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Interactive comment on "A Model to Calculate Fatigue Damage Caused by Partial Waking during Wind Farm Optimization" *by* Andrew P. J. Stanley et al.

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Response to Reviewer 1

Andrew P. J. Stanley, Jennifer King, Christopher J. Bay, and Andrew Ning

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First, we would like the express our gratitude for your review of our paper. We realize that you took time out of a busy schedule to read this manuscript and provide feedback, for which we are very grateful. We have structured this response to be clear and easy to follow. Each of your original comments will be shown in blue, immediately followed by our response in black. Note that the page number/line number indicating where the minor remarks are referring to is for the original submission. The revised manuscript will be slightly offset as we add/edit content.

The manuscript deals with an important issue with respect to wind farm optimization. The proposed inclusion of fatigue damage will certainly be applied soon in practice.

Major Remarks

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the applied coordinate systems as well as the different wind speeds (undisturbed, wake, instantaneous, averaged over blade, averaged over rotor) should be appropriate introduced, e.g. in an added section 2.0; use can be made of e.g. graph of a wind turbine like fig. 7. Furthermore, all names / symbols should be consistently used. The term "effective" should be avoided since it is unclear. Furthermore a capital letter should be used for an averaged value and a lower case letter for instantaneous values), e.g. mean wind speed in wake averaged over rotor: Uwake-rotor ; instantaneous wind speed averaged over blade: ublade(ψ,t)

We agree, this can be much more clear in the paper! We have made the following changes in the revised manuscript:

1. We added a paragraph in the beginning of section two to appropriately introduce the different wind speeds and turbulence intensities that apply to a point value, average over the entire rotor, or average over a single blade.
2. We removed all uses of “effective” referring to the wind speed or the turbulence intensity. This was unclear, and reworked to clarify that it was referring to the average wind speed acting over the blade or the entire rotor.
3. We changed the instantaneous variable of wind speed to be a lower-case u.

We did not add an additional figure, we feel like the current descriptions and equations are sufficient to understand each variable, and what an additional figure would add to the reader’s understanding is minimal.

In line with the point above it would be better to indicate the velocities and TI in step 3 and 4 with wake velocities and wake TI. Furthermore, it would be better to move lines 247-252 to step 5 (averaging over a blade) and line 253-254 to step 8 (considering the entire rotor)

For clarification of the velocities and TI, we certainly agree. We believe the changes we made for the previous comment should clarify this as well. In regards to moving the explanations of the TI calculations to subsequent sections, we definitely understand the logic behind this move. For some it may be more clear to have this organization. However, we think the current organization which discusses the wind speed and TI calculations in separate sections is also acceptable and clear. Additionally, our current organization makes it more clear that the TI calculations do not need to be made within the turbulence and azimuth loop.

The weakest point of the proposed method is the generation of turbulence samples, section 2.1. It can easily be improved by e.g. using the method of Veers https://prod-ng.sandia.gov/techlib-noauth/access-control.cgi/1988/880152.pdf By doing so the turbulence will have the correct spectrum (which is essential for a fatigue analysis). Since in section 2.7 the instantaneous wind speed is needed, varying with azimuth, the so-called rotational sampled wind speed should be used, e.g. at a radius of 3/4 R. This can be obtained by first generating a wind field on a rectangular grid (Veers) and next take the wind speed as seen by a blade element (at 3/4 R) rotating through this turbulent wind field.

This is a very helpful comment. We have added to the explanation of the turbulence samples the following sentences to address this comment and orient readers.

“Although the turbulence samples used in this paper have the important statistical qualities required for the fatigue calculations in this paper, there are a variety of other methods that could be used to generate the turbulence values. One method could be to use the Sandia method, also known as the Veers method, introduced in 1988 (cite). Another could be to us the turbulence generator TurbSim to generate the turbulence samples, which has made several improvements since the Sandia method was introduced (cite). Using one of these methods could create more realistic turbulence history, but requires using an external program. For the results shown in this paper, the turbulence samples we generated are sufficient for demonstrating our method, and had appropriate statistical properties to compare well with high fidelity simulations."

