Response to Reviewer Reports

"Dynamic response and loads analysis of a large offshore wind turbine under low-frequency wind fluctuations"

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We thank both reviewers for the thorough and constructive evaluation of our manuscript. The comments have helped us improve the clarity and depth of the work. Below, we address each point in turn. Additions and changes to the manuscript are indicated in the revised text using blue (additions) and red (deletions).

Response to Reviewer 1

The manuscript provides a comprehensive assessment of offshore wind turbine loads under the influence of low-frequency wind field fluctuations within a recently introduced extension of the Mann inflow turbulence model [Syed, A. H., Mann, J., Bound.-Layer Meteorol. 190, 1 (2024)]. This extension accounts for potential anisotropic wind-field structures at low frequencies by superimposing an additional two-dimensional wind field on the standard Mann wind field box. The inflow turbulence model parameters for each wind bin, which, in addition to the standard parameters (integral length scale L, variance of wind field fluctuations, and shear distortion parameter) include an anisotropy parameter ψ, a correlation length of two-dimensional wind field fluctuations, and a high-frequency cut-off z_i, are extracted from ultrasonic anemometer measurements recorded at FINO1. Using aeroelastic simulations, it is explicitly demonstrated that including low-frequency components in the wind field increases the damage-equivalent loads (DELs) of an IEA 15 MW turbine compared to the standard 3D model and primarily affects thrust-related moments, such as the tower base fore-aft and blade root flapwise moments. A third wind field is also introduced, based on the original Mann model and matching the variance of wind-field fluctuations in the extended (2+3)D model, with increased kinetic energy at high frequencies. The aeroelastic simulations are also repeated for a floating wind turbine setup.

The manuscript is well written and certainly of general interest from both an academic and an industrial perspective, as it provides a more realistic load assessment *and modeling of wind turbines that are susceptible to long-lived, anisotropic wind-field structures offshore. I recommend publication in Wind Energy Science after the following comments have been taken into account:*

General Comments

1. *Although the results presented in Fig. 5 are rather interesting, I have some difficulties with their interpretation and the study's overall design: Intuitively, adding an additional 2D wind field to an existing 3D field increases the kinetic energy content of the wind field, as shown in the variance plots of the u- and v-components in Fig. 4. Therefore, one might actually expect that damage-equivalent loads are increased for both the new (2+3)D wind field model and the rescaled 3D model. I would suggest strengthening this main part of the manuscript to make the study clearer: It seems that the rescaled 3D model (green) in Fig. 5 only shifts the DELs and does not result in any shape change, unlike the extended model (orange). How can the higher variability in DELs for the (2+3)D wind field model in Fig. 6 be explained? How do the wind field structures change? As mainly thrust-related moments are affected, it might make sense to depict slices through the rotor planes of or even isosurface volume renderings of the u-components which produce high-amplitude events, e.g., in the tower base fore-aft or blade root flapwise moment time series.*

Response: Thank you for pointing this out. We will strengthen the discussion of Figs. 5 and 6 in the manuscript. We have added the following explanations to the discussion. We believe these explanations in the discussion section address the reviewer's concern without requiring an additional figure.

Regarding the shape change of DELs for the 2D+3D wind field in Fig 5 (see line 163): "The main difference between the rescaled 3D and the 2D+3D wind fields is how the variance is distributed across the frequency and rotor plane (their total variance is the same). The rescaled 3D field amplifies high-frequency fluctuations uniformly, which are spatially incoherent across the rotor, while the 2D+3D field adds energy at low frequencies (below 2×10^{-3} Hz), where the longitudinal wind component is coherent across the rotor plane. At low wind speeds, when the pitch controller is not active, spatially coherent fluctuations increase thrust, driving fore-aft and flapwise moments. At wind speeds above the rated wind speed, the pitch controller actively regulates rotor loads and effectively attenuates the response to slow wind variations."

Regarding the higher variability in DELs for the 2D+3D wind field in Fig 6 (see line 176): "The higher seed-to-seed variability in DELs observed for the 2D+3D case in Fig. 6, particularly at low wind speeds, is a consequence of the low-frequency nature of the added turbulence. A simulation length of one hour contains only a few cycles of fluctuations at periods approaching 500 s. Whether a high-amplitude, low-frequency event occurs within a given realization is therefore highly stochastic, resulting in a large spread across seeds. This highlights that more or longer simulations may be needed to obtain statistically converged DEL estimates when low-frequency wind fluctuations are included."

