Fatigue load estimations of intermittent wind dynamics based on a Blade Element Momentum method

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Abstract. Fatigue loads related to a statistical feature of wind are investigated: Super-Gaussian distributed wind velocity increments as a result of intermittency of turbulence and their impact on the longevity of wind turbines are in the focus. Two types of synthetic wind fields are fed to a common Blade-Element Momentum theory based wind turbine model of the NREL 5MW reference wind turbine. A special effort has been made in the generation of these fields in order to isolate the effect of the increment statistics. Besides these intended differences other statistical features like mean wind speed, turbulence intensity and spectral properties and coherence are equivalent. Based on these wind field characteristics, we are able to show an increase in fatigue loading.

1. Introduction
Reducing uncertainties within the planning, operation and design of Wind Turbines (WT) is a constant demand in wind energy. This holds especially true for modern blade designs, which are often relatively large and slender and push the limits of the design tools and models. A challenging task within the design process is the estimation of the turbine’s fatigue life, which strongly depends on the WT’s load response to highly dynamic, turbulent inflow. So called wind models are used to describe the dynamic behaviour of wind. Common models focus on representing the spectral properties of wind velocity components and their coherence, cf. Ref. [1, 2]. This approach is widely accepted and reproduces the targeted features of wind well. However, due to the seemingly endless complexity of wind and atmospheric turbulence, modelling efforts focus on specific features, while neglecting others, as they are assumed to be of minor importance.

This work examines a special turbulence feature of wind: The probability distribution of wind speed changes \( \delta u_\tau \) over the time \( \tau \).

\[
\delta u_\tau(t) = u(t + \tau) - u(t) \tag{1}
\]

These changes or increments are known to be non-Gaussian distributed for small scales, which is related to the more complex concept of turbulence intermittency introduced into turbulence
theory by Kolmogorov in 1962 (K62, cf. e.g. Refs. [3, 4]). In general, intermittency can be defined as the non-linear scaling behaviour of the structures functions $S_n$ which are the central moments of increments

$$S_n(\tau) = E[(\delta u_{\tau})^n].$$

In this study we focus exclusively on the effect of the non-Gaussian behaved increment statistics, related to the fourth structure function $S_4$.

As an example, Fig. 1A shows increment distributions, which are typical for intermittent wind field data. As of now, these dynamics are neglected in the design process of wind turbines, since all models featured in the International Electrotechnical Commission (IEC) standard [1] imply Gaussian increment statistics. Increments can be understood as primitive gusts and therefore, their statistics may be related to the performance and loads of WT. Previous works investigated the impact and relevance of the presented dynamics to the wind turbine systems. Milan et al. found turbulence-like dynamics in the power output of wind turbines [5], which gives reason to believe these statistics also have the potential to alter the loading. This problem has already been investigated by several authors [6, 7, 8]. However, the conclusions of these studies do not agree well with another, wherefore we aim to contribute to this discussion and shed light on some new aspects. Finally, the goal of this work is to examine if the fatigue load results change due to non-Gaussian wind speed increment statistics.

2. Methodology

In this work synthetic wind fields specifically designed for the analysis of the intermittent dynamics are fed into a Blade Element Momentum (BEM) based wind turbine model of the National Renewable Energy Laboratory (NREL) 5MW reference WT [9]. Resulting time series for prominent load sensors (rotor thrust and torque, blade root bending moment out of plane and tower base bending moment in fore-aft direction) are analysed with common fatigue estimation algorithms. Besides the wind field generator, the methods and tools utilized in this work are aimed to be in accordance with design guidelines and comparable to those used in industrial applications.

2.1. Wind fields

The synthetic wind fields have been generated by utilization of a Continuous-Time-Random-Walk (CTRW) based model, proposed by Kleinhans [10]. This model allows for the generation of two types of wind fields: Those with purely Gaussian statistics and so called intermittent fields, which feature Gaussian wind statistics (or one point statistics) and non-Gaussian wind increment statistics (or two point statistics, cf. Eq. 1). Examples for both types of fields are shown in Fig. 2. It is not possible to distinguish the Gaussian from the intermittent time series using basic statistics, namely one point statistics or spectral analysis. A comparison of the increment statistics, as shown in Fig. 1A, exhibits their differences. The model parameters were selected carefully so that the resulting increment histograms for the intermittent fields (cf. Fig. 1A) agree well with atmospheric measurements, carried out at FINO1 (germ. abr. Research Platforms in the North sea and Baltic Sea), cf. Ref. [11]. Furthermore we isolate the effect of the increment statistics by assuring that both field types differ by less than 1% in mean velocity and turbulence intensity. Correlations and spectral properties are in very good agreement as well, cf. Fig. 1B. Note that the differences in the increment statistics are not captured in the spectral representation. Therefore, both fields are identical according to the criteria in the IEC standard. For both types of fields ten stationary wind field samples with a length of one hour at a sampling frequency of 20Hz at seven different wind speeds with a turbulence intensity of 10% were tested. In summary, the wind fields are highly comparable. The difference between them lies in the statistical distribution of the wind speed increments cf. Eq. 1.
Figure 1. A: Comparison of histograms of wind velocity changes $\delta u_\tau$ for different values of $\tau$ for intermittent and Gaussian wind. The histograms have been normalized by their corresponding standard deviations $\sigma_{\delta u_\tau}$ and shifted vertically for better representation. B: Comparison of power spectral densities for intermittent and Gaussian wind time series.

