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Reply to reviewer comments - wes-2026-61

The authors thank the reviewer for the valuable comments, suggestions, and corrections that were provided. Very pertinent suggestions of changes definitively contribute to improve the clarity of the paper. The following text addresses all the questions raised point by point, quoting the corresponding changes in the revised manuscript in red whenever relevant. The reviewer comments are shown in blue, while the replies are shown in black.

Reply to RC1

Thank you for the opportunity to review the Manuscript wes-2026-61 entitled "**Predicting wind turbine aerodynamic loads using laser scanned blade geometry with validation based on operational and structural data**" for the Journal of **Wind Energy Science**.

To the best of my knowledge, I have thoroughly reviewed the manuscript, and I would recommend in **accepting the manuscript** based on my review.

Thanks again for providing the opportunity to contribute the review support to maintain the quality standard of **Wind Energy Science** Journal.

I look forward to contributing more review support, so please share any additional manuscripts within my area of expertise. Thank you!

The authors sincerely thank the referee for taking the time to review our manuscript and for this positive assessment of our work.

Reply to RC2

The manuscript presents a methodology for an accurate prediction of aerodynamic loads in a wind turbine with an 80 m rotor diameter using OpenFAST, supported by TLS measurements and validated using SCADA data and tower strain measurements. This is an important and relevant research topic and this reviewer found the manuscript very interesting to read. The manuscript is well-written and well-understandable with nice supporting figures.

Still, this reviewer has some comments and questions regarding the procedure and the results, which is why some clarifications should be made before the paper is accepted for publication.

1. Please specify if you refer to onshore or offshore wind turbines. I suppose your study is only applicable to onshore wind turbines as it becomes very difficult to perform TLS offshore, but you do not mention/define this in the text. Also, please specify the installed capacity in this regard in lines 17ff, do you mean total capacity or are you only considering onshore wind here?

   In the revised manuscript, the adopted case study is now presented as an "onshore multi-megawatt wind turbine" in the abstract, Introduction, and Data Sources section. In the quantification of the installed wind capacity in EU, it is now mentioned "onshore and offshore" in the beginning of the Introduction. The presented figures were also updated to 2025, taking into account more recent publications.

2. Figure 4:

   a. Please highlight for cross-section B which are the dummy gauges for temperature compensation and which are the actual strain gauges – maybe even within the notation. This is especially important with regard to your explanations in lines 135f, regarding the high scatter in M_SS.

We believe that this comment arose due to a lack of clarity in the text, which did not explain sufficiently well that each point marked with "S" in the figure corresponds not to a single strain gauge, but an ensemble of sensors that includes dummy gauges or temperature sensors for temperature compensation. So, the active and the dummy gauges are not in separate locations along the section. The text was rewritten to clarify this (lines 177ff):

"Each cross-section includes four measurement locations (identified with "S"), distributed around the inner circumference of the tower and sampled at 5,Hz. The sensor distribution is shown in Fig. 4 together with the turbine wind rose. At each measurement location, the strain signal is obtained through a bridge circuit. In cross-section A, quarter-bridge configurations are used, with co-located temperature measurements (identified with "T"). In cross-section B, full-bridge configurations are used, consisting of two active and two dummy gauges for temperature compensation."

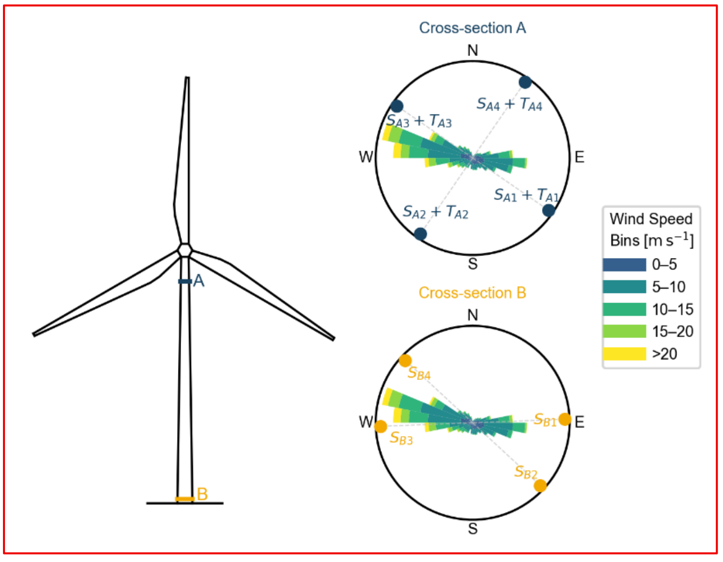
b. Please define the notations (S=strain, T=temperature). It is pretty clear but, still, this should be defined in the text. Also, it is a bit unfortunate that the strain gauges have the same notation for the two cross-sections. Maybe consider to put the cross-section or height in the names so that they are unique (not only by color in the figure).