2. *If I understand correctly, the model parameters are determined for each wind bin using the FINO1 measurement data, i.e., they vary across wind bins. For the anisotropy parameter ψ, for instance, it appears that deviations from isotropy are rather small except in the low- and high-wind speed regimes. This could also be attributed to a lack of statistical convergence (see Fig. 1(a)). To assess this, it would be beneficial to i.) include error bars (e.g., from the least-squares of the spectral fits), and ii.) determine the total length of the time series in neutral conditions in FINO1.*

Response: We appreciate the reviewer's concern regarding the statistical convergence. The following text has been added, and the error bars are now introduced in Fig 4 (formerly Fig. 3).

See line 112. The number of 1-hr time series in each bin is shown in Fig. 4(a). Thus, the total number of hours processed is 6226. The spectra of all three wind components were recorded for all 1-hr time series, and for each wind speed bin, the power spectra of all three components were averaged. This averaging ensures that the spectra do not contain any random artifacts or non-stationarities and are a true representation of neutral atmospheric conditions at FINO1. The resulting spectra are displayed in Fig. 3. Averaging makes the spectra smoother and more reliable for calculating turbulence model parameters.

See line 122. Because these parameters are derived from ensemble-averaged spectra over many hours per bin (the lowest number of hours is 16 for $\overline{U} = 24.5\text{ms}^{-1}$), the standard error of the mean(SEM) (SEM measures the dispersion of sample means around the true population mean) is negligible for most of the parameters. Consequently, error bars are only plotted for ψ and L_{3D}, where the SEM was not so insignificant.

3. *In synthesis of points 1. and 2., it appears that, at least in the test case of FINO1, anisotropic two-dimensional wind field structures appear only as slightly oblate spheroids (see also Syed, A. H., Mann, J., Bound.-Layer Meteorol. **190**, 1 (2024)). Do the authors have any intuition or perhaps even preliminary studies for what systematic changes in ψ would imply for the damage-equivalent loads?*

Response: We thank the reviewer for this insightful comment. We have added the following text in the Discussion section (see line 280).

An interesting topic of investigation is whether systematic changes in the anisotropy (ψ) of 2D turbulence structures have any implications for DEL. The dominant drivers of thrust-induced loading on the tall wind turbines are primarily the variance (σ_{2D}^2) and the spatial coherence of the wind components (mainly u) across the rotor disk. The coherence is mainly governed by L_{2D} rather than the anisotropy ψ, since for horizontal coherent structures with $L_{2D} \gg D_{rotor}$ (more than 500 times), the rotor is always embedded with a single eddy regardless of its horizontal shape. Oblate structures, where $\psi < 45°$ would result in increased v-fluctuations and thus a higher lateral coherence affecting side-side and yaw moments, and vice-versa. However, these variations in ψ would have only a negligible effect on DEL due to the extremely large size of the structures in 2D turbulence. A dedicated sensitivity study of L_{2D} and ψ on DEL would be valuable and is recommended as future work, particularly because measurements at sites with stronger atmospheric stability stratification or in other marine environments may yield stronger anisotropy Syed and Mann (2024).

Specific Comments

1. *In l. 45, the acronym TIMESR is not defined, and it is not clear to which of the references this model belongs.*

Response: TIMESR is not an acronym; it's a feature in the TurbSim tool developed by NREL for turbulence simulation. We have added the following details to remove any doubt (see line 46):

The TIMESR turbulence model is a feature of the TurbSim tool (Jonkman et al., 2014), developed by NREL, USA. It requires a time series of wind measurements as an input and outputs a constrained turbulence field.

2. *Concerning the generation of the three different wind fields, for comparability, I assume that the authors used the same random seeds for the wind field generation of the underlying 3D Mann wind field box, correct? If yes, I suggest adding a sentence on this issue in Section 2.2.*

Response: The following sentence has been added in paragraph 2 of Section 2.3 (see line 137):

To limit stochastic variability, 20 turbulence realizations based on random seeds were generated for each of the 22 wind speed bins between 3 and 25 ms^{-1}. We used the same random seeds for the 2D turbulence fields as well as the underlying 3D turbulence boxes.

