Accuracy of load assessments based on modelled turbulence - The German example

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Summary. This study investigates the accuracy of wind turbine fatigue loads based on modelled ambient turbulence for sites typical of Germany. It is analysed if modelled turbulence from the microscale models WAsP Engineering and WAsP-CFD can reproduce fatigue loads based on measured turbulence. The microscale models are applied to 23 locations with high quality wind measuring masts, mostly ≥100 m. Fatigue loads are estimated for each mast position for the main turbine components, first using the measured turbulence and second using the modelled turbulence. The results allow a direct assessment of the error introduced by the modelled turbulence and show only a small difference between using WAsP Engineering and WAsP-CFD across the 23 sites in non-complex terrain. When combined with the 'COV=0.2' assumption both models result in fatigue loads on tower and blades, which are close to bias free (-3% to +2%) with a standard deviation of SD=5-6%. This variation can be accounted for either by (1) applying a deliberate positive bias using COV=0.3 instead COV=0.2 or by (2) adding a 2xSD safety margin (i.e. ~10%) to site load estimates when comparing to design loads.

1. Introduction

In mature wind energy markets such as Germany and Denmark with thousands of operating wind turbines, it is not common practice to install wind measurements prior to developing a new wind power project. Instead, production data from surrounding wind farms is used to calibrate the wind flow model. This is a well-established approach for non-complex terrain, which results in sufficiently accurate wind distributions and production estimates for investment and financial decisions.

Another important aspect of developing a wind farm is to ensure turbine site suitability according to the relevant design standards, e.g. IEC61400-1 [1] or DIBt 2012 [2]. These standards require more detailed wind climate measurements as such turbulence, wind shear, flow inclination and air density. Turbulence is the main driver of fatigue loads and, hence, the most critical of these site parameters in particular in projects with many existing or planned turbines and increased turbulence due to wake effects. When no measurements are available, suitability decisions are based solely on modelled values of the ambient turbulence. The objective of this study is to investigate the accuracy of wind turbine fatigue load estimates based on modelled ambient turbulence for sites typical of Germany.

2. Approach

Previous studies on the accuracy of modelled ambient turbulence in a German context focused on detailed aspects of the accuracy of modelled versus measured turbulence, e.g. [3]. Aspects such as the accuracy of capturing the directional variation of turbulence or the variation of turbulence with height or wind speed. These analyses are highly relevant and interesting for evaluating and improving the accuracy of the microscale flow models to predict details of the turbulent wind field. However, due to the highly non-linear and complex relationship between turbulence and fatigues loads, it is very difficult to conclude directly from these analyses to the consequence for the accuracy of the resulting fatigue loads based on modelled turbulence.

This study focuses directly on evaluating the accuracy of wind turbine fatigue load estimates based on modelled turbulence. Fatigue load estimates for the main wind turbine components are the key decision parameters when evaluating wind turbine site suitability, in particular for North European sites where extreme wind speeds are rarely a problem.

The approach of this study is based on wind measurements from 23 high quality wind power masts positioned in Germany and neighbouring countries. For each mast position first step of the approach is to estimate the 'true' site fatigue loads for the main wind turbine components using the measured wind climate (A), simplified as defined in IEC 61400-1 [1]. In second step, the measured turbulence is replaced by modelled turbulence predicted using a microscale model (described in section 3). All other climate parameters remain unchanged, and fatigue loads are estimated as in step 1, but using the new (B) climate. The resulting fatigue load estimates at each mast position for the wind climates A and B, allow a direct assessment of the error introduced by using the modelled turbulence in (B) instead of the original measured turbulence in (A).

