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THRUST COEFFICIENTS USED FOR ESTIMATION OF WAKE EFFECTS FOR FATIGUE LOAD CALCULATION

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ABSTRACT SUMMARY

Installation of wind turbines in a wind farm will lead to additional loading due to the so called "wake effects". These effects must be taken into account when the site suitability of the turbines is assessed by a site-specific load calculation.

For four exemplary turbine types the effective turbulence intensities are calculated and additionally aero-elastic fatigue load calculations are undertaken to determine the fatigue loads for different cases considering different thrust coefficients. The effective turbulence intensities are obtained considering the generic thrust coefficient and the individual turbine specific thrust coefficient as input values.

The effective turbulence intensities calculated by using the generic turbine thrust coefficient are conservative compared to the results obtained by using the turbine specific thrust coefficients. The fatigue loads of the different turbines can only partly preserve this conservatism of the approach. Especially the stall regulated turbine simulation model applied shows that the usage of the turbine specific thrust leads to higher fatigue loads.

OBJECTIVES & MOTIVATION

Development of wind farms using modern turbine technology and micro-siting procedures will result in a turbine spacing that will cause the neighbouring turbines to influence each other. The influence is caused by the so called “wake effects”. The wake effects have two main consequences that are important for the commercially successful wind farm development: (1) the loss of energy and (2) the increased fatigue loading. This research will only discuss the second subject.

During the wind farm development a load calculation is carried out to analytically determine the site-specific turbine loads including the influence of the wake effects. State-of-the-art to take into account the wake effects for this purpose is the method of equivalent turbulence intensity and thus a calculation of an “effective turbulence intensity” ([7], [2], [3], [5] & [1]) and the subsequently application of the effective turbulence in the wind field modelling for the aero-elastic load calculation. With the method of effective turbulence intensities, the effects of all load generating mechanisms are packed in into an adjustment of the intensity of the free flow turbulence. The method was calibrated on the loading of flap-wise blade bending fatigue loads [7].

The aim of this research is to determine to what extend the analytically calculated wind turbine fatigue loading of turbines installed in wind farms depends on the methodology for the estimation of the wake effects. For the consideration of the wake effects the effective turbulence intensity developed by Sten Frandsen [7] is used. The approach of the effective turbulence intensity is also suggested by most modern standards ([3], [5] & [1]). The basic equation is:

$$I_{eff} = \frac{1}{V_{hub}} \left[(1 - N p_w)\sigma^m + p_w \sum_{i=1}^{N} \sigma_T^m (d_i) \right]^{\frac{1}{m}}$$

Equation 1

In this equation V_{hub} is the average wind speed at hub height, N is the number of neighbouring wind turbines, p_w is the probability density function of the wind direction, m is the Woehler exponent (material SN-exponent) and σ is the ambient wind speed standard deviation. The maximum centre-wake wind speed standard deviation is expressed as σ_T and calculated as discussed in Equation 2.

The methodology formulated in [7] uses the thrust coefficient (C_T) as an input parameter to estimate the characteristics of the wake effect of the wake producing turbine. In particular the added turbulence will be a function of the thrust coefficient. Therefore the equation of the maximum centre wake at hub-height in the “original” expression [7] is given as:

$$\hat{\sigma}_T = \sqrt{\frac{0.9 V_{hub}^2}{(1.5 + 0.8 \frac{d_i}{\sqrt{C_T}})^2} + \hat{\sigma}_1}$$

Equation 2

In Equation 2 the “factor” 0.9 was part of discussions but is now implemented in the informative annex in the recent IEC 3rd Edition [3]. For this research the “factor” has been adjusted to 1.0 and used in all calculations consistently. d_i is the distance to the neighbouring wind turbine, normalised by the rotor diameter. The thrust coefficient of the wind turbine rotor C_T is modelled as given in Equation 3, which is an approximation [7] that is supposed to fit for most of the modern wind turbines.

$$C_T = \frac{3.5(2V_{hub} - 3.5)}{V_{hub}^2} \approx \frac{7\frac{m}{s}}{V_{hub}}$$ **Equation 3**

In the original method this “generic thrust coefficient” is suggested to be used as a simplified worst case value (or curve).

