). The common pattern can be seen in the figure among each Wohler coefficients up to a coefficient of eight, after which the order of the pattern becomes chaotic. These higher Wohler coefficients are typical of composite materials.
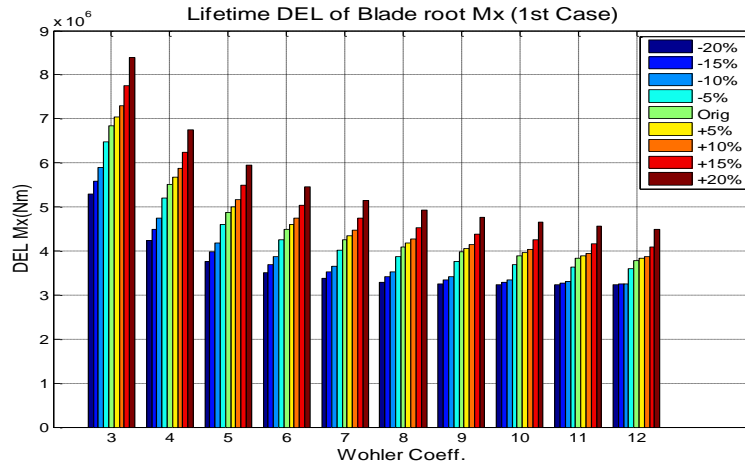
Figure 4: Lifetime DELs of Mx blade root of the 1st case

The features of the 2nd case modification are depicted in figure 5. There is a consistent and clear pattern that repeats for each Wohler coefficient. It is a result of the unchanged natural frequency of blade as the applied modifications in the 2nd case had kept the natural frequency constant compared to the reference model.
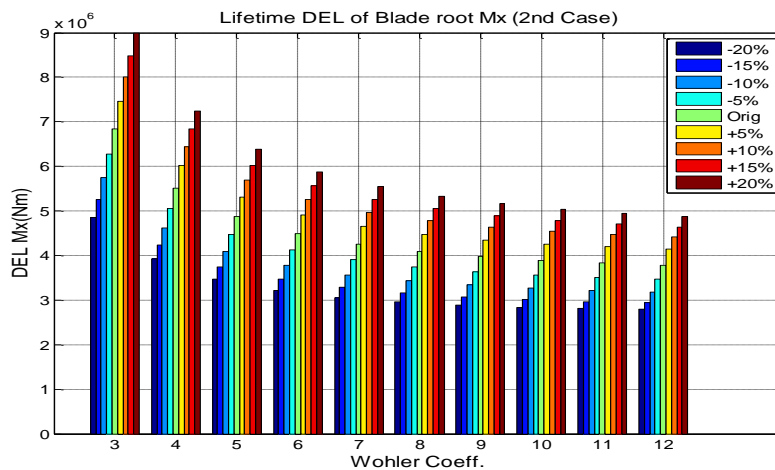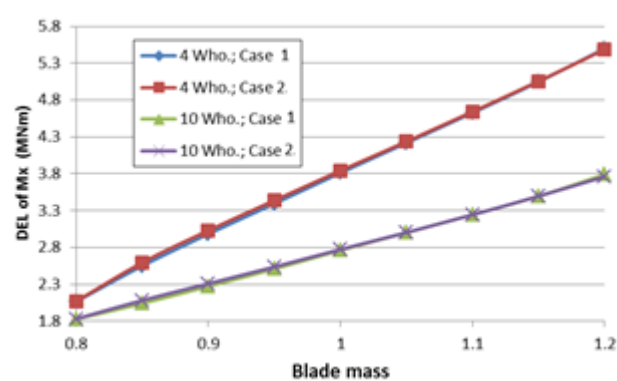

Figure 5: Lifetime DELs of Mx blade root of the 2nd case

The two abovementioned figures of lifetime DELs demonstrate the possibility to generate a trend of lifetime DELs function of the properties under modifications by using the original controller as long as the frequencies of the original model are preserved.

4.3. *Deterministic lifetime damage equivalent loads (DELs)*:

The graphs of deterministic lifetime DEL of both cases look the same. It is difficult to notice any deviation between the two figures. In this case the Wohler coefficients values of four (steel) and ten

(composite material) were chosen to compare the differences between the two cases. The following figure shows this comparison. The horizontal axis is a factor of blade mass which is the reference for other modification within the blades.

