Responses to Reviewers' Comments for Paper

Automotive lidars for rotating wind turbine blade monitoring

Addressed Comments for Publication to

Wind Energy Science

by

Liqin Jin, Jakob Mann

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 I

General Comments. The manuscript presents a new wind turbine rotor blade monitoring concept based on the use of automotive-grade lidars. The flapwise deflection measurement data recorded with the lidar were validated against the strain measurement data of one of the three rotor blades. This is an important and relevant research topic and this reviewer found the manuscript well-written and very interesting to read.

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.

Response:

Dear Reviewer, we are glad that you find our research valuable and interesting. After reading through your comments, we implemented changes to our manuscript including your suggestions. We will now address, one by one, your comments and suggestions.

Comment 1

Lines 58ff: I see and agree with the limitations of embedded sensors, but to my knowledge, monitoring a structure using sensors belongs in the category of NDE/NDT, regardless whether they are embedded or mounted?

Response:

Thank you for pointing this out. Yes, you are right. We have changed "non-destructive evaluation (NDE) techniques" to "non-contact evaluation techniques" in **L59**. Now the sentence is To address the limitations of embedded sensors, increasing attention has been directed toward non-contact sensing and monitoring techniques.

Comment 2

Lines 69ff: maybe also mention that camera-based systems usually require a solid ground to stand on and are, thus, often restricted to onshore use. However, your approach can also be applied offshore (you did not mention this advantage with regard to camera-based systems anywhere I believe)

Response:

Thank you for your valuable comment. We agree with this comment and implemented in **L70** and **L97**: First, many optical and laser-based systems are primarily limited to onshore applications because they rely on stable ground-based setups, have limited measurement ranges, and require complex and time-consuming installation procedures [Ozbek et al., 2010, Poozesh et al., 2016, Lehnhoff et al., 2020]. and Combined with advanced pitch control strategies, direct lidar-based deformation measurements could improve power generation, reduce the risk of blade–tower collisions, and enhance overall operational safety for both onshore and offshore wind turbines.

Comment 3

General comment: You often write "structural monitoring" – is this on purpose or do you mean "structural health monitoring"? If so, please remain consistent in the wording.

Response:

Thank you for pointing this out. Yes, you are right. We mean "structural health monitoring". We have changed all the "structural monitoring" to "structural health monitoring" in the manuscript.

Comment 4

You often mention that the considered blade is relatively stiff and larger blades exhibit larger deflection – wouldn't the lidar miss some deflections, especially at the blade tip, because the blade is simply out of sight at some point? Did this at no time happen in the current measurements?

I read the short paragraph in the conclusion section about this, maybe consider discussing this earlier on and in even more detail (I thought about this often while reading)

Response:

Thank you for this insightful comment. We agree that this issue can occur. As shown in Figure 7 (c), the last segment near the blade tip does not fully cover the points at the very tip, resulting in some missing points in this region. To address this issue, we have increased the length of the tip segment so that it encompasses more points and provides a more complete representation of the blade tip. In addition, the translation and rotation of each segment are performed based on its centroid. This treatment helps to mitigate the influence of missing points, particularly near the blade tip, and improves the robustness of the proposed approach. However, we implemented this comment in the manuscript in **L172**. Now the sentence is The increased length of the outermost segment compensates for the reduced spatial point density associated with the blade's tapered geometry and the long measurement distance from the lidar sensor, while also accounting for missing points near the blade tip caused by blade bending and partial occlusion (Figure 7 (c)).

Comment 5

Lines 161ff: Please mention that this is a local optimization algorithm. As such, it is dependent on the starting point. What do you "give" as the starting point in your case(s)?

Response:

Thank you for this nice comment. We implemented this in the text and added "local" in **L182**. The new sentence is This local optimization technique performs multidimensional function minimization through iterative simplex transformations.

Thank you for this comment. The initial translation and rotation matrices for the Amoeba method were calculated using the measurement of the first frequency interval and the reference position obtained from the Leica station. For each subsequent frequency interval, the results from the preceding measurement were used as the initial values for the next calculation. We explained this in **L181**: For each frequency interval, the optimal parameters obtained from the preceding interval were used as the initial values for the subsequent optimization.

Comment 6

Is it possible to place the figures more near the actual mentioning in the text? They are often two pages down.

Response:

Thank you for pointing this out. We applied command "[ht]" to all the figures in the manuscript, trying to put the figure as close as possible to the text. In the final type setting, the publisher Copernicus will take care of this.

Comment 7

Figure 7:

- Can you visualize the centroid for each segment – because you refer to it in the text quite often.
- Can you turn the figure (similar to Figure 6) and have all three subfigures fit into one so that z is continuous and you don't need the subfigures?

Response:

Thank you for these great comments. We have implemented these two points in Figure 7, to visualize the centroid for each segment and also put the three sub-figures into one.

Comment 8

Lines 165ff: This simply means that it is not applicable in real time at the moment, but with a slight time gap, correct?