In the recent amendment of the IEC standard [4] the interpretation of the thrust curve has changed and the thrust coefficient is now defined as follows:

> C_T *is the characteristic wind turbine thrust coefficient for the corresponding hub height wind velocity. If the thrust coefficient for the neighbouring wind turbines are not known, a generic value* $C_T = 7\,c\,/\,V_{hub}$*, where* c *is a constant equal to* 1 m/s*, can be used.*

Also in the recent DIBt Guideline (2004) [5] the application of the thrust coefficient is different from the “original” formulation. There the thrust coefficient is defined as follows:

> C_T *thrust coefficient of the rotor, with respect to the rotor plane.*

These formulations rely on the real turbine thrust coefficient (as a turbine specific characteristic, measured or analytically calculated) as an input parameter for the calculation of the centre wake.

The objective of this research is to apply both the real turbine specific thrust coefficient and the generic thrust coefficient (Equation 3) in a parametric study and to compare the results of the effective turbulence. Further these effective turbulences are used to calculate fatigue loads and to compare these respectively.

ASSUMPTIONS

Turbine Types

To discuss turbine specific results, four typical modern wind turbine types are used for calculation of the effective turbulence intensity and simulation of the fatigue loads. These turbines range from 500kW to 2MW with hub heights between 50m and 100m. The most relevant turbine details are listed in Table 1.

The turbines 1 to 3 are three-bladed systems, with the rotor arranged on the windward side with power output limitation by blade adjustment and active yaw. The turbine 4 is a three-bladed system, with the rotor arranged on the windward side with stall controlled power limitation and active yaw. For all four turbines the relevant parameters of a control and safety system are taken into account during the power production and idling load cases. The shut-down and start-up procedures have been neglected in this research to exclude further turbine specific disturbances of the results.

Table 1: Turbine Geometry and Control Data

No.	Turbine ID	MW-Class	D/H *	Control
1	WEA-01-P	1 - 2 MW	1,1	Pitch
2	WEA-02-P	1 - 2 MW	0,8	Pitch
3	WEA-03-P	1 - 2 MW	0,8	Pitch
4	WEA-04-S	0.5 - 1 MW	0,9	Stall

* ratio of the rotor diameter to the hub height

Thrust Coefficients

As discussed above (Section Objective & Motivation) the model used for assessing the wake effects is largely relying on the thrust coefficient of the turbine. These thrust coefficients can be given by the manufacturer or can be calculated with an adequate simulation software if the needed simulation data is available. The thrust coefficient curves typically available are determined using Blade Element Method simulating the wind turbine. In this research the validity and accuracy of the thrust coefficients applied is not analyzed. Nevertheless the thrust coefficients from the official specifications have been cross checked with the simulation results and were found to be in good agreement with the specified values (manufacturer specifications).

For each of the 4 turbines the turbine specific thrust coefficients are needed for all wind speed bins between cut-in and cut-out wind speed. These values are taken from the turbine specification (if available) or derived using a turbine simulation program.

Figure 1 shows the 4 turbine specific thrust coefficient curves and the generic thrust coefficient curve. The thrust coefficient curves for the WEA-01-P turbine and WEA-02-P turbine exceed the generic thrust coefficient. The other two thrust coefficient curves for the WEA-03-P turbine and WEA-04-S can be considered to be within the “envelope” of the generic thrust curve.

