Response to Referee #1

MS Number: wes-2018-80

Title: System-level design studies for large rotors

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We would like to thank referee Christopher Kelley for his review and comments on our research paper. In the following, we have tried to address all the referee's comments. The following table collects the referee's comments, the authors' responses to each point, and the authors' changes in the manuscript. In addition, a color-coded version of the manuscript is provided, in which all changes can be easily identified. Additional revisions to the submitted manuscript were added after an internal review by the National Renewable Energy Laboratory on behalf of some of the co-authors. We have used the red color to indicate text that has been removed from the submitted manuscript. The descriptions in blue represent the added or re-written parts, addressing the referee's comments.

Comments of Referee #1	***Authors' Responses***
1. By considering the rotors bending motion only a function of azimuthal angle, are you ignoring the fact that resonance of the structure may be uncorrelated with azimuth? In other words, the structures flapping due to resonance may sometimes align with a specific azimuthal angle on one revolution, but not another? I think this is a source of confusion for me since I am not as familiar with this harmonic analysis. But maybe this is the key simplification to reduce computational cost, as opposed to letting random blade motion and turbulence appear with long timeseries like in FAST. A further explanation would be useful.	**Answer:** Yes, this is the key simplification to reduce the computational expense associated with performing the full set of simulations necessary to find design loads. We found that only considering the loads due to wind shear and turbine self-weight provides a representation of the loads that can be used to compare different turbines. E.g., turbines with larger blades will experience a larger 1P blade load and will also experience a similar increase in loading due to turbulence and non-periodic loads. These non-periodic components are not modelled by the transformation and considered as part of the turbulent component of the load in Section 6. **Changes in manuscript:** When introducing the harmonic model, the simplification and use for the harmonic loads is explained: In this section, we describe harmonic loads m^H, which are derived from constant and periodic loads that arise due to steady wind loading, wind shear, and turbine self-weight. These harmonic loads can be mapped, or transformed, into estimates m^{Est} of design loads m^{DLC} that are computed using operational DLC simulations in Sect. 6. The key simplification of the harmonic load model compared to design loads computed using DLC simulations is the omission of load components at non-periodic

	frequencies, which arise because of wind speed and direction changes, as well as the component's natural frequencies. It is clarified again when discussing the derivation of peak and fatigue loads from the harmonic components of simulations with a constant, sheared inflow: The loads at higher harmonic and natural frequencies contribute to both fatigue and extreme loads, but since our goal is to derive a mapping from a simplified computation (harmonic load) to a more expensive simulation (design load), their effects are neglected and considered as part of the uncertainty of the transformation in Section 6. Finally, it is mentioned in Section 5.2 (Harmonic versus turbulent loads) that non-periodic loads are not modelled in the transformation from harmonic to design loads: The structural loads on a wind turbine originate from ~~both steady-state effects and~~ constant and periodic effects, modeled by the harmonic load, as well as from dynamics due to turbulence ~~and wind direction changes~~, which are not necessarily correlated with the azimuthal position of the rotor and are not modeled in this transformation.
2. In Section 4, when discussing the closed loop controller, it would be good to describe what pitch rate was the outcome of the gains for the PI controller to make sure the maximum blade pitch rate is physically possible. For a 13 m blade 5-10 deg/s is reasonable, but for a 13 MW blade 1-3 deg/sec would be realistic. This can drastically change the 50-year DLC 1.1 result.	**Answer:** During turbulent simulations (DLCs 1.2 and 1.3), the maximum pitch rate for the SUMR-13A is 2.45 deg./sec. and 2.18 deg./sec. for the SUMR-13B. During the extreme coherent gust with direction change (DLC 1.4), the maximum pitch rate limit of 4 deg./sec. is not violated for either the SUMR-13A or SUMR-13B. For comparison, the NREL-5MW reference turbine (with 63-meter-long blades) has a maximum pitch rate limit of 8 deg./sec.
	Changes in manuscript: A sentence on the pitch actuator rates is added in Section 4: The pitch actuator has a maximum pitch rate limit of 4 $°s^{-1}$; maximum pitch rates between 1 and 3 $°s^{-1}$ were recorded in the turbulent simulations that were run.

