Response to Referee 2

From the center of wind pressure to loads on the wind turbine: A stochastic approach for the reconstruction of load signals

Referee's comment (RC) in blue
Author's comment (AC) in black

The references to lines in the manuscript (e.g., 'L.80') are given with respect to the **new version** of the paper.
In gray: text from the revised version of the manuscript.

GENERAL COMMENTS

REFEREE:
The authors state that the surrogate model is very fast, and can generate long time series. Thus it can be used to replace uncertain load extrapolation techniques or replace costly long-term simulations of the wind turbine – at least for certain load components. This is a very interesting prospect, but it's not thoroughly demonstrated in the paper. Regarding long-term load extrapolation (for example – loads with a one- or fifty-year occurrence probability) the PDF plots shown in Fig. 11 (and many other throughout the paper) – despite showing good agreement even in the tails of the PDFs, only reach relatively high levels of probability. I would recommend to show the ability of the method to predict extreme loads with a one-year occurrence period – which should not be computationally too intensive to achieve with a "traditional" BEM simulation-based approach.

In alternative, authors could try to compare the proposed surrogate to existing long-term datasets in the literature. The dataset generated by Barone et al. – also used by Dimitrov and Zhang (cited in manuscript) in their study – contains long-term extreme loads for the sametestcase used in this manuscript. Alternatively, the dataset by Papi and Bianchini contains 50 years of loads for the NREL 5MW – albeit on a floating foundation. Please note that other references may exist, although I am not aware of them. Here are the mentioned references ([...]). As per Journal reviewer guidelines, feel free to use or not use them as you see fit.

Thank you very much for your comment. We must admit that the main application of our current method was not stated accurately. The method could indeed be used to replace uncertain load extrapolation techniques or replace costly long-term simulations of the WT. However, additional steps are still required for achieving a complete assessment of the lifetime loads on a WT. First, transfer functions should be derived for rescaling the values of the CoWP to the actual low-frequency components of the loads. These transfer functions will depend on the specific turbine characteristics. Second, an additional model must be added to reproduce the high-frequency component of the signals. Third, the incorporation of the statistics of local wind conditions (e.g., annual mean wind speed distribution) is required for calculating the long-time loads. Combined with these three numerical descriptions, our proposed low-frequency model, based on the CoWP, could replace costly long-term simulations for assessment of the loads on WTs.

Concerning the second additional element, namely an additional model to reproduce the high-frequency contribution of the load signals, we could evidence that a simple surrogate stochastic model can be used (We refer to this point later in this response letter. See 'RESULTS' section). Then, it remains open the turbine-specific transfer function and the site-specific wind conditions.

To partially address your comment and provide the correct scope of our model, a description of how the method could be applied for engineering applications (e.g., lifetime calculations including loads with fifty-year occurrence probability) has now been included as follows:

in L.82: In its current state, the method is limited to the modeling of the dynamics of the low-frequency components of the bending moments. However, when combined with a description of the high-frequency components, a validated rescaling procedure, and the characterization of the site-specific wind conditions, this approach enables a novel method for a fast assessment of the lifetime loads in WTs.

in L.166: However, the implementation of the stochastic method for lifetime load assessment in engineering applications (i.e., including both the high- and low-frequency components of the loads) is constrained in its application. To ensure a comprehensive lifetime model, it is necessary to incorporate additional elements. A turbine-specific transfer function for rescaling the magnitudes of the loads is required. A complementary model for the high-frequency components of the loads must be integrated. Finally, the occurrence of the loads must be weighted by the distribution of the mean wind speed at the location of the WT (e.g., annual Weibull distribution).