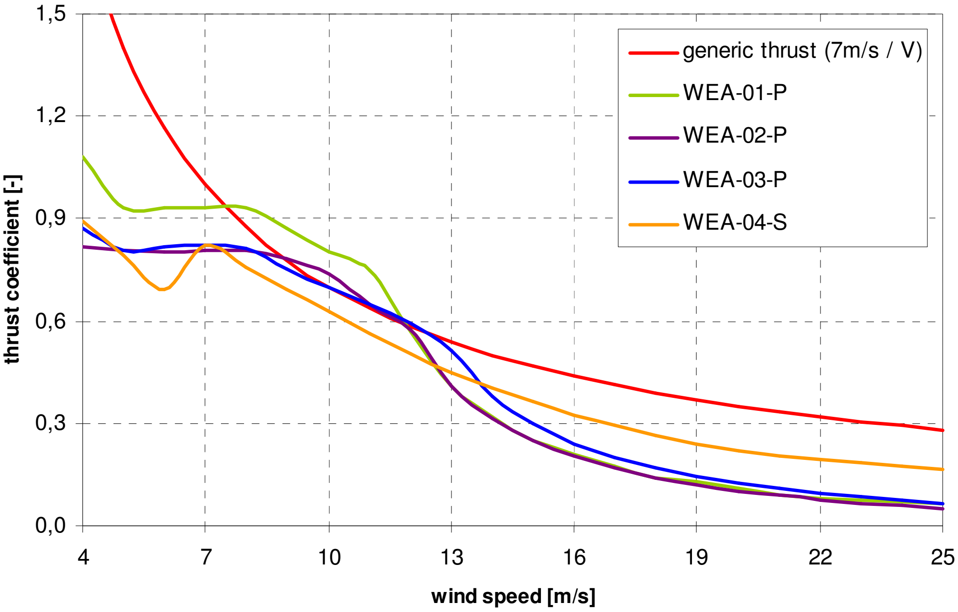

Figure 1: Thrust Coefficients of the Turbines

Wind Farm Configuration

The assumed wind farm layout comprises nine wind turbines. The layout is illustrated in Figure 2. The wind farm layout chosen is in accordance with the industry standards and best practice in terms of inter-turbine spacing. The normalised distances between the turbines (distance / rotor diameter) are summarised in Table 3.

Table 3: Normalized Distances of the Wind Farm

direction	normalised distance d_i
main wind direction (X-direction: West-East)	7
other directions (Y-direction: North-South)	3

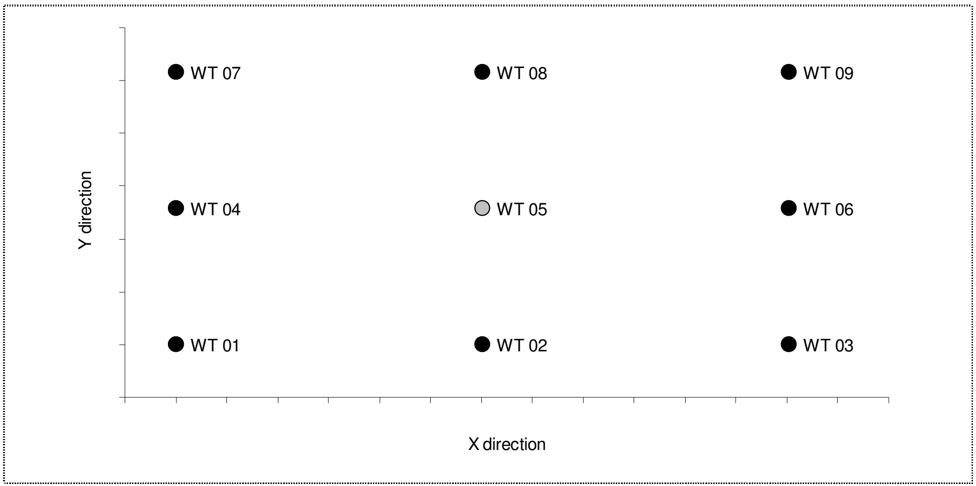

Figure 2: Wind Farm Layout

Ambient Wind Conditions

For the calculation of the effective turbulence intensity the wind direction distribution is needed. Figure 3 shows the wind direction distribution assumed for this research. It is an artificial distribution with a prevailing wind direction from west.

Ambient turbulence is assumed to be I_{15} = 18% as a characteristic value with the typical IEC 61400-1 (2^{nd} Edition, 1999) class A distribution over the wind speed bins.