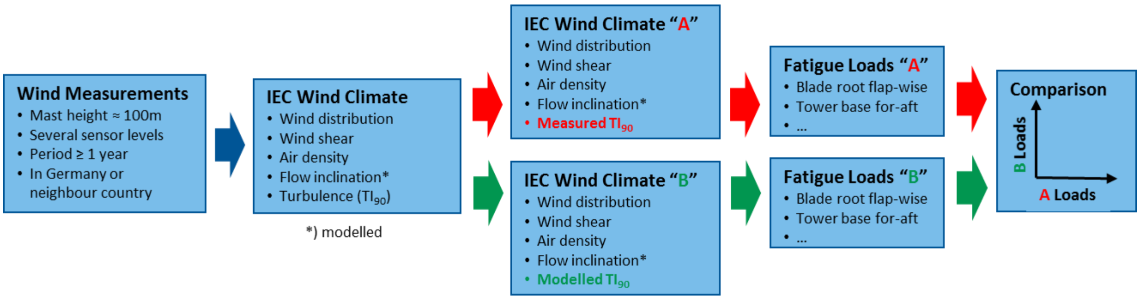

Figure 1: *Sketch of the work flow in the approach used in this study.*

3. Turbulence models and assumptions

The modelled turbulence is predicted using two different and commonly used microscale models: 'WAsP Engineering' ('WEng') and 'WAsP-CFD'. Both models are readily available in windPRO, and are developed by the Danish Technical University (DTU). WEng is a PC-based fast and linearized flow model, whereas WAsP-CFD is a non-linear, cluster-based flow solution. The actual CFD solver behind WAsP-CFD is DTU's Ellipsys3d [4], which runs on EMD's Cerebrum cluster as an on-demand cluster service. Both microscale models predict only mechanical contributions to ambient mean turbulence due to terrain and roughness in steady state simulations, and neglect thermally generated turbulence and dynamical effects. This prevents direct use of the modelled turbulence as the IEC standard [1] requires the 90th percentile of ambient turbulence (TI_{90}) as a function of wind speed. Calculation of TI_{90} requires both the mean (TI_{μ}) and the standard deviation (TI_{σ}) of turbulence via the expression below.

$$TI_{90} = TI_{\mu} + 1.28 \cdot TI_{\sigma}$$

To derive the required TI_{90} from the modelled turbulence an additional assumption is needed to estimate the standard deviation. Two different assumptions have been introduced in commercially available software and in the following they are referred to as 'COV=0.2' and 'WAT/NTM'[1]. The 'COV=0.2' assumption has been used historically in Germany and was first implemented in the windPRO SITE COMPLIANCE module. This assumption does not compensate for the lack of thermal contributions to turbulence, and simply assumes a fixed coefficient of variation (COV) of 0.2 as shown in the expression below.

$$TI_{\mu} = TI_{model} \text{ and } TI_{\sigma} = 0.2 \cdot TI_{model} \qquad \text{('COV=0.2')}$$

The WAT/DTU assumption was introduced in the DTU software tool 'WAT' and seeks to account both for the lack of standard deviation, but also for the lack of thermal effects, by introducing a strong wind speed dependence of the mean turbulence. This assumption uses equations and numbers inspired by the IEC Normal Turbulence Model (NTM) outlined below.

$$TI_{\mu} = \frac{5+u}{u} TI_{model} \text{ and } TI_{\sigma} = \frac{1.92}{u} \cdot TI_{model} \qquad \text{('WAT/NTM')}$$

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[1] In windPRO the 'WAT/NTM' assumption is named 'Traditional Risø-DTU'.

Both these assumptions are implemented for use with WEng in windPRO, but just ‘COV=0.2’ for WAsP-CFD. Hence, to focus this study on what can be done with the current version of windPRO the analysis is performed for the three combinations available in windPRO 3.0:

1) WEng + ‘COV=0.2’ 2) WEng + ‘WAT/DTU’ 3) WAsP-CFD + ‘COV=0.2’

Figure 2 illustrates the two different assumptions to obtain TI_{90} from a modelled turbulence of $TI_{model}=0.12$. Notice how the ‘WAT/NTM’ assumption leads to very large values of TI exceeding 30% at low wind speeds, due to its strong wind speed dependence of TI from assumed thermal effects. This behaviour is very different from the wind speed independent signature of the ‘COV=0.2’ assumption. At 25m/s the ‘WAT/NTM’ and the ‘COV=0.2’ coincide and at even higher wind speeds ‘WAT/NTM’ has lower values than ‘COV=0.2’, as it assumes a coefficient of variation (COV) which decreases with increased wind speed.

