Responses to Reviewers' Comments for Paper

Automotive lidars for rotating wind turbine blade monitoring

Addressed Comments for Publication to

Wind Energy Science

by

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Dear Reviewers,

Please find enclosed the revised version of our paper entitled "Automotive lidars for rotating wind turbine blade monitoring". We would like to express our gratitude to you both for providing valuable comments that have greatly contributed to the improvement of our work. In this revision, we have carefully considered and addressed the comments raised, aiming to enhance the quality and clarity of the paper.

Below, we provide a summary of the main modifications made and a detailed point-by-point response to your comments. We sincerely appreciate your time and effort in reviewing our paper, and we are grateful for the opportunity to address your concerns.

Sincerely,

Liqin Jin, Jakob Mann

Authors' Response to Reviewer II

General Comments. The paper under review presents a very interesting and original approach for monitoring wind turbine blade bending deflections and torsional rotations.

The proposed methodology is still at an early stage of development, with room for improvement (as fairly acknowledged by the authors). Nevertheless, it has already demonstrated its capability to provide valuable results for characterizing both the static and dynamic structural behaviour of wind turbine blades under real operating conditions.

The reviewer believes that the paper contains sufficient innovative contributions to merit publication in this journal. However, there is still scope for improvement regarding clarity, completeness of the presented information, and the accuracy of some statements and derivations.

Response:

Dear Reviewer, we appreciate the time and effort that you have dedicated to providing your insightful comments on our paper. After reading through your comments, we implemented our manuscript including your suggestions. We will now address, one by one, your comments and suggestions.

Comment 1

Title: considering that the main advantage of the proposed monitoring methodology is its low cost, I suggest highlighting this aspect in the paper title, for example: Cost-Effective Automotive-Grade Lidar for Rotating Wind Turbine Blade Monitoring.

Response:

We appreciate your insightful comment. We have implemented this comment in the manuscript and the new title is Cost-effective automotive-grade lidars for wind turbine blade monitoring.

Comment 2

Measurement campaign: A description of the strain gauge monitoring system used for validation would be welcome in this section, as the details of this installation are important for understanding the results presented later. The strain gauge configuration (quarter-bridge, half-bridge, or full-bridge) and the calibration procedure should be described.

Response:

Thank you for this valuable comment. We agree with this point and have added a paragraph in the Measurement Campaign section to describe the strain gauges in **L117**. The added paragraph is The turbine is also equipped with electrical strain gauges for load measurement. Strain gauges are installed on all three blades at two measurement stations, located 1.4 m and 6.6 m from the rotor center, with spare stations at 1.5 m and 6.7 m, respectively. The strain gauges measure the flapwise (M_x) and edgewise (M_y) bending moments. All strain gauges are configured as full bridges and were calibrated using blade-pull tests for gain calibration and load-sensitivity investigations for offset calibration [Yankova and Kock, 2018]. In this study, the strain gauge located 1.4 m from the rotor center was used as the reference sensor for comparison with the lidar measurements.

Comment 3

Measurement campaign (line 138): It should be explained why the sensor angles are slightly different for each blade, how these angles were determined, and whether their adjustment could further improve the results through better blade coverage. It would be also nice to have a better idea of the work associated with the system installation in the field, needed resources and time.

Response:

Thank you for this great comment. We have added some sentences in the manuscript to answer this comment.

- **why the sensor angles are slightly different for each blade, how how these angles were determined**. The explanation is in **L153**: The orientation angle was determined by rotating each lidar head to a horizontal orientation, using the flat ground surface at the turbine site as the reference and assuming that the ground is level. The slight differences in orientation angle among the three lidar units may be attributed to manufacturing tolerances during the welding of the aluminum heads, minor offsets of the hub center hole from the geometric center, and differences in the tension of the guy wires.
- **whether their adjustment could further improve the results through better blade coverage**. Yes, we agree with this. We have added explanation in **L133**: To adequately capture the blade tips with a higher point density for improved comparison, as depicted in Figure 3 (b), each lidar sensor was oriented at approximately 57° relative to the boom centerline, with each sensor dedicated to scanning one blade independently.
- **It would be also nice to have a better idea of the work associated with the system installation in the field, needed resources and time.**. We have added one sentence in **L131**: The entire system was installed by four technicians in roughly 3 hours.

Comment 4

Figure 6: The differences observed between blades should be explained. Presumably, they are related to slight variations in the sensor installation angles.

Response:

Thank you for pointing this out. We agree with your comment and have added the explanation in **L158**: Blades B and C show good alignment between the lidar scans and the Leica data, whereas Blade A exhibits some misalignment at the leading edge, which is likely due to slight variations in the sensor orientation angle.