For the fatigue load calculation the mean wind speed and the shape parameter of the wind distribution are needed. These values are V_{ave} = 8.5m/s and k = 2.0.

These wind conditions are kept identical for all simulations. All other external conditions needed for load calculation are assumed to be standard IEC and are identical for all simulations.

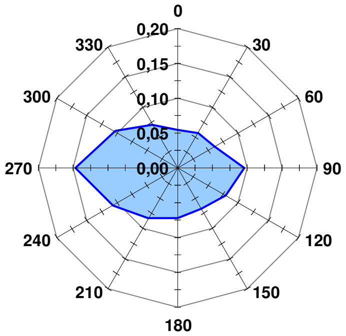

Figure 3: Wind Direction Distribution

METHODOLOGY

Wake Effect Calculation

To consider the influence of the wind turbines on the loads the wake effects are modelled using the method of equivalent turbulence intensity. Thus the calculation of the effective turbulence intensity ([7], [3], [5] & [1]) is performed. Therefore the Equation 1 was used for the computational model. The probability density function p_w has been adjusted to the wind rose displayed in Figure 3 and the layout according to Figure 2.

For each turbine type two sets of calculations are performed:

A) applying Equation 1 with the centre wake calculated using the generic thrust coefficient according to Equation 3;

B) applying Equation 1 with the centre wake calculated using the turbine specific thrust coefficient displayed in Figure 1.

To keep the computational effort low the effective turbulence intensity is calculated for two different Woehler slopes: (1) the slope of m = 4 for steel materials (e.g. tower) and (2) the slope of m = 10 for glass fibre reinforced plastic (e.g. rotor blades).

All results displayed are the results of turbine location no 5 (WT05), which is considered to be the highest loaded turbine.

Turbine Fatigue Load Calculation

The fatigue load calculation methodology is based on IEC 61400-1 (2nd edition, 1999) [2] as most turbines currently installed are designed and certified according to this standard.

For the fatigue load examination, calculations are performed in consideration of the site-specific wind speed distribution, air density, shear and wind up-flow angle. These assumed wind and external conditions are outlined above.

For the fatigue load calculations the effective turbulence intensities are used to model a three-dimensional turbulent wind field. Idling below cut-in and above cut-out wind speed is considered. The calculated values of the effective turbulence intensity are used for the wind field modelling and to perform the fatigue load calculations. The shut-down and start-up procedures are not taken into account to avoid turbine specific load differences.

The load cycles of the simulated time histories for the calculations are quantified using the Rainflow counting method. This is performed using the associated wind speed distribution for a 20-year lifetime. These load spectra are converted, assuming S/N-curve slopes of m=4 and m=10 and a reference number of load cycles of N_{ref} = 1.0 * 10^7, into damage-equivalent constant-range load spectra (DELs) for the relevant load components.

RESULTS

Effective Turbulence Intensities

As a first result the effective turbulence intensities (for Woehler slope m=10) are compared for all four turbine types. In Figure 4 these values are displayed for the calculation performed using the turbine specific thrust coefficient. When using the generic thrust coefficient the results for the different turbines are all identical, respectively.

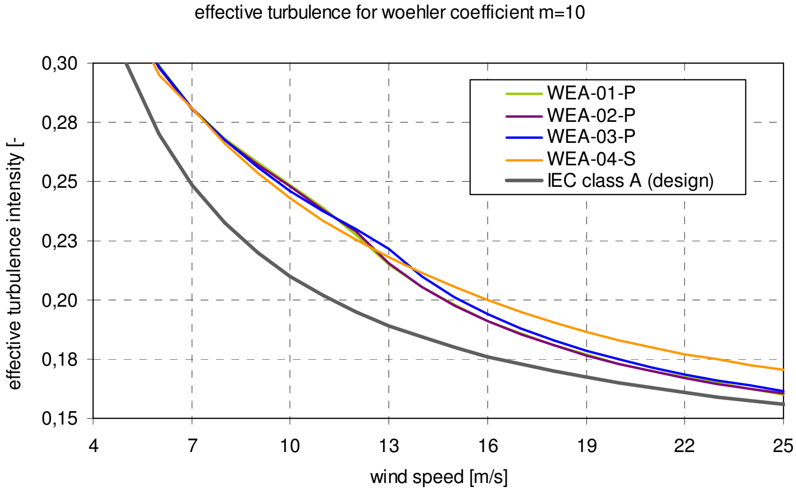

Figure 4: Effective Turbulence Intensities for Different Thrust Coefficients

To highlight the difference of the effective turbulence intensity results between the turbine specific thrust coefficient and the generic thrust coefficient the results are shown using the percentage of the margin (Equation 4).