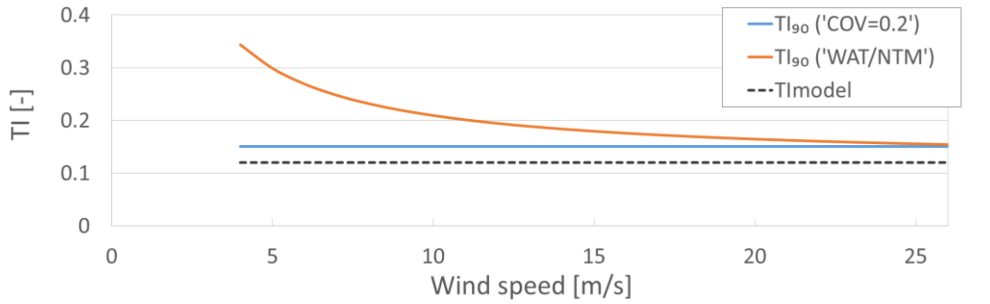

Figure 2: *Illustration of the ‘COV=0.2’ and ‘WAT/NTM’ assumptions for* $TI_{model}=0.12$.

4. Wind data

The wind data of this study originate from 23 high quality measuring masts installed for wind power development. All masts have top anemometers around 100m (104m on average) either top-mounted or with double-anemometry to minimize mast shadowing effects. The majority of the masts are situated in Germany and the rest, are situated in neighbouring countries with similar terrain and meteorology. Mast settings span from off-shore, over coastal sites to sites hundreds of kilometres inland. Land cover type ranges from forested to open land.

For each mast the measured wind climate is simplified according to the requirements in IEC61400-1 [1]. Hence, for each mast the following quantities are estimated from the measurements: wind speed distribution (Weibull), 90th percentile of turbulence versus wind speed (TI_{90}), vertical wind shear exponent, mean air density and maximum flow inclination. None of the masts measure flow inclination, so all flow inclinations are estimated using WAsP-CFD. Due to the high measuring heights and relatively simple terrain, all flow inclinations are close to zero.

For the top anemometer of each mast TI_{90} is estimated as the ‘Effective turbulence’ at each wind speed bin according to IEC61400-1 ed. 3 [1]. Hence, the directional variation is integrated out across the 12 direction sectors using the Wöhler exponent. Figure 3 illustrates the resulting observed effective TI_{90} versus wind speed for each of the 23 masts (grey) and their mean (black).

Note that most TI_{90} curves and their mean curve (cf. Figure 3) are nearly constant for wind speeds above 7-8m/s, and not so different from the ‘COV=0.2’ curve in Figure 2.

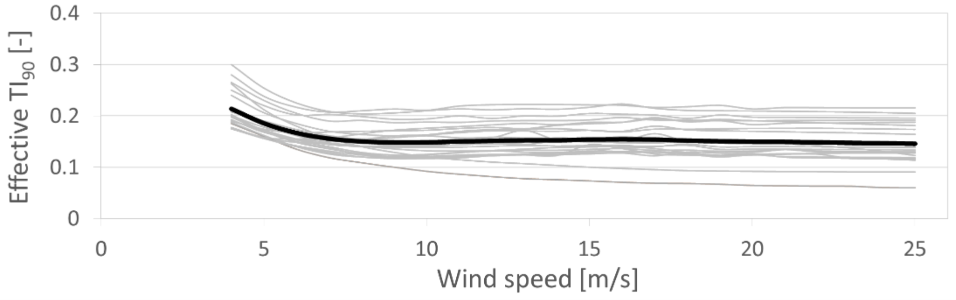

Figure 3: *Plot of Effective* TI_{90} *for the 23 masts (grey curves) and their mean (black curve).*

5. Fatigue load estimation

Fatigue load estimates are based on the main fatigue design load case ‘Normal Operation’ (DLC 1.2) in IEC61400-1 [1]. For the aero-elastic simulations the NREL simulation codes ‘FAST’ [5] and ‘Turbsim’ [6] are used. The turbine model is the ‘NREL 5MW’ turbine reference model [7]. Since all presented results are relative, either to a specific design class or to results based fully on the measurements, the results depend little on the actual turbine model and are of general validity.