and, in the conclusion of the manuscript L.393-412,

However, the development of lifetime predictions in engineering applications necessitates the incorporation of additional elements in conjunction with the proposed stochastic method for modeling the low-frequency component of the loads. Initially, a turbine-specific transfer function for rescaling the CoWP to the magnitudes of the low-frequency component of the bending moments should be derived. Secondly, a numerical model of the high-frequency component of the loads is required. A stochastic Gaussian model has been demonstrated to be a viable approach. Thirdly, site-specific wind characteristics should be considered. These characteristics should include the long-term standard wind conditions, such as the annual Weibull distribution of the wind speed. Additionally, spatial descriptions (i.e., perpendicular to the main flow) of the wind structures are necessary to describe the dynamics of the CoWP at the given location. These spatial descriptions may be derived either from measured data over a two-dimensional area (e.g., using LiDAR techniques), or from accurately modeled wind data, which includes realistic information about the wind structures in the spatial domain. Once the three complementary elements have been resolved, the complete prediction of the yaw and tilt bending moments at the main shaft of a turbine can be applied as follows: site-specific wind data over relatively short intervals (e.g., 10 minutes), which are used for the calculation of the CoWP. Subsequently, the dynamics of the large-scale wind structures described by the CoWP are derived by using the Langevin stochastic approach. The parameters of the Langevin model for the specific wind conditions (i.e., drift and diffusion coefficients) are then estimated. Next, stochastic realizations of the low-frequency component of the loads are generated by combining the dynamics of the CoWP and the previously determined turbine-specific transfer function. Afterwards, the high-frequency component is modeled. Subsequently, the high- and low-frequency load signals, which have been modeled independently, are combined. Finally, the long-term distribution of the mean wind speed $p(\bar{u})$ at the specific location is used to assess the entire lifetime damage of the bending moments (i.e., by applying the standard IEC procedure for load assessment based on mean wind speed binning and design load cases).

On the other hand, we appreciate the recommendation on using long-term data sets available in the literature. However, such data only comprises data on loads. The corresponding wind fields are required for calculating the CoWP and then validating our model.

As a side note, we would like to highlight that the application of the proposed stochastic approach is not limited to the estimation and extrapolation of loads. It also presents a method for modeling large-scale wind structures that the IEC standard wind models do not adequately describe. The IEC wind models assume the wind gusts to occur spatially homogeneously over the entire rotor plane. However, this assumption is not likely to be valid for modern wind turbines with rotor diameters around 200 m. Instead, gusts approach the rotors as localized structures. Thus, the question of the location of the gust becomes relevant. This location can be potentially grasped by the proposed CoWP.

Therefore, the second use of the method in the context of wind characterization should not be underestimated, as it proposes an extended description relatively simple but might be relevant for the structural life of the WT. In this regard, we reinforce in the manuscript the capability of the method for extended wind characterization.

L.78 in the introduction of the manuscript has been modified,

Our model thus offers a twofold approach. On the one hand, it facilitates the characterization and modeling of large-scale wind structures. The wind energy sector is in urgent need of a comprehensive description of these large-scale structures, as standard wind models are likely to oversimplify them. Modern large wind turbines are particularly vulnerable to this oversimplification. On the other hand, our stochastic model [...]

L.416-419 in the conclusions have been added,

For instance, wind structures such as gusts are assumed by the standard wind models to be homogeneous in space. The CoWP has the capacity to grasp localized wind structures over the rotor plane. A parametrization of the dynamics of the CoWP from atmospheric wind would thus describe the realistic, likely non-homogeneous, spatial characteristics of the gusts.

INTRODUCTION

[prev.]L26: "However, they do not yet incorporate turbulent flow structures." – Spectral models include spatial coherence functions. They do not explicitly resolve eddies; I imagine this is what authors intend here. Please clarify.

Thank you for the comment and correction. The sentence L.29 has been modified in the manuscript.

However, they do not yet explicitly resolve the turbulent eddies, i.e., the spatial characteristics of the turbulent flow structures. For the spatial coherence of turbulence, an exponential decay with distance is assumed.

[prev.]L27-30: Why are increased dimensions related to additional uncertainty in the impact of turbulent inflow on loads?

Thank you for this question. The sentences have been reorganized to state clearly and emphasize that the additional uncertainty of the estimated loads is attributable to structural properties that are distinctive of modern larger turbines, i.e., higher flexibility of the blades.

The sentences, L.34-38, have been modified in the manuscript.

Recent advancements in WT design show a persistent trend towards increasing dimensions, including higher heights and larger rotor diameters. Accordingly, certain structural properties are significantly modified within the designs of the larger WTs. Specifically, a higher degree of flexibility is characteristic of the larger and slimmer rotor blades. This may raise concerns about the validity of the assumptions or the omission of specific turbulent structures within the aforementioned standard wind models currently used by the WT industry.

[prev.]L35-40: Can more details be added regarding the observation of manufacturers: "According to manufacturers and operators of WTs, numerical simulations of the specific WTs and the standard IEC wind modeling assumptions do not adequately reflect certain load events that may be important for the structural integrity of the machines in operation."