$$\%TI_{marging} = \left\{ \left(\frac{TI_{realC_T}}{TI_{genericC_T}} \right) - 1 \right\} \cdot 100\%$$

Equation 4

The margins of the effective turbulence intensities are given for each turbine type separately in Figure 5 to Figure 8.

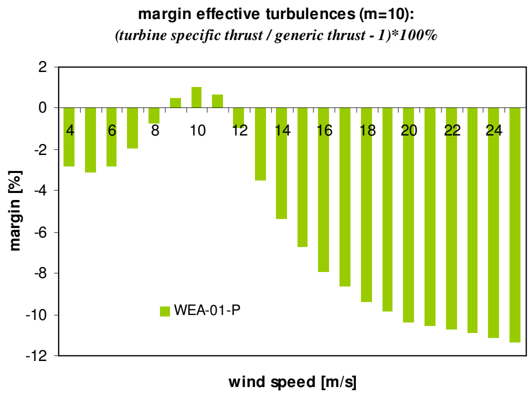

Figure 5: Margin of the Effective Turbulence Intensity, Turbine WEA-01-P

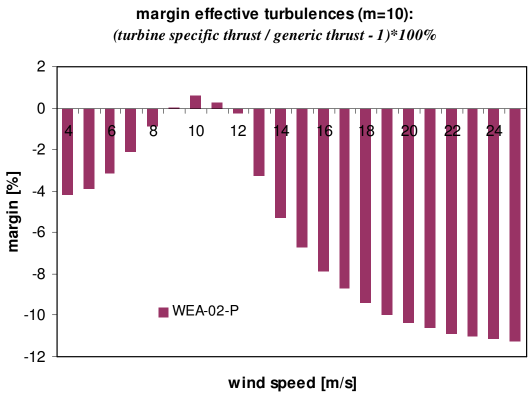

Figure 6: Margin of the Effective Turbulence Intensity, Turbine WEA-02-P

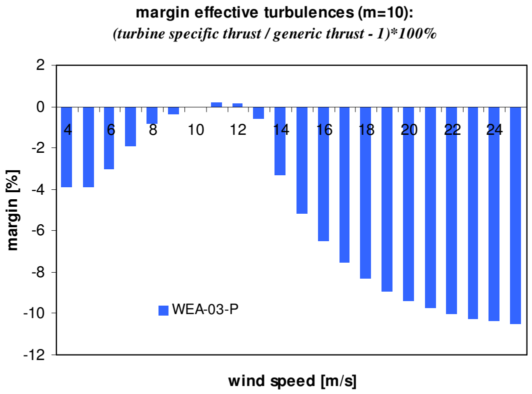

Figure 7: Margin of the Effective Turbulence Intensity, Turbine WEA-03-P

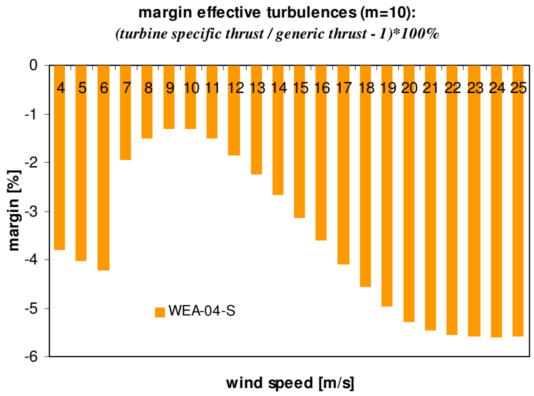

Figure 8: Margin of the Effective Turbulence Intensity, Turbine WEA-04-S

The results in the graphs of the different turbines show that for three turbine types the calculations with the generic thrust coefficient give more severe results in some wind speed bins. Nevertheless the higher values of effective turbulence intensities are restricted to the wind speed bins between 9m/s and 12m/s. This could be expected from the comparison of the thrust curves in Figure 4.