Line 128 / 129: "The tuning constants . . . depend on the blade azimuth angle"; it is unclear why that is the case since there is no periodic loading (like yaw, shear, turbulence and tower shadow)

The tuning constants vary slightly based on azimuth angle because the turbine that we used had a non-zero tilt angle. This was clarified in the text.

Line 272: "just considering these two azimuth angles is sufficient"; this implies that each revolution will lead to exactly 1 load cycle. In reality, each revolution will contain plenty of smaller load cycles as well. Since fatigue behaves rather nonlinear one can't tell in advance that neglecting these smaller load cycles is allowed.

In addition to the explanation given throughout the rest of this paragraph, we changed the last sentence to the following to acknowledge the presence of small load fluctuations:

"In reality, there are a multitude of small fluctuations that occur throughout the entire rotor rotation. However, for most conditions, just considering these two azimuth angles is sufficient as they capture the largest load differences which contribute the most to fatigue damage."

Comparison with SOWFA/FAST; an appendix can be added in which the steady turbine response is compared (i.e.: CT, P, Ω, θ, Mflatwise, Medgewise) for just 1 wind speed (say 13 m/s) during say 4 to 5 revolutions. In the model (section 2) the same wind input should be used

Great idea. This would certainly be an interesting figure to demonstrate how the higher fidelity SOWFA/FAST modeling compares with the steady-state CCBlade. Like many other potential figures we agree this would be interesting, however the not quite appropriate for this paper. Especially when we consider how lengthy the initial manuscript is, plus the additions we have made to address the excellent feedback we have received, we feel that we can rely on previous documentation and publications of BEM methodology.

Minor Remarks

Line 27: add "wind shear"

This was added to the revised manuscript.

Line 77: mention one of these "interactions"

This was added to the revised manuscript.

Line 95: change "wind speed" into "undisturbed mean wind speed"; see also 1st bullet point Major Remarks

This change was incorporated into the revised manuscript.

Line 99/100: change “effective wind speed across the blade” into “wind speed averaged over blade”; see also 1st bullet point Major Remarks

This phrase was clarified in line with the 1st bullet point of the Major Remarks.

Section 2.2: since the Loads Surrogates are derived only once, it is not clear why not the more sophisticated package FAST has been used

Good question. In our original formulation, there was no surrogate, but the loads were calculated directly inside the optimization using CCBlade. We added the following sentence to address your comment:

“A higher fidelity model could also be used to calculate the loads for this step, and our choice to use CCBlade was to allow for an easy transition to evaluating the loads directly in the optimization loop if desired.”

Eq. (2); perhaps it is better to use the symbol q for a force per length instead of F

This was changed in the updated manuscript:

$$M = \int_0^{R_{tip}} q(r)r\ dr$$

Table 1: mention the units of the constants a to g as well as Psi and Theta

Units were added for a to g in the table, and Psi and Theta units were added in the table caption.

Figure 5: why does the x-axis not continue until the cut out wind speed?

Thanks for this comment! We extended the x-axis out to the cut out wind speed of 25 m/s. Even though the wind speeds we used in this paper never reached that high of a value, we agree that it is important to include in this figure. In addition, we removed the figure showing the surrogate fit with no pitch. This was unnecessary because only the surrogate with pitch was used in the fatigue calculations.

Mention if these curves apply for the case Theta is less then OR greater than 0.05 rad. (Table 1)

We’re not exactly sure what you mean with this comment, but will do our best to respond here. The blade pitch is determined by the average turbine wind speed (shown in Fig. 3). The surrogate constants that are used from Table 1 are then determined by the pitch angle of the blades. The figure showing the comparison of the surrogate to the higher fidelity data contains calculations that were made with both constant values, depending on the inflow wind speed/blade pitch.

Line 141: This is in contradiction to the outcome of a BEM calculation I did (based on the NREL 5 turbine): the effect of a change of 1 degree in pitch correspond to about a variation of rotational speed of 8 %

Yes excellent point. The variation of pitch angle may very well affect the rotation speed of the turbine. The statement on line 141 is referring to the sensitivity of the *loads* to the pitch angle and rotation speed. The loads are sensitive to the pitch angle, but not very sensitive to the rotation speed. This does not mean that rotation speed will not vary with pitch.