Thank you for the question. With this sentence, we want to mention that unexpected measurements drive the main motivation for our work on operating

WTs. However, further details on the measurements or details of the specific WTs are not allowed due to confidentiality reasons in the framework of our research collaboration with the manufacturer.

[prev.]L45-53: This paragraph appears a bit confused. Some works on numerical models are mixed with works on load extrapolation techniques and work on control techniques. Please reorganize this section in the context of the introduction.

Thank you for the comment. The referenced investigations have been introduced in a more comprehensive and structured way. The paragraph has been modified in the manuscript L.51-62.

A general requirement within the wind industry is to simplify the complexity of WT representations in turbulent wind environments to allow practical implementation and minimize computational costs. As stipulated in the standard guidelines (IEC, 2019), numerical simulations of a wide range of operational scenarios are required for the validation of WT designs. Consequently, optimizing the computational time and power is imperative while ensuring satisfactory accuracy of the estimations of the responses of the WT. Some approaches have been proposed to reduce the complexity of the interaction between the wind and the WT. Examples of approaches based on a given wind field include a modified actuator sector model (Mohammadi et al., 2024) and the calculation of extended equivalent wind speeds over the rotor area (Choukulkar et al., 2016). Conversely, techniques are employed to extract characteristics of the incoming flow field from load measurements at the WT, such as blade-load-based estimators (Coquelet et al., 2024). Furthermore, due to the limitations in computational power, the loads on the WT are typically estimated over short intervals, e.g., 10 minutes. Consequently, numerical techniques have been proposed for extrapolating the loads estimated from such short time scales to lifetime load scenarios containing extreme events (Zhang and Dimitrov, 2023; Qingshan et al., 2022).

[prev.]L190: is data also filtered for direction? If the flowfield is misaligned with respect to the inflow how may this affect the measured coherence of the eddies and the results in this study?

Thank you for your question. Yes, the GROWIAN measurements have been filtered by direction to guarantee an undisturbed flow. A sentence, L.214, has been added to the manuscript to mention this information.

To guarantee an undisturbed flow, the wind direction over the 10-min periods remains within a 100° range with respect to the location of the two met masts (i.e., main direction of the flow).

The way the GROWIAN data is stretched is unclear. Is it a mix of interpolation and extrapolation? More details would be requited here. Moreover, is wind direction included in the dataset? Wouldn't changes in the man incoming wind field affect the measured coherence and size of the eddies?

Thank you for your comment. In fact, some details were missing. The details have been added to the manuscript in L.217-223.

The rescaled GROWIAN fields are defined on a stretched grid of 152 m x 150 m. The stretching is performed by increasing the distance between neighboring points of the original grid by factors of 1.5 and 2 in the vertical and horizontal directions, respectively. The green circles in Fig.4 illustrate the rescaled GROWIAN spatial arrangement, centered at $y = 0$ m and $z = 125$ m. The wind speed measurements at the 16 original locations have not been modified. The four grid points at the corners of the stretched grid are filled with the data from the next neighboring grid point at the same height. For example, the wind speed at the corner point (-76m, 50m) is assumed identical to the point at (-76m, 25m).

Regarding the distortion of the eddies, we fully agree with your comment. This is addressed in L.233-237 in the manuscript. The stretching of the GROWIAN spatial arrangement is a simplification with limitations. The method can certainly be improved. However, for practical uses in our paper, we assume the validity of the self-similarity of turbulent flows, and hypothesize that typical wind structures on the scale of the WT are obtained through the simple stretching method.

RESULTS

The BEM results are low-pass filtered as CoWP is a good description of large-scale turbulent fluctuations. The signals are also zero-meaned and normalized to have a standard deviation of 1. In the context of developing a surrogate model the manipulations that are done to the data seem to be significant. What is the effect on the long-term statistics and extrapolated loads of the filtered-out high-frequency component?

Thank you for your question. The differences of the calculations between the low-pass filtered and the total signals have been a topic of discussion, also inquired by the other referee. The contribution of the low- and high-frequency components of the loads to the total signal were investigated. The main results of the analysis are now included in Appendix B in the manuscript.

As a summary, it was found first, that the high-frequency component has a minor contribution, compared to the low-frequency, to the DEL calculated from the complete load signal. The significance of each component is quantified by the factors α and β in Eq. (B1). Second, the high-frequency signals can be assumed as noise with added autocorrelation and a dominant frequency. Then, it can be easily modeled by a simple stochastic process (see Fig. B2).