Comment 5

Lines 168–171: The concepts of flatwise and edgewise may be misleading. It should be explicitly stated that, in this paper, these directions are defined relative to the rotor plane rather than the blade chord, which is the more commonly adopted definition.

Response:

We appreciate your insightful comments. We agree with this point and have added statement in **L191**: For clarity, all directions defined here are referenced to the rotor plane.

Comment 6

Results: The analysis is focused exclusively on Blade C, which is acceptable for the objectives presented. However, it would also be important to demonstrate the consistency of the results across all three blades in order to assess the reliability and repeatability of the monitoring system.

Response:

Thank you for pointing this out. We agree with you comment. Our intention is to employ three lidars to independently monitor three blades. However, the strain gauges on Blade A and B does not work. Besides the DTU Vestas V52 turbine uses collective pitch control. For these two reason, we chose only Blade C for both deflection and torsional twist comparison. We have explained this in **L192**: Although three Livox Avia lidars were deployed to simultaneously capture the motion of all three blades, validation against strain gauge measurements and SCADA data is presented only for Blade C. This choice was motivated by two considerations. First, strain gauge data for Blades A and B were unavailable during the measurement campaign and, therefore, could not be used for comparison of the flapwise and edgewise deflections. Second, the DTU Vestas V52 turbine employs collective pitch control, in which all three blades are pitched simultaneously by the same angle [Behera and Gambier, 2018]. Therefore, the SCADA-derived pitch signal is identical for all blades. Blade C was consequently selected as the representative case for validating the lidar-derived measurements against both strain gauge and SCADA data.

Comment 7

Results: If the system operates continuously, why are only a few events of 10–15 minutes analysed? A larger dataset would enable a more comprehensive statistical analysis. Furthermore, for two of the selected events, wind mast data are unavailable. The rationale behind the selection of these specific events should be clarified.

Response:

Thank you for this comment. The lidar system was not operated continuously because each sensor records up to 240,000 points per second, resulting in a very large data volume. Continuous operation would therefore require substantial storage capacity. For example, operating all three lidar sensors simultaneously for 10 minutes generates approximately 6 GB of data. Therefore, we limit the measurement duration. To implement this comment, we removed the word "continuously" in **L141** and modified the sentence as Equipped with 2 TB of storage, the computer recorded data during individual measurement periods, typically lasting about 10 to 15 minutes. Given the high data acquisition rate of approximately 240,000 points per second for each lidar sensor, longer measurement periods would generate substantial data volumes and place greater demands on storage capacity. Therefore, the measurement duration was limited to facilitate efficient data storage and post-processing.

Although mast data were unavailable for these two cases, we retained them in the analysis because their mean hub-height wind speeds were close to the rated wind speed. These cases are important because they allow the proposed monitoring approach to be evaluated under near-rated-wind-speed operating conditions. We explained in **L215**: For Case 8 on 2025-06-29 and Case 9 on 2025-07-03, although wind speed data at the key measurement heights were unavailable for calculating the shear exponent, both cases were included in the analysis because their mean hub-height wind speeds were close to the rated wind speed.

Comment 8

Results (lines 207–210): This paragraph lacks accuracy and important supporting information. The relationship between blade tip deflection and blade root bending moment should be established more rigorously. Tip displacement depends on the double spatial integration of the bending moment distribution along the blade span. Therefore, in theory, the same root bending moment may lead to substantially different tip deflections. Under specific assumptions regarding load distribution, these quantities can be correlated. Moreover, the relationship between strain gauge measurements and bending moments is not straightforward, as it depends on the sensor installation and calibration, which should be characterized in Section 2.

Response:

Thank you for this valuable and technically important comment. We agree that the original description was overly simplified. Tip deflection and root bending moment are related through the blade's structural response, but they are not directly equivalent quantities. In particular, the tip deflection depends on the bending-moment distribution along the entire blade span and is therefore influenced by the spatial distribution of the applied loads and the structural properties of the blade. As a result, the same root bending moment can result in different tip deflections under different load distributions.