Response:

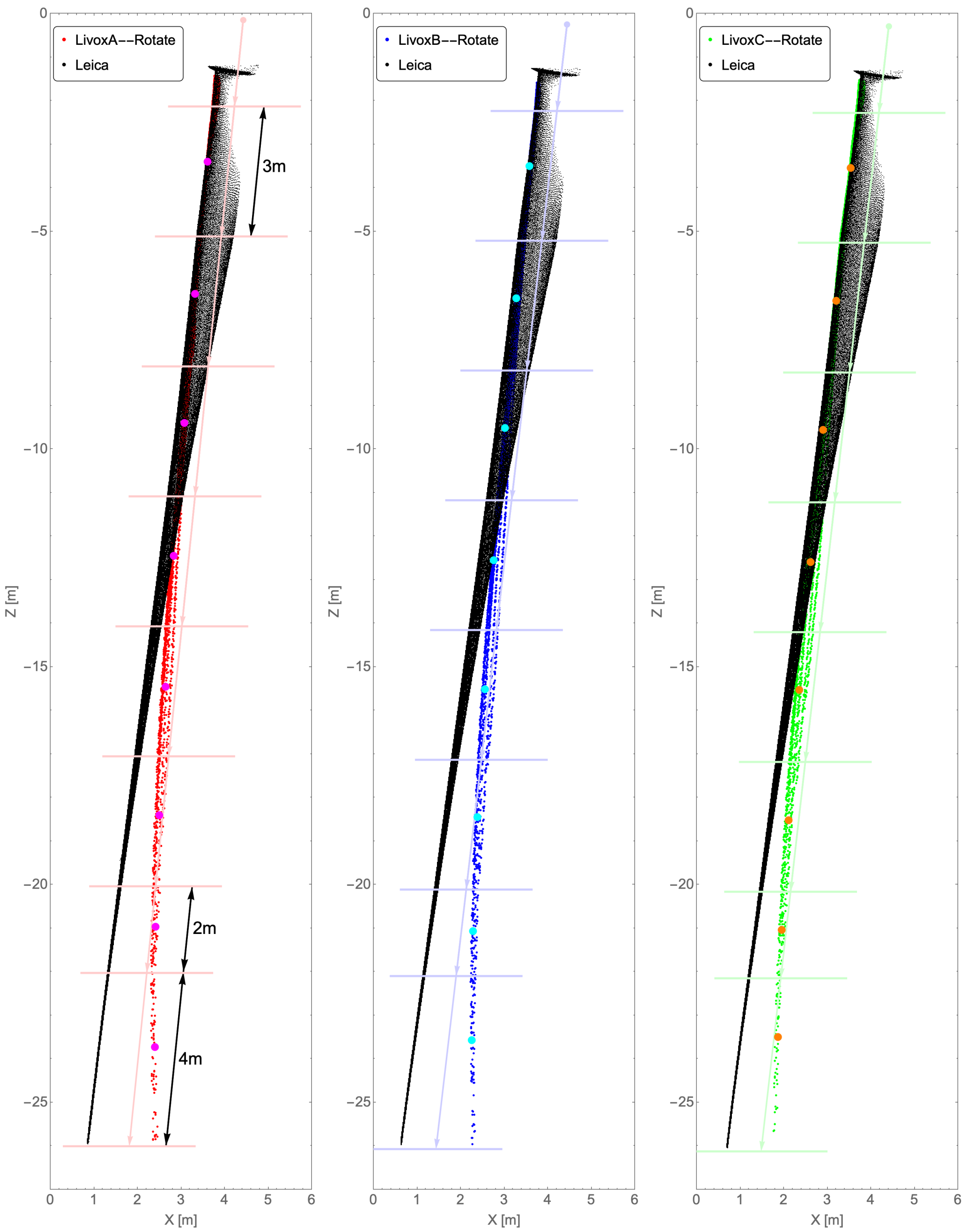
Thank you for pointing this out. Yes, you are right. Currently, we need 10 seconds to process 1 second lidar data, from point cloud extracting, coordinate alignment, blade segmentation, applying translation and rotation matrix. But this can be shortened by optimizing lidar-data analysis using parallel processing and GPU-accelerated computing.

Comment 9

Table 2: Please add numbers for the different cases and refer to those in the following text (and figures) – this would simply make it easier for readers to follow which case you refer to rather than search for the correct date.

Response:

Thank you for this helpful comment. We have added numbers for different cases and also changed the corresponding text in **L214**, **L215**, and **L298**. The new sentences are: This introduces a velocity deficit at the mast location, resulting in a biased estimates of the shear exponent for Cases 1 and 4 relative to the undisturbed atmospheric shear profile., For Case 8 on 2025-06-29 and Case 9 on 2025-07-03, the mean hub-height wind speeds were close to the rated wind speed. However, data at the key measurement heights were unavailable for these two cases. and Except for Case 8 on 2025-06-29 and Case 9 on 2025-07-03, for which shear data were unavailable, all measurement cases exhibited positive shear exponents.



(a) (b) (c)

Figure 1: Segmentation of the three DTU Vestas V52 blades into eight spanwise segments for deflection and pitch angle analysis, with the segment centroids indicated by colored points. Black point clouds: stationary reference scan obtained using the Leica station; colored point clouds: dynamic lidar scans during turbine rotation; colored vectors: blade vectors from the rotor center.

Comment 10

Regarding the motion of the boom:

- If I understood correctly, you correct the boom motion by removing the displacement you measured for the root segment – but using what assumed direction? Or for each "measured line" (cf. Figure 6) individually? I suppose you assume one direction of boom motion for this, but what if the boom motion is also crosswise to this direction? Would/does this affect the correction?
- Would, e.g., additional accelerometer(s) at the boom tip (where the lidars are installed) be of interest to find out the exact motion even more accurate?

Response:

- Thank you for pointing this out. In this study, we focus on correcting the effect of boom vibration on the flapwise blade deflection, which is along the X-direction with positive direction pointing toward the tower. For the data analysis, the proposed correction is applied to each segment rather than to each individual measurement line shown in Figure 6, because the translation and rotation matrices are applied at the centroid