3. In equation 11, is m^{SS} for steady state amplitude equivalent to the 0th order amplitude, m^0?	**Answer:** Thank you for raising this question; these terms can be confusing. In eq. (11) we are referring to the harmonic load (peak or fatigue) that is derived from the mean load m^0 and dominant harmonic load component m^{nP} across wind speeds. The harmonic load is used as a surrogate model to estimate the design loads that are computed from DLC simulations.
	Changes in manuscript: Throughout the article we have eliminated the usage of "steady" and "quasi-steady" to use more precise language when describing how the load was generated, e.g., using harmonic loads m^H, we derive estimated loads m^{Est} that should approximate loads computed from DLC simulations m^{DLC} with some residual.
4. For Figure 6, I think a further explanation of interpreting the turbulence factor and std error/mean would be helpful. Is f^{turb}indicative of the mean error between the harmonic model and the FAST simulations? And is std error/mean indicative of the average dynamic error?	**Answer:** Thank you for this comment. f^{turb} is used to indicate how much of the load can be attributed to turbulence versus steady and periodic effects (harmonic load). For example, the mean harmonic (m^H) peak main bearing load about the y-axis is approximately 10 MNm, the mean DLC (m^{DLC}) peak main bearing load is approximately 40 MNm. Thus, we say the mean turbulent (m^{turb}) load is approximately 30 MNm, using the definition in (11), and the turbulence factor f^{turb} is 0.75. Std. error/mean is not indicative of the average dynamic error between the harmonic and turbulent simulations. We tried to point out that the proper term to use here is residual, which indicates the error between the observed points (m^{DLC}) and the estimated loads (m^{Est}) that are found via linear regression in (14). Normalizing by the mean of the load across turbines provides a qualitative comparison (Fig. 6, bottom, right) between different turbine parts. It's not a perfect metric, as small mean values can be inflated (like Tower Clearance, which was removed from this plot). However, the appropriate values for the residual uncertainty are placed in the figures of Sections 8 to 11.
	Changes in manuscript: A more detailed explanation and example for computing the turbulent load contribution is provided in Section 6: [We quantify the turbulent load contribution using the turbulence factor f^{turb}] to compare between different turbine parts on how much of the design load m^{DLC} is attributed to turbulent versus harmonic loading. For example, the 3-bladed peak main bearing loads in Fig. 6 (top, left) has an average design load (m^{DLC}) of approximately 40 MNm, while the average harmonic load (m^H) is approximately 10 MNm. Thus, the average turbulent load (m^{turb}) is approximately 30 MNm by (11). Thus,

	using (12), $f^{turb} \approx 0.75$, as shown in Fig. 6 (left, bottom) along with a selection of the ~~component~~ other turbine loads. Throughout the article, we have replaced error with residual to better represent its meaning. The sentence describing the standard deviation of the residual being normalized by the mean has been re-worded to more clearly describe its use: In Fig. 6 (bottom, right), we normalize the standard deviation of the residual by the mean load over all rotors to compare the fit of the transformation across different turbine parts.
5. In equation 13, does this mean you need two calibration constants for each of the 3 azimuthal modes you are considering?	**Answer:** We use different calibration (renamed as transformation) constants (a^{trans}, b^{trans}) that are determined separately for 2- and 3- bladed rotors, each load axis, and both peak and fatigue loads. **Changes in manuscript:** A sentence was added after equation (13) to clarify this point: Because 2- and 3-bladed rotors sample turbulence differently, we define a ~~calibration set (a^{cal}, b^{cal})~~ transformation set $(a^{trans}; b^{trans})$ separately for each, illustrated by the different fits of Fig. 6 (top, left). There are also different transformation sets for each design load: at each axis and for both peak and fatigue loads. To estimate the design load, the ~~same calibration set~~ transformation set corresponding to the desired component, axis, and number of blades is used: …
Figure 9 seems to be showing a lot of interesting trends. It might be useful to inform the reader which design load cases were the driving cases. For example, increasing damage equivalent load but decreasing maximum peak load might be ok if tip deflection is the driving DLC.	**Answer:** Thank you for this comment. Our design goals can be made more clearly. The design driving load for the SUMR-13A is the peak flapwise bending moment. To account for this and to increase power capture, the design goal for the SUMR-13B is to constrain peak flapwise bending moments and increase AEP. Due to its more massive blades, the design driving loads for the SUMR-13B are the edgewise fatigue loads; this leads to the design study in Section 8.2.1.

	Changes in manuscript: A paragraph was added to Section 8.1 describing the design driving loads of both rotors and the goal for the SUMR-13B: The SUMR-13A blade design was driven by extreme loading along a combined flapwise and edgewise direction. Since edgewise loads are deterministic, varying with a near constant amplitude with respect to the rotor azimuth, the design goal of the next rotor iteration, the SUMR-13B was to constrain peak flapwise loads and increase power capture using the aerodynamic design changes previously described. The SUMR-13B is not necessarily cost optimal. Using larger blades with both greater power capture and structural loading could result in a net cost benefit compared to the SUMR-13B. However, in the absence of a detailed cost model, these design choices are difficult to make and depend on a wide array of factors. Larger rotors with both increased loading and power capture will be investigated in future design iterations. The SUMR-13B does, however, provide a demonstration for using the harmonic loads and results in Fig. 9 to guide design: the aerodynamic design changes can be applied in combination. Since the goal of the SUMR-13B is to constrain peak flapwise loads and increase power capture (AEP), some combination of increasing the blade length, decreasing the axial induction, and increasing the cone angle should provide a blade with the desired properties. Looking at the peak flapwise blade load (leftmost in Fig. 9), if we start at the SUMR-13A, the black dot at (1,1), and increase the available rotor power to 16.9 MW, we will have a rotor with the relative power and load at the blue diamond. Then, if we decrease the axial induction to 0.2, the change in power and load is as if only the axial induction (and corresponding blade length increase) were changed by that amount (red, dashed vector). Finally, by increasing the cone angle from 5 deg. to 12.5 deg., the change in power and load is equivalent to the change indicated by the yellow, dashed vector. The combination of these design changes result in the AEP and structural loading of the SUMR-13B: it increases AEP by 11 % compared to the SUMR-13A, while constraining peak blade flapwise loads to the level of the SUMR-13A. The same changes can be applied in combination to the flapwise DELs and edgewise DELs. The increased blade length of the SUMR-13B increases the flapwise DELs due to the enhanced effect of wind shear and edgewise

	DELs due to the additional blade weight. For the SUMR-13B, the design driving blade load is the fatigue DEL in the edgewise direction, which will be the focus of Sect. 8.2.1.