Our intention was not to assume a direct one-to-one relationship between the two quantities. We assume that only the fundamental mode of the blade was exited during the experiment. Based on this assumption, the tip flapwise deflection can be compared with the root bending moment measured by strain gauge after both signal are dimensionless. We have modified the paragraph to clarify this and to avoid implying a direct theoretical equivalence between tip deflection and root bending moment. We have modified the corresponding text in **L231**: Assuming that the blade response during the experiment was dominated by its fundamental mode, the tip deflection and root bending moment are expected to exhibit consistent dynamic behavior, which can be used to assess the consistency of blade response captured by the two monitoring techniques. The lidar-derived tip flapwise deflection and the strain-gauge-derived bending moment have different physical units, namely meters and mV/V, respectively. To enable direct comparison, both signals, the boom-corrected lidar deflection and the strain gauge data, were normalized by subtracting their respective means and scaling by their standard deviations, resulting in dimensionless signals. The comparison specifically examines the tip segment flapwise deflection, computed at its centroid located 23.8 m from the rotor center with a sampling frequency of 32.9 Hz, against the bending moment measured by the strain gauge embedded at 1.4 m from the rotor center with a sampling frequency of 50 Hz.

Regarding the strain gauge measurements, we agree that the relationship between the measured electrical output and bending moment depends on the sensor configuration and calibration. The strain gauge installation, full bridge configuration, and calibration procedures are described in **L117** in Section 2.1, which is The turbine is also equipped with electrical strain gauges for load measurement. Strain gauges are installed on all three blades at two measurement stations, located 1.4 m and 6.6 m from the rotor center, with spare stations at 1.5 m and 6.7 m, respectively. The strain gauges measure the flapwise (M_x) and edgewise (M_y) bending moments. All strain gauges are configured as full bridges and were calibrated using blade-pull tests for gain calibration and load-sensitivity investigations for offset calibration [Yankova and Kock, 2018]. In this study, the strain gauge located 1.4 m from the rotor center was used as the reference sensor for comparison with the lidar measurements.

Comment 9

Results (Section 4.2): Please justify the use of the median instead of the mean.

Response:

Thank you for this comment. We implemented this point in **L266**: The median is used because it is less sensitive to outliers and therefore provides a more robust representation of the measurements.

Comment 10

Results (Section 4.2): The relationship between wind speed and flapwise deflection should be discussed in greater detail. Wind loading generates a distributed aerodynamic load that depends on the local aerodynamic characteristics of each airfoil section. This load distribution produces a bending moment distribution, which in turn determines the deformation profile. Consequently, assuming a simple quadratic relationship between tip deflection and wind speed may not always be valid.

Response:

Thank you for this valuable and technically important comment. First demonstration of this lidar-based monitoring technique, We agree that the original description was overly simplified and could be interpreted as implying a direct quadratic relationship between flapwise deflection and mean hub-height wind speed. This was not our intention. The aerodynamic loading on a wind turbine blade is distributed along the blade span and depends on the local aerodynamic characteristics, relative flow velocity, blade geometry, angle of attack, and rotor operating conditions. The resulting distributed load determines the bending moment distribution and, consequently, the blade deformation profile.

The primary objective of this study is to provide an initial field demonstration of automotive-grade lidar-based monitoring of wind turbine blade deformation. A more detailed comparison with model-based simulations is beyond the scope of the present study and will be addressed in future work, as noted in the Conclusion section. To avoid implying a necessarily quadratic relationship between wind speed and flapwise deflection, we have revised the text and removed the formulation $F_{\text{load}} \propto U_{\text{hub}}^2 C_T$. The revised text clarifies that the relationship between wind speed and flapwise deflection depends on both the aerodynamic loading distribution and the structural response of the blade.

The new paragraph in **L265** is: All measurement cases were acquired over durations of approximately 10 to 15 minutes. Figure 11 presents the median flapwise deflection for each measurement period as a function of mean hub-height wind speed for the eight spanwise segments. The median is used because it is less sensitive to outliers and therefore provides a more robust representation of the measurements. For the three tip-adjacent segments at radial positions of 18.4 m, 20.8 m, and 23.8 m (Figure 11 (a)), the curves clearly delineate the distinct operational regimes of the blade. Below the rated wind speed of 12 m/s, flapwise deflection generally increases with wind speed. From a simplified cantilever-beam perspective, flapwise deflection is governed by both the aerodynamic loading and the structural properties of the blade. As wind speed increases below the rated condition, the aerodynamic loading generally increases, resulting in higher bending moments and, consequently, larger flapwise deflection. However, a detailed investigation of the relationship between flapwise deflection and mean hub-height wind speed below the rated condition is beyond the scope of the present study and will be addressed in future work.

Comment 11

Results (line 247): The maximum thrust force is typically observed at the onset of pitch control, which for this turbine is presumably around 10 m/s, slightly below rated wind speed. Since SCADA data are available, this behaviour could be analysed and incorporated into the case study description in Section 2.1.

Response:

Thank you for this valuable comment. We agree that including this information would further strengthen the manuscript. However, data on the maximum thrust force are not available for the DTU V52 turbine. We will consider this aspect in our future work.