In response to your comment, and after the analysis of the high-frequency modeling, L.293-299 have been added.

It is essential to acknowledge that the discussion on the DELs presented in our work is exclusively focused on the DELs from the low-frequency component of the signals. This choice is based on a particular interest of our research partners. In order to assess the complete DELs (e.g., from both the low- and high-frequency load events), it is necessary to establish an additional model for incorporating the contribution from the high-frequency signal. In this direction, a simple surrogate stochastic model has shown satisfactory results. The characteristics of the original high-frequency load signal are well reproduced. The proposed stochastic model for the high-frequency signals, and calculations on the differences between the DELs from the low- and high-frequency load components, and total DELs are shown in Appendix B.

Regarding the normalization of the signals – given the excellent statistical agreement between the normalized signal statistics, it would be interesting to see a transfer function mapping the CoWP to yaw bearing bending moments or other wind turbine load sensors as the author see fit.

Yes, we agree entirely with your suggestion. A transfer function between the calculated CoWP from the wind fields and the low-frequency component of the bending moments at the main shaft of the WT is the immediate next step of our method. Such a transfer function would be turbine-specific, as the magnitudes of the loads will depend on the structural properties of the WT.

Along with the analysis presented in this paper, such a transfer function corresponds to a simple linear scaling parametrized by the mean and standard deviation of the original load signals. However, the term transfer function remains general, as there may be more complex cases requiring more than a linear scaling.

The transfer function between the CoWP and the loads is one of the key elements for the applicability of the approach for load assessment of operating WTs. Although the formulation and validation of such transfer functions is out of the scope of this paper, a sentence, in L.267, has been added into the manuscript.

A turbine-specific transfer function for rescaling the normalized values of the CoWP to magnitudes of the low-frequency component of operational bending moments would be necessary for the assessment of the loads in engineering applications. Such a transfer function will therefore depend on the structural properties of the WT and particular control mechanisms.

The topic is also now discussed as part of the outlook in the manuscript (L.393-396).

However, the development of lifetime predictions in engineering applications necessitates the incorporation of additional elements in conjunction with the proposed stochastic method for modeling the low-frequency component of the loads. Initially, a turbine-specific transfer function for rescaling the CoWP to the magnitudes of the low-frequency component of the bending moments should be derived.

Figure 8: When commenting this figure I would highlight the fact that the DELS agree well in an aggregate sense, but less so on a simulation per simulation

perspective. Indeed, while statistics are in very good agreement (c, d) and correlation is good (a, b) a large spread in the data con be seen in figures 8 (a) and 8 (b).

Thank you very much for the suggestion. In fact, it is very important to make a comment on this. L. 289 has been added to the manuscript.

Overall, the data in Fig. 8 reveal a very good agreement between the DEL and DEL_{CoWP} in a statistical sense. Although a spread of the data is observed, the statistics and correlation are consistent. In an aggregate sense, these results indicate an equivalence between the CoWP and the bending moments.

Finally, please provide more details on the BEM numerical setup. Some details are included in the provided reference but should be repeated herein since the simulations constitute the reference for the entire work.

Thank you for the request. The repetition of the information in this paper adds important details of the simulations. The paragraph, L.226-231, has been modified in the manuscript.

The multi-body model alaska/Wind incorporates several coupled sub-models: the foundation, the tower, the nacelle, the yaw drive, the pitch drive, the rotor, the drive train, the generator, and the controller. A Beddoes-Leishman-type dynamic model and a flexible wake model respectively consider the unsteady airfoil aerodynamics and the wake effects. Among the specified degrees of freedom are the radial degree in the drive train for torsional effects of the gearbox; the nodding degree in the yaw drive; and the side-to-side, fore-aft, and torsional motions of the tower. These considerations on the modeling assumptions of the simulations follow the simulations in [1].

A new version of the manuscript is provided along with a diff file.

References

[1] Schubert, C., Moreno, D., Schwarte, J., Friedrich, J., Wächter, M., Pokriefke, G., Radons, G., and Peinke, J.: Introduction of the Virtual Center of Wind Pressure for correlating large-scale turbulent structures and wind turbine loads, Wind Energy Sci. Discuss. [preprint], 2025, 1–19, https://doi.org/10.5194/wes-2025-28, *in review*, 2025.