It is revealed that resulting effective turbulence intensities calculated with the generic thrust coefficient are conservative compared to the effective turbulence intensities calculated with the real thrust curves. Even if in some wind speed bins the conservatism is not given for the majority of the wind speed bins, the effective turbulences calculated using the generic thrust coefficient are higher.

Turbine Fatigue Load Results

The loads for selected components of the wind turbine structure are compared similar to the scheme for the effective turbulence intensities. The margin is calculated as given in Equation 5.

$$\%DEL_{marging} = \left\{ \left(\frac{DEL(TI_{realC_T})}{DEL(TI_{genericC_T})} \right) - 1 \right\} \cdot 100\% \qquad \textbf{Equation 5}$$

In this equation $DEL(TI_{realCT})$ is the DEL, calculated using the effective turbulence intensity derived by applying the turbine specific thrust coefficient of the turbine (Figure 1). $DEL(TI_{genericCT})$ is the DEL, calculated using the effective turbulence intensity derived by applying the generic thrust coefficient (Equation 3), respectively.

The load deviations for the major components are presented as a bar chart in Figure 9 and Figure 10.

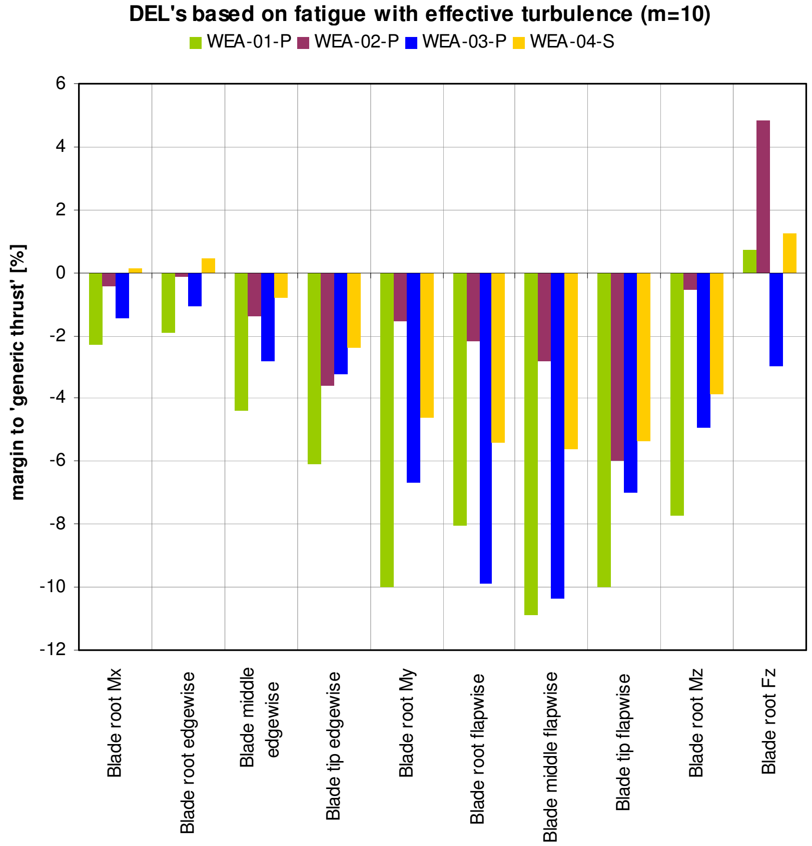

Figure 9: Margin of the DELs for all Turbines and Components Applicable to Woehler Slope m=10.