Figure 2. Exemplary wind velocity time series at hub height. Dashed lines represent mean and $\pm$ one standard deviation. A: Intermittent wind sample. B: Gaussian wind sample.

2.2. Wind turbine model

A common, well-known BEM based aerodynamic model of the NREL 5MW turbine is considered in this analysis. Furthermore, FAST v8.15 with an AeroDyn v15 aerodynamic model is used (cf. Ref. [12, 13]). Several wind turbine model setups have been tested to evaluate e.g. the
difference in the results between an activated and deactivated pitch controller (not shown here). The results presented in this paper correspond to a purely aerodynamic model, as they need to be understood before more complex dynamics due to pitch and speed control are included. The latter will be carried out as future work.

2.3. Load calculations
During the evaluation of loads experienced by wind turbines, one distinguishes ultimate loads and fatigue loads. Standard fatigue load calculations are based on all local extrema in a given load time series. In the most simple of approaches, ultimate loads can be estimated based on single events, namely global extrema, within a wind sample. More advanced techniques – such as statistical extrapolation (cf. Ref. [1] Annex F) – exist, but are out of scope for this work. Since the velocity distributions for both types of wind fields are equivalent, the global extrema are equivalent as well. In conclusion, global load extrema caused by global wind extrema are not expected to be statistically different for the two field types. If a global load extremum is not caused by a global wind speed extremum, but instead by an extreme velocity increment, these kind of global load extrema are expected to behave statistically different between the two field types. However, from our experience global load extrema are often related to global wind extrema. While it is not the aim of the authors to rule out the possibility of an impact of the presented wind dynamics on ultimate loads, we believe that an effect on fatigue loads is both of higher relevance and more probable. Therefore, we aim to study the effect on fatigue loads first. Ultimate load analysis is planned for future work. Hence the load calculation is conducted as follows:

Fatigue loads are quantified in terms of Equivalent Fatigue Loads (EFL), cf. Eq. 3. The load ranges $r$ are obtained from the simulation load time series by utilization of a Rain-Flow Counting (RFC) [14] algorithm. Further, $m$ represents the stress-cycle (S-N) slope coefficient. The resulting expression is normalized with the time span of the simulated data in seconds $T$.

$$\text{EFL} = \left( \frac{1}{T} \sum_{i=1}^{N} r_i^m \right)^{\frac{1}{m}}$$

3. Results
To quantify the effect of intermittent increment statistics, fatigue loads for the rotor thrust and torque are shown in Figs. 3 and 4. The data is represented by means of EFL cf. Fig. 3A, and in a normalized fashion cf. Fig. 3B, where all data points are expressed in percent of the average Gaussian result. A clear increase in fatigue loads for the intermittent fields in the order of 5% to 10% for all presented load sensors can be observed. In general, the contribution of the wind dynamics to the fatigue of a given load sensors varies between the sensors which is also reflected in the results presented in this study. For instance, the edgewise blade root bending moment in operation mode is usually dominated by a periodic oscillation due to gravitational forces. The amplitude of these oscillations is commonly large compared to edgewise loads caused by the wind. In contrast, the rotor thrust dynamics are related to the wind dynamics more directly (especially, if rotor axis tilt and wind shear are neglected).

A peak for the rotor thrust and tower base moment at $9\frac{m}{s}$ can be observed (cf. Fig 3B and 6B). Changes to the unsteady aerodynamics model (not presented here) showed that the increased relative difference at these wind speeds are strongly dependent on the selected model, in this case a modified Beddoes-Leishman type [13, 15]. In conclusion, the validity of this peak difference is at question. Further research is needed to shed light into the WT’s response close to rated conditions ($11.4\frac{m}{s}$). Similar trends can be observed for the tower base bending moment out of plane cf. Fig. 6, which is closely related to the rotor thrust. The results for the blade
root bending moment out of plane cf. Fig. 5 are not as clearly divided as for e.g. the rotor thrust. The reason for this is that these results are based on the rotational sampling of only one rotor blade while all other sensors rely on the sampling of all three blades. Therefore the differences between both types of fields are more scattered for the blade root as for the other presented sensors.