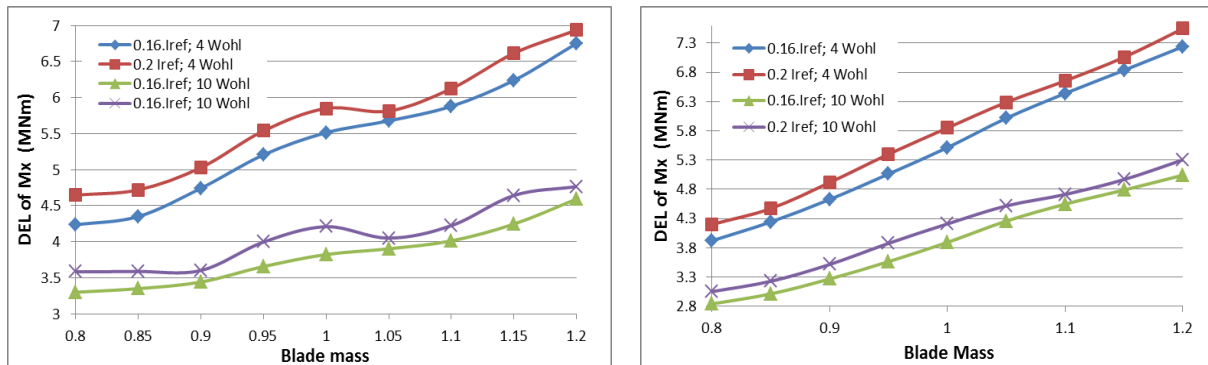**Figure 6:** Periodic Lifetime DEL of Mx blade root, comparison of two cases

The lines of Wohler coefficient four and ten values of two scenarios overlap each other. Therefore the determistic lifetime DELs of Mx blade root is almost identical for both cases. Hence, the changes between figure 4 and 5 are a result of the stochastic loads part.

4.4. *Turbulence effect lifetime damage equivalent loads (DELs)*:

In this section the turbulence effect on lifetime DELs is presented for both cases in the following figures 7a and 7b. The comparison between different turbulence conditions is presented for Wohler coefficients values of four and ten, which correspond to steel and composite materials respectively. Figure 7a depicts characteristics of the first case and figure 7b shows the second case. It is noticeable from figure 7a that the curves have a general trend, but the curves with greater turbulence reference intensity (Iref = 0.2) are more spread out than the curves with lower turbulence reference intensity. In figure 7b the curves show a linear trend for lower and greater turbulence reference intensity.

It is a result of the applied modifications which changed the natural frequency in the first case, but in the second case the natural frequency was kept the same as the original one as for the reference 3MW unit. As mentioned before the control system was not changed and it was tuned for specific natural frequencies of the original model. The modification implemented in the 1st case changed the natural frequency of the blades. As a result the control system does not operate at optimum for the 1st case because the lifetime DELs of deterministic loads demonstrated a linear trend and almost identical values for the 1st and 2nd case (see figure 6). In this case the difference in lifetime DELs is caused by the stochastic loads part generated by wind turbulence. The control system of wind turbine has to alleviate turbulence loads.

Figure 7a & 7b: Comparison of total Lifetime DEL of Mx (edgewise) blade root between two turbulence intensity at specific Wohler coefficients (7a – Case 1; 7b – Case 2)

The value of deterministic lifetime DELs is not presented here as the deterministic lifetime DEL does not depend on the different wind conditions, because the curves of two dissimilar wind conditions are identical. The increase in lifetime DELs is a result of an increase in the stochastic lifetime DELs.

Table 1 demonstrates the average increase in the lifetime DELs of each Wohler coefficients for the 2nd case due to the increased reference turbulence intensity. It is noticeable that the magnitude of the increase of total lifetime DELs becomes larger at higher Wohler coefficients.

Wohler Coef.	3	4	5	6	7	8	9	10	11	12
Average increased of Lifetime DEL (Case 2)	5.6%	5.5%	5.9%	6.6%	7.4%	8.3%	9.1%	9.9%	10.6%	11.3%

Table 1: Average increased of Lifetime DEL due to 0.2 I_{ref} compared with 0.16 I_{ref} for 2nd case

5. Conclusion:

This research aimed to generate a trend of lifetime DELs of blade root edge-wise moment based on two cases of blade modifications of the reference three-bladed 3MW upwind wind turbine model operating with variable speed and pitch control. In the 2nd case the modifications were applied in a manner that preserved the natural frequency of the reference model. The 1st case demonstrated a general trend of lifetime DELs but with distortions at Wohler coefficients which are typical of composite materials. The 2nd case proved the possibility to generate a linear trend between lifetime DELs and the employed modifications. According to that any modifications of wind turbine properties require the retuning of the control system to evaluate sufficient loads data, as the modifications change the dynamic of the machine or values of natural frequencies as the control system of large wind turbines is set up for specific dynamics of an unit.

The deterministic lifetime DELs of two cases demonstrated that it does not depend on turbulence conditions. The turbulence affects the stochastic part of loads. Additionally, it showed that the turbulence loads increase due to the non-optimum operation of the control system as the deterministic lifetime DELs was almost identical for both cases.

Future work will involve an investigation into changes in tower loads due to modifications within properties of blade. Consequently the reference wind turbine model has to be scaled up in steps up to a 10MW rated power. Each of these steps requires a new control system design as proven by this paper. Designing the control system and running lifetime DELa calculations requires a lot of time. As a result the area of investigation may be reduced to regions of rated power production and near shut down.

Acknowledgement:

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