3. *In l. 164, it is stated that the rescaled 3D Mann field has higher PSD at high frequencies, and the authors refer to Fig. 7 corresponding to the tower fore-aft moment. However, in this plot, I only see deviations at low frequencies. Perhaps this sentence refers to Figure 8?*

Response: The sentence: "As expected, the scaled 3D wind turbulence has the highest PSD at high frequencies." is now removed from the text. We agree that this description does not belong to Figure 7 or Figure 8. Even though we observe high PSD values at high frequencies for the scaled 3D turbulence model, that is not clearly visible in Figures 7 or 8.

Response to Reviewer 2

> *The paper addresses an interesting topic related to modelling the turbulent wind field. They have applied a newly developed 2D turbulent wind generator to the load simulation of a floating wind turbine, comparing both DEL and response. The topic is of broad international interest since the floating wind turbine is an industry that is growing in several regions.*
>
> *The paper is well written with a clear objective to investigate both DEL and response from the floater. The method seems to be clearly described and reproduceable. The results are also presented in a clear way. The discussions are all well argumented for.*
>
> *I recommend this paper for publication, after including the comments below comments:*

We thank the reviewer for the positive assessment of our work and for the helpful and precise comments. We address each point below.

1. *Why are the simulations limited to one wave condition? It could have been interesting to have a typical wave for each wind speed, as they are important for how the response is for each wind speed. It would also give more realistic contribution to the DEL and to the response for each wind speed. I understand that the main focus here is the contribution of the wind to the DEL, but maybe the wind is contributing less to the DEL at higher wind speeds and so the relative importance is actually less. It may not be necessary to run the simulations over again, but it should at least be commented and mentioned.*

Response: We agree with the reviewer and have added the following text into the manuscript (see line 314):

A wind-speed-dependent wave climate would provide more representative DEL estimates and could also affect the dynamic response of the floating wind turbine, especially at higher wind speeds when wave loading may dominate wind loading. We acknowledge this limitation and recommend that future work incorporate wind-speed-dependent wave conditions in aeroelastic simulations to improve the reliability of the results.

2. *Line 96: which is the IEC recommended model. Both the Kaimal spectra with coherence model and the Mann turbulence models are recommended by IEC; consider rephrasing to "one of the recommended models by IEC".*

Response: The sentence has been revised per the reviewer's suggestion (see line 99).

3. *Line 105: time Syed and Mann (2024b). Please improve the citation so that both name and year is within the brackets.*

Response: The citation has been improved (see line 109).

4. *In Figure 3(b) the scaling parameter c is plotted. How is this related to the L_{2D} and σ_{2D} values that are discussed in lines 93–95? I might have missed it when reading, but I could not see the link.*

Response:

The following sentences are added to the text (see line 96):

In addition, the scaling parameter (c) for the 2D turbulence model is derived from the magnitudes of both σ^2_{2D} and L_{2D} using equation (A1) in the article Syed and Mann (2024). A large value of the scaling parameter (c) implies a large variance in the flow field.

5. *Line 148. Stating that inclusion of 2D increases DEL is wrong; it is true for most cases, but not all cases.*

Response: The text already highlights this distinction. It is now slightly modified to strengthen this point (see line 159):

Relative to unscaled 3D turbulence, inclusion of 2D turbulence increases DELs for moments dominated by longitudinal loading, such as tower base fore–aft (Fig. 5(a)) and blade root flapwise (Fig. 5(d)), with a larger effect below rated wind speeds. In contrast, the effect of 2D turbulence on tower base side–side (Fig. 5(b)) and tower top yaw moments (Fig. 5(c)) is small, while for blade root edgewise moments (Fig. 5(e)) the 2D+3D case reduces DELs above rated conditions.

References

Jonkman, B. et al. (2014). Turbsim user's guide v2. 00.00. *Natl. Renew. Energy Lab.*

Syed, A. H. and Mann, J. (2024). A model for low-frequency, anisotropic wind fluctuations and coherences in the marine atmosphere. *Boundary-Layer Meteorology*, 190(1):1.