Eq. 5: Delta_u and u_infinity: use capital letters instead; change "d" into "D"

Apologies, we're not certain what you mean with this comment, as the delta before the u is already capitalized. Perhaps you are suggesting to capitalize the u's in this equation, which we think is a good idea for consistency. We have gone through and changed all lower case u's in equations to upper case.

Line 153: also introduce delta and z_h

These variables were defined.

Line 168: add: and delta=0

This was added.

Eq. (10): add nTurbs (upper bound summation)

This was added to the updated manuscript.

Figure 7: add a figure with the variation of the wind speed as function of azimuth (for an offset of e.g. 1D) and compare with the averaged value (over the azimuth) as well as the average of the 4 sample points

As we understand this comment, the purpose of your proposed added figure is to demonstrate that the 4 sample points enough to sufficiently represent the inflow and calculate the average inflow speed to the rotor. We have added a subfigure that shows the average rotor inflow speed of a downstream turbine as is moves across the wake of a downstream turbine. We have done this for 3 number of points (1, 4, and 100), demonstrating that 4 sample points is graphically similar to 100 sample points.

Figure 8; "offset" has not been properly introduced yet

An introduction for "offset" was added before this figure.

Title section 2.4: change "Intensity" into "Intensities" (in line with Fig. 1)

This change was made in the updated manuscript.

Line 205: change "mean" into "undisturbed mean"

This was changed.

Page 13: Also introduce delta (from Eq. (11))

This was added.

Eq. (23): add, for clarity: TI(r)=TI_a + Delta_TI, with Delta_TI given by Eq. (11)

This was added in the explanation of the referenced equation.

Title 2.5: adopt; see 1st bullet point Major Remarks

This change was implemented, in the text and in Fig. 1.

Eq. (24): change U into U(r); + mention the equation for U(r) (is it Eq. (10)?)

Great suggestion, this was added.

Section 2.6; show in an appendix a few examples of wind speed, rotational speed, pitch angle and bending moments varying over the azimuth angle.

This would be another interesting figure! However, as was mentioned in our response to a comment before, we feel like it is not and exact fit for the this paper. Although it would be interesting, in this paper we only consider the extreme azimuth angles that are most affected by partial waking, and explain this in the text. A figure showing the full variation of these values over the azimuth, although interesting, is not necessary for this paper.

Eq. (26): adopt; see 1st bullet point Major Remarks; make 2 versions (Eq. 26a and 26b): one with TI averaged over blade (from Eq. (23)) and one with TI averaged over rotor

This change was made, and an additional equation was added to section 2.9 with the turbulent wind speeds calculated for the blade.

Line 282: I guess it should be step 4 (instead of 3)

Yes! This was corrected.

Section 2.9 / line 296: refer to Eq. (26a)

We think you mean to refer to equation 26, as there is no 26a, which we think is a good idea. This was added.

Section 2.7: refer to Eq. (26b)

We aren't sure what you mean with this comment, as there is no equation 26b, and section 2.7 is where equation 26 is defined. We haven't made any edits based on this comment.

Line 361: change step 7 into step 8

This was fixed in the revised manuscript.

Line 404 (end): typo "us"

This was fixed in the revised manuscript.

Line 442: add a statement about tower shadow

The following was added to this section:

"We assumed that tower shadow is negligible, meaning that the power is only a function of inflow wind speed with no adjustment required."

Line 495: skip "about 6 times more" (such a comparison doesn't make sense)

This was removed in the revised manuscript.

Caption Figure 17: add for clarity that 0.04 corresponds with 0.07 normalized

This was added in the revised manuscript.

Line 521: skip digit: about 5%

This was changed in the revised manuscript.

Section 5: you may add for further research: to performan several SOWFA simulation in order to determine the spread of the SOWFA results (Fig. 6, 9, 10 and 11)

Good suggestion. The following was added to the proposed future work paragraph:

"First, further validate and improve our proposed damage model with more SOWFA runs for a wide variety of wind conditions. In this paper we have presented a range of wind speeds, amounts partial waking, distances downstream, and two ambient turbulence intensities. Further confidence could be achieved with more high fidelity data."

Line 631: is wind shear included?

Yes, the shear exponent we used was 0.12. We added this to the appendix.