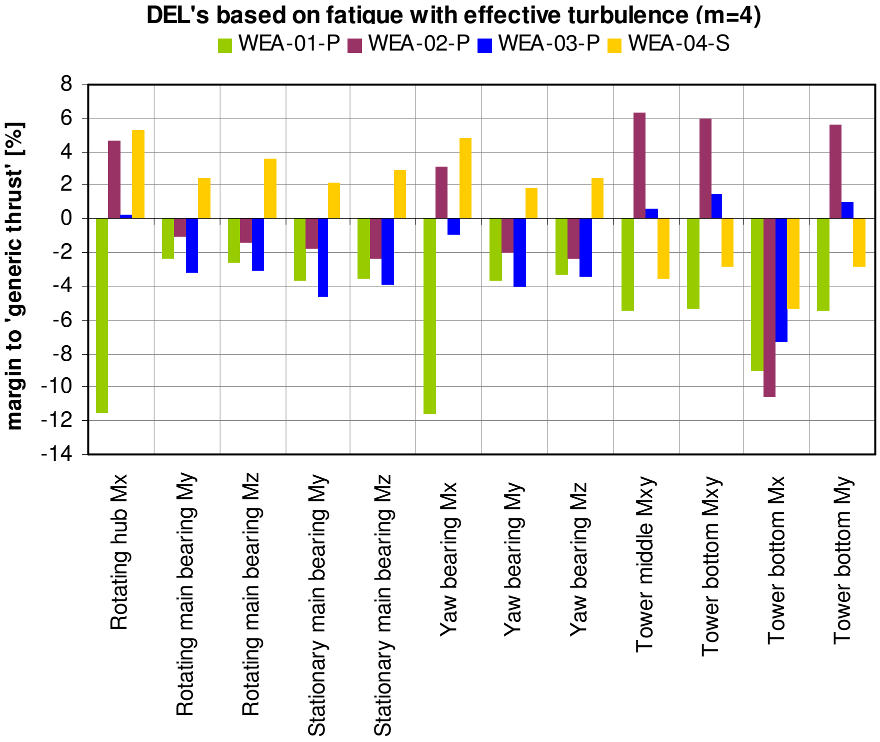

Figure 10: Margin of the DELs for all Turbines and Components Applicable to Woehler Slope m=4.

The following main results are evident:

- Figure 9 shows that for all turbine types and therewith all thrust coefficients considered the usage of the generic thrust coefficient is conservative with respect to the loading of the components discussed (Blades, Woehler slope $m = 10$).
- Figure 10 shows that the usage of the generic thrust coefficient for turbine WEA-01-P and WEA-03-P is conservative or equivalent to using the turbine specific thrust coefficient.
- For turbine WEA-02-P the usage of the generic thrust coefficient is not conservative especially for tower bending, but for most of the other components.
- For turbine WEA-04-S the usage of the generic thrust coefficient is not conservative for all components. Only for the tower bending conservatism appears.
- For the performed load calculations the results show that the conservatism seen in the results of the effective turbulence intensity can not be maintained throughout the resulting DELs for all components.
- For two of the four turbines even in the DELs the conservatism of the approach is not present anymore but for one turbine type only the tower bending moment is not conservative.
- For the stall regulated turbine most of the components seem to result in higher DELs, when the effective turbulence intensity calculated by using the generic thrust coefficient is used.

CONCLUSIONS

The analysis investigates the influence of thrust coefficients as an input parameter for the calculation of the effective turbulence intensity and the subsequent fatigue load calculation.

The approach of using a generic turbine thrust coefficient is conservative regarding the results of the effective turbulence intensities.

Considering the results of the fatigue load calculations, the majority of the turbines have conservative results if the generic turbine thrust coefficient is used for calculating the effective turbulence intensity. Only for one stall regulated turbine type the approach of using the generic turbine thrust coefficient must be considered as not conservative.

For the load calculation results that are not conservative the load deviations are minor, keeping in mind the overall uncertainty in fatigue load calculations.

In conclusion the usage of the generic turbine thrust coefficient can be assumed to be fairly straight forward and conservative for the majority of the relevant turbine types.

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