The actual site specific fatigue loads are estimated from a limited number of pre-run aero-elastic simulations using the response surface methodology presented in [8] and implemented in windPRO 3.0 LOAD RESPONSE module. As documented in [8] this response surface method is very efficient and accurate for site specific fatigue load estimation with expected errors of <1% for the key components presented in this study.

Figure 4 illustrates a simple overview of the fatigue response of a wind turbine to variation in turbulence and in wind speed for ‘blade root flap-wise bending’ (left part) and for ‘tower bottom for-aft bending’. To focus this study, results are only presented for these two critical key components, which are highly sensitive to turbulence.

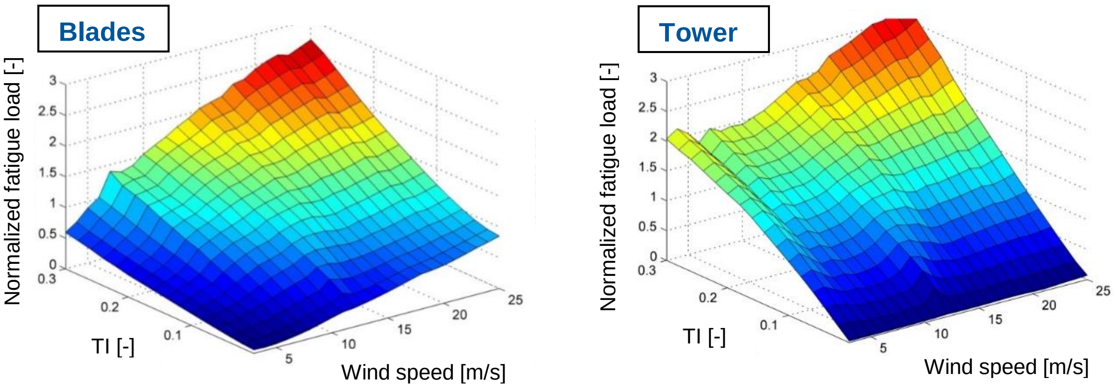

Figure 4: *Fatigue response of blade (blade root flap-wise bending) and tower (tower bottom for-aft bending) as a function of turbulence level and mean wind speed.*

Note the strong increase in fatigue for increased turbulence for both tower and blades, but also that tower is much more sensitive to high turbulence at low wind speeds than blades.

6. Results

Figure 5 illustrates the resulting fatigue loads for each of the 23 masts, comparing the results using the measured TI_{90} at each mast to the results using the three different turbulence methods. To ease the comparison all results for each mast are normalized to the results using the measured TI_{90}. Hence, all results using measured TI_{90} form a horizontal (black) line equal to 1.0 across the masts, which are on the horizontal axis.

Note that the WEng+’WAT/NTM’ method consistently results in too high fatigue loads, in particular for tower loads which are overestimated by more than 40% for most masts. For blades the overestimation of the WEng+’WAT/NTM’ method is less severe, but still consistently above 20% for most masts. The WAsP-CFD+’COV=0.2’ and WEng+’COV=0.2’ methods perform quite consistently and their results vary closely around the ‘true’ value based on the measurements, and are within ±10% for all masts.

As all sites are situated in non-complex terrain typical of Germany, it is anticipated that the linearized WEng model and the non-linear WAsP-CFD model produce consistent results. However, for sites in semi-complex and complex terrain the results would be more different and WAsP-CFD more accurate as the non-linear flow effects will become increasingly important and be captured better by the non-linear model WAsP-CFD.