The notations S and T are now defined before the figure. The notation was also changed to include a section-specific indication (SA1-4 and SB1-4), avoiding repeated names for sensors in different sections.

c. (Very minor:) Maybe put the wind speed bin legend on the right side of the figure, next to the actual wind speed characterization.

The legend location was changed accordingly.

The updated version of figure 4 is shown below:



3. I am no expert on the calculation you present in Section 3. It is well-explained, however, what I don't understand here fully is how the two cross-sectional measurements go into Equation 4? You explain the calculation using the example of having only one (cross-sectional) measurement if I understand Figure 8 correctly? How is the second cross-section included? Or

do you calculate the tower-top value two times based on two cross-sections and take a mean (if so, you did not mention anything about this)? Please clarify.

Equation 4 explains how the bending moments at a generic section relate to the tower-top loads. With the adopted modelling approach, it has 4 unknowns: two forces and two moments at the tower top ($F_{x,top}, F_{y,top}, M_{x,top}, M_{y,top}$). Therefore, it is solved exactly using data from 2 sections. The calculation of the tower top loads therefore consists of writing a system of four equations (two for each direction), essentially made up of equation 4 twice for 2 different values of z_{twr} and the corresponding values of M_{FA} and M_{SS}. Since this was not sufficiently clear in the manuscript, the text was modified to have a better explanation (lines 168ff):

"In this work, the two instrumented tower cross-sections yield measurements of the bending moments in the fore-aft and side-to-side directions M_{FA} and M_{SS} at two tower heights z_A and z_B. Estimating the tower drag with parameters $C_d = 0.5$ and $\alpha_{shear} = 0.2$, this system has four unknowns: the tower-top forces $F_{x,top}$, $F_{y,top}$ and moments $M_{x,top}$ and $M_{y,top}$. Using the measured bending moments at the two cross-sections, Eq. 4 can be written twice for two values of z_{twr}, yielding a system of four equations with four unknowns, which can be solved to estimate the tower-top loads."

4. Please define which version of OpenFAST is utilized.

Section 5 was updated to include the version of OpenFAST (v4.0.0). The citation in the beginning of this section was also updated to correct a mistake in the cited version, which was incorrectly indicated as 4.0.1 before.

5. Please provide more information regarding the optimization process in Section 4.2. Is it a local gradient-based optimization algorithm, what are the settings regarding number of evaluations and other possible hyperparameters?

The description of the optimization in section 4.2 was expanded to include more information about the algorithm and its stopping criteria, which is not based on number of evaluations but on observed convergence of the objective function. Since section 4.2 is also addressed by comment 6, the response to that comment has the full quotation of the section, which was rewritten to improve clarity.

6. I am not sure if you answered this in the text (Section 4): How did you discretize the blade length into the different cross-sectional airfoil scans? Based on this, how many optimization procedures did you conduct exactly? I believe you only state "for all candidate airfoils", line 222 – are those all you measured? Did you select some? Please provide more details.

The discretization into two-dimensional sections is explained in the opening paragraph of section 4, which mentions that each 2D station at a distance z^* was defined as the set of points satisfying $|z_{bld} - z^*| < 0.2\ m$, and the values of z^* are spaced by $1\ m$. The designation "candidate airfoils" referred to the database of theoretical airfoil shapes which are expected to be present in the blade (explained in section 4.2). For each discretized station, all candidate foils were fitted to find the optimal values of the transformation parameters c, α_x, t_x, t_y. As the text in the preprint generated some confusion about this, section 4.2 was rewritten in a way that we believe offers better clarity, also addressing comment 5. The full rewritten section 4.2 is quoted below with the relevant changes in red (lines 208ff):

"Following the consensus-based alignment, each of the selected 39 spanwise stations is represented by an aligned two-dimensional point cloud describing the local blade cross-section. At this stage, points from all retained scans were pooled together, yielding a single aggregated representation of the section geometry. The next step was to fit an airfoil shape to the aligned point cloud.