![Graph A](image1.png) ![Graph B](image2.png)

**Figure 3.** A: Equivalent fatigue loads for the rotor thrust. Shaded regimes represent ± one standard deviation. Data points have been slightly shifted horizontally for better discriminability. B: Relative equivalent fatigue loads. 100% corresponds to the mean EFL obtained for the Gaussian wind fields.

![Graph A](image3.png) ![Graph B](image4.png)

**Figure 4.** Equivalent fatigue loads for the rotor torque. Cf. Fig. 3.
Figure 5. Equivalent fatigue loads for the blade root bending moment out of the rotation plane. Cf. Fig. 3.

Figure 6. Equivalent fatigue loads for the tower base bending moment in fore-aft direction. Cf. Fig. 3.

4. Conclusions and future work
An increase in the fatigue response in the order of 5% to 10% between both types of fields can be detected. Since the fields differ only in the distribution of the wind speed increments, this increase can be linked to the increment statistics and possibly even higher statistics. This impact is significant enough to possibly affect the design process of blades and reduce safety factors. Furthermore, this work shows that the differences can not only be detected in load
increment statistics as already documented by Mücke et al. [7], but also within a fatigue load calculation conform with the IEC standard, which is a novelty. To some degree, the sensitivity of RFC algorithms to the presented dynamics was at question, as RFC simplifies a provided load time series dramatically so that time information are lost. With this work it is shown that RFC based analysis can detect an impact in the fatigue loads related to intermittency.

Overall this work illustrates that a characterization with higher order statistics (in this case two-point statistics) contains additional and valuable information which can be relevant to load calculations.

The reported increase in fatigue loads are dependent on modelling details and can vary between the tested sensors. The dependence of the presented results on the coherence and size of wind structures and the overall correlation between the wind dynamics and the dynamics of a given load sensor needs to be investigated further. This might also be a possible explanation between the contradiction in the conclusions between Ref. [8] and this study or e.g. Ref. [5] with respect to the relevance of intermittency in wind turbine systems. Testing the interrelation of the presented dynamics with other wind field parameters is future work.

Another key aspect in the presented results is the BEM based wind turbine model. Future work aims at shedding light into the validity of highly dynamic load responses obtained with BEM based wind turbine models: Transient BEM simulations with turbulent inflow rely on correction models, most importantly for unsteady aerodynamics. In the presented study a Beddoes-Leishman type [13, 15] is utilized. Thus, evaluating the aerodynamic response to the presented fields with more advanced models, e.g. Ref. [16], would be very interesting.

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References
[1] International Electrotechnical Commission 2005 IEC 61400-1 Standard
[2] Mann J 1994 Journal of Fluid Mechanics 141–168
[3] Pope S 2000 Turbulent Flows (Cambridge University Press) ISBN 9781139643351
[4] Frisch U and Kolmogorov A N 1995 Turbulence - The Legacy of A. N. Kolmogorov (Cambridge: Cambridge University Press) ISBN 978-0-521-45713-2
[5] Milan P, Wächter M and Peinke J 2013 Physical Review Letters
[6] Gontier H, Schaffarczyk A P, Kleinhans D and Friedrich R 2007 Journal of Physics: Conference Series
[7] Mücke T, Kleinhans D and Peinke J 2011 Wind Energy 14 301–316
[8] Berg J, Natarajan A, Mann J and Patton G 2016 Wind Energy 19 19751989
[9] Jonkman J, Butterfield S, Musial W and Scott G 2009 Definition of a 5-MW reference wind turbine for offshore system development Tech. Rep. TP-500-38060 National Renewable Energy Laboratory 15013 Denver W Pkwy, Golden, CO 80401, USA
[10] Kleinhans D 2008 Stochastische Modellierung komplexer Systeme Ph.D. thesis Westfälische Wilhelms-Universität Münster Schloßplatz 2, 48149 Münster, Germany
[11] Website of the research platforms in the North Sea and Baltic Sea (germ abr FINO) 2016 http://www.fino-offshore.de/de/
[12] Jonkman J M and Buhl M L 2005 FAST User’s Guide Tech. Rep. EL-500-38230 National Renewable Energy Laboratory, Colorado
[13] Jonkman J, Hayman G, Jonkman B and Damian R 2016 AeroDyn v15 User’s Guide and Theory Manual (draft version) Tech. rep. NREL
[14] Matsushita M and Endo T 1968 Proc. Japan Society of Mechanical Engineers 37 40
[15] Leishman J G and Beddoes T S 1989 Journal of the American Helicopter Society 34 3–17
[16] Pirrung G, Madsen H A, Kim T and Heinz J 2016 Wind Energy 19 2053–2069