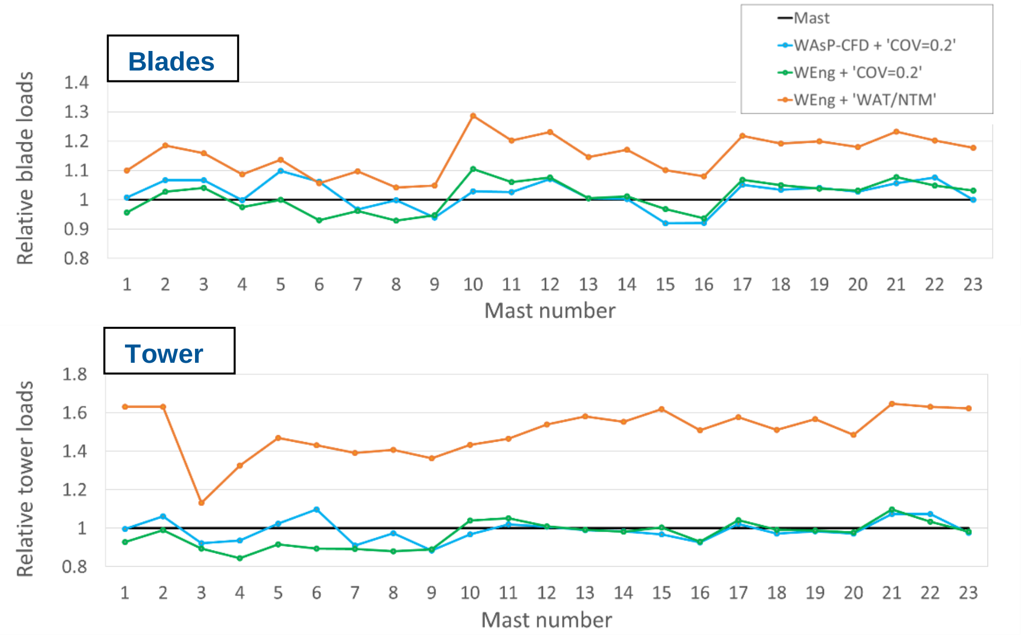

Figure 5: *Results for each mast location for each of the three model setups. The results are normalized to the 'true' value using the measured turbulence. Top: Blade root flap-wise bending, bottom: Tower bottom for-aft bending. Note the very high values for WEng+'WAT/NTM', in particular for tower loads.*

7. Summary and conclusion

Table 1 summarizes the results of this study as presented in Figure 5. The results are summarized as the mean bias and standard deviation of bias (SD bias) for each of the turbulence methods.

Table 1: *Summary of results for all 23 masts for each of the three turbulence methods analyzed in this study.*

	WAsP-CFD + 'COV=0.2'		**WEng + 'COV=0.2'**		**WEng + 'WAT/NTM'**	
	Mean bias	SD bias	Mean bias	SD bias	Mean bias	SD bias
Blade	2%	5%	-1%	5%	15%	6%
Tower	-1%	5%	-3%	6%	50%	12%

Overall these results show that on average blade and tower loads are estimated with negligible bias using the 'COV=0.2' assumption no matter if the flow model is WEng or WAsP-CFD. The bias SD of 5-6% indicates a consistent performance and limited increase of uncertainty. The WAT/NTM method on the other hand has a significant bias of +15% for blade loads and +50% for tower loads. The surprisingly high overestimation for tower loads is explained by comparing Figures 2, 3 and 4. The Figures 2 and 3 show how the 'WAT/NTM' assumptions overestimate measured turbulence most severely at the lowest wind speeds, due to its very strong wind speed dependence of TI_{90}. Figure 4 shows how tower loads, in particular, are sensitive to high turbulence at low wind speeds.

In conclusion, the findings of this study suggest that use of the 'WAT/NTM' assumption for site suitability when no measurements are available is extremely conservative, in particular for tower loads, and should be avoided. On the other hand use of the 'COV=0.2' assumption with WAsP-CFD or WEng will on average lead to unbiased fatigue loads. But the SD of 5-6%, which indicates the uncertainty, shows that loads are slightly underestimated for half of the sites. To avoid underestimation due to the increased uncertainty two alternative options are suggested:

1) Increase the assumed COV to 0.3 to deliberately bias the assumption towards conservative results. For COV=0.3 worst case bias is limited to be within -3%.
2) Compensate the increased uncertainty by adding a 2xSD safety margin to site fatigue load estimates when comparing to design loads. (i.e. add ~10% to site loads).

References

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