To constrain the fitted shapes to physically realistic profiles and to improve computational efficiency, a predefined database of candidate airfoils was defined, based on two airfoil families which were specified by the manufacturer (also including circular airfoils, and mixtures of circular airfoils with the specified families, to better capture the region near the root). Each airfoil geometry was stored in normalized form (unit chord with the leading edge at the origin) and discretized using 200 points along the contour. These candidate airfoils are expected to cover the range of airfoil shapes used along the blade span.

For each spanwise station, every candidate airfoil in the database was evaluated independently. The evaluation consisted of fitting the candidate airfoil to the section's point cloud through a transformation with four parameters: a scale factor c, an in-plane rotation angle α_x and translations t_x and t_y in the x_{bld} and y_{bld} directions, respectively. This transformation and its parameters are depicted in Fig. 12. For each candidate airfoil, the transformation parameters were adjusted to minimize a fitting error between the transformed airfoil contour and the measured point cloud. The best-fitting airfoil was then selected based on the lowest fitting error. This procedure was repeated for all spanwise stations.

The optimal set of parameters fitting each candidate airfoil shape to each spanwise station's point cloud was obtained by minimizing a nearest-neighbour distance measure between them. For each measured point, the Euclidean distance to the closest vertex of the discretized airfoil contour was computed. A Huber loss function (Huber, 1964) was applied to the resulting distance vector to reduce sensitivity to outliers and poorly resolved regions, and the mean Huber loss was used as the objective function. The resulting bounded nonlinear optimization problem was solved with respect to the four transformation parameters using the gradient-based optimization algorithm L-BFGS-B (Zhu et al., 1997). The process was stopped automatically when further parameter updates produced no meaningful reduction in the fitting error, or when the estimated local slope of the objective indicated that a minimum had been reached.

Thus, this procedure selected the best-fitting airfoil shape from the database for each spanwise station and provided an estimate of each station's scale, orientation, and position. Examples of fitted airfoil shapes at two representative blade sections are compared with the aligned point cloud in Fig. 13."

7. Figure 21: Is the rotor thrust and torque a value that is an output from OpenFAST or did you calculate that also using Section 3 from the simulated bending moments? Please add this information.

   The following sentence was added before figure 21 to explain this (lines 357ff): "The simulated values were calculated from the OpenFAST outputs of rotor thrust and torque coefficients."

8. Please list the main observed discrepancies as bullet points for better overview (lines 377ff).

   Section 6.5 was updated to list the observed discrepancies as bullet points.

9. Good job on the parameter study and the associated explanation and discussion of the results. Are there any additional parameters that can be looked at on top of the five selected parameters – maybe you can elaborate on that? (Not that you should do additional parameter studies, simply discuss what else can be of influence – if there is anything?)

The following sentence was added at the end of section 7.1 (lines 424ff):

"It should be noted that other parameters not studied here may also play a role in the observed discrepancies, such as wind shear, drivetrain/generator efficiency, and air density. Nevertheless, the five selected parameters are expected to be the main sources of uncertainty for a typical aeroelastic model."

10. You show what has influence and what is plausible and what isn't. But what is your suggestion now, what can be done about it? You only state "future work will focus on the calibration". But please add already in this manuscript a (short) discussion about what can be done next to be able to go on with the model, e.g. for load or even lifetime calculations. Is it simply the user's definition and experience? Maybe an optimization process can be helpful – of course with realistic parameter ranges based on the available information (in your case more than usual due to the TLS measurements)? Something else to look at?

    A paragraph with the recommended discussion was added to the conclusions section (lines 489ff):

    "A natural next step targeting improvement in load predictions would be to perform a constrained optimization of uncertain model inputs, using realistic parameter bounds informed by the available measurements, and using SCADA and SHM data as simultaneous objectives. For a more holistic modelling improvement aiming at, for example, lifetime estimation, the main next step is not to further tune the aerodynamic model, but rather to calibrate the structural part of the model (e.g. blade mass and stiffness distributions), gaining insight into the structure's response to the already adequately modelled aerodynamic loads."