Comment 12

Results (Figure 10): These results are very interesting; therefore, presenting equivalent results for all three blades would significantly strengthen the paper.

Response:

We appreciate the reviewer's insightful comments and agree with the reviewer's suggestion. As explained in our response to **Comment 6**, three lidar sensors were installed to enable independent monitoring of each blade. However, due to the unavailability of strain gauge data for Blades A and B, only Blade C could be analyzed in the comparison with the strain gauge measurements. This limitation has highlighted the importance to ensure the availability and proper operation of the strain gauge sensors throughout future measurement campaigns. We will therefore take this into consideration in our future experimental work.

Comment 13

Results (Figure 13a): Could the vibration observed in this figure be associated with the torsional natural frequency of the boom? It appears to be concentrated within a relatively narrow frequency band.

Response:

Thank you for this valuable comment. We agree with the reviewer that the periodic pattern observed in Figure 14(a) is likely related to the vibration of the boom. Similar behavior was observed during the flapwise deflection analysis, for which we applied the proposed boom-vibration correction method. However, the corresponding correction for the pitch angle shown in Figure 14 is still under development.

Comment 14

Future work (lines 379–380): The last proposed alternative architecture is not clearly described and should be explained in greater detail.

Response:

Thank you for pointing this out. We explained in more detail in **L410**: a rear-mounted lidar configuration, in which lidar sensors are positioned behind the rotor plane, either in the space between the blades and the nacelle or on the suction side of the blades, enabling observation of the blades' suction side and direct measurement of their flapwise deflection and torsional twist along the blade span.

Comment 15

Future work: It would be interesting to investigate the use of these measurements for performing modal identification of the blades.

Response:

We appreciate your insightful comments and implemented it in **L413**: Future work will include modal identification of the blades, aeroelastic comparison with HAWC2 (Horizontal Axis Wind turbine simulation Code 2nd generation) simulations, and expansion of the measurement campaign to include adverse weather conditions, such as rainfall and snowfall.

Comment 16

Minor Corrections

Abstract (line 3): "...eventual inability to repair a sensor..." (sensors installed in some blade locations may be inaccessible and therefore difficult to repair).

Response:

Thank you for this comment. We have modified the text in **L3**.

Comment 17

Figure 1 caption: "…turbine blade collapse…"

Response:

Thank you for pointing this out. We have changed "failure" to "blade collapse" in Figure 1 caption.

Comment 18

Line 41: Remove the final closing parenthesis ")".

Response:

We appreciate this observant comment. We have remove the final closing parenthesis in **L40**: These are governed by a combination of environmental conditions (e.g., ice, sand, and rain) [Mishnaevsky Jr, 2019], gravitational and aerodynamic loading conditions (including wind speed, turbulence, wind shear, and tower stagnation effect), and structural characteristics such as geometry and material properties.

Comment 19

Lines 51–52: The statement regarding the need for 200 strain gauges and three weeks of installation appears exaggerated. Naturally, the required number of sensors depends on the intended application. For example, accurate estimation of blade root bending moments can often be achieved with only a few strategically placed strain gauges and just one day for installation.

Response:

Thank you for pointing this out. We agree that the number of strain gauges and the required installation time depend strongly on the monitoring objective, the desired spatial resolution, and the blade configuration. Our intention was not to suggest that 200 strain gauges or a three-week installation period are generally required for strain-gauge-based blade monitoring. Rather, we intended to highlight the practical limitations associated with the point-sensing nature of strain gauges when dense spatial measurements along a large blade are required. To avoid overgeneralization, we have revised the statement in **L49** in the manuscript accordingly, which is Despite their demonstrated effectiveness and accuracy, embedded sensor systems face significant practical limitations when dense spatial measurements are required. Owing to their point-sensing nature, high spatial coverage over large utility-scale blades can involve substantial instrumentation and installation effort. For example, previous studies have reported the use of approximately 200 strain gauges for a 50-meter blade [Amador et al., 2024] and an installation period of three weeks [Poozesh et al., 2017].

Comment 20

Line 170: z-axis (positive outward).

Response:

Thank you for pointing this out. We agree with your comment, but it should be inward, pointing to the rotor center during the spinner rotation. We have clarified this definition in **L190**: The rotational parameter corresponding to yaw about the z-axis (positive inward) determines the pitch angle of each blade segment.

Comment 21

Line 268: “blade gravity” ? gravitational load acting on the blade?

Response:

Thank you for this comment. We agree with it and have modified in **L296**: Several factors may influence the observed azimuthal variation, including gravitational load acting on the blade, wind speed, wind shear, and yaw misalignment.

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