11. Would measurements inside the blade have been helpful? Or in general additional measurement positions? What about modal data also for further validation purposes, would that be helpful provided that the sampling rate is high enough to look at the first eigenmodes (of the whole turbine and maybe of the blades if sensors would have been installed)? Did you have access also to accelerometers or were only strain gauges installed? (You don't have to answer all of this in the manuscript, this is more my own interest and maybe something for you to consider or is this not interesting for your purposes?)

    In general, additional measurements would be beneficial, and they are the subject of ongoing work within the research group. The instrumentation setup in the analyzed wind turbine also includes one accelerometer in the tower, as well as strain gauges and accelerometers in the blades. This paper is part of a broader project about using measurements to improve numerical models, which addresses the aerodynamic and the structural components of the model separately. This paper focuses on the aerodynamic component, which depends mainly on the blade's outer geometry (chord, twist, airfoil shapes), while the structural part depends on the inner geometry (mass and stiffness distributions of the beam inside the blade).

    The aerodynamic model could be further validated by having measurements of bending moments at more locations. In particular, measurements of blade bending moments (using strain gauges, analogously to the tower moments in this work) would provide a more direct validation for rotor loads, without the reconstruction of thrust and torque from tower measurements. However, calculating bending moments in blade sections has much more uncertainty than in the tower, because the geometry is not necessarily circular and the materials are not uniformly distributed and often have unknown properties. Thus, the 2 tower sections provide a simpler and more robust method for aerodynamic load estimation.

The structural model's development could be supported by geometric measurements inside the blade or measurement of modal parameters (especially with accelerometers). However, measuring the blade's interior geometry would leave a great deal of uncertainty when determining the mass and stiffness distributions, since they depend not only on geometry but also on material distribution, which is complex and unknown. Thus, it would give much less information than the laser scan of the outer geometry. Modal parameters, however, will form the basis of the structural model calibration approach. Global modes of the tower are easy to identify and an extensive work is being done to improve the identification of the rotor-dominated modes in diverse operating conditions. These will be used as targets for a model updating process which adjusts the mass and stiffness distributions.

Some additional minor comments:

12. Please specify the word "utility-scale" (lines 5f, 61) earlier than in Section 2 and add a number (range) regarding, e.g., rotor diameter so that the reader has an idea of what you are considering already when reading abstract and introduction.

    Replaced "utility-scale" with "multi-megawatt" throughout the text, a formulation which we believe gives an idea of the turbine dimensions without breaking confidentiality. The rotor diameter is referred in section 2 (80 meters).

13. Similar comment regarding the considered uncertainties (lines 11, 66) – please give at least examples of what you are analyzing in particular so that the reader does not have to wonder what exactly you are considering until reading Section 7.

    In the revised manuscript, the parametric study variables are now specified in the abstract and introduction.

14. Line 19: Do you have a more recent number than the one in 2024?

    The numbers and the citation were updated to their 2025 counterparts.

15. Line 61: What exactly are "structural health measurements"? Please be more precise. E.g. in line 335 and the title of Fig. 19 & 20 you call it "SHM measurements", I would recommend to simply speak of strain measurements or the calculated loads based on these strain measurements.

    We agree with this comment, so the legends and captions in figures 19, 20, and 21 were changed accordingly, as well as the mentions of "SHM measurements" or similar in the text around them.

16. Please be consistent regarding the use of Section or Sect. / Figure or Fig.

    Please note that this inconsistency matches the requirements of this journal, which indicate that the abbreviated forms "Sect." and "Fig." should be used in running text, while "Section" and "Figure" should be used at the beginning of sentences (https://www.wind-energy-science.net/submission.html).

17. Title of Figure 9 should include "estimated rotor loads **at the tower top** based on …"

    The figure label was changed to "estimated rotor loads **at hub height**", which according to the derivation in section 3 is more rigorous than "tower top".

18. Line 349 & 360: **F**igure(s)

    The figure designation in these lines was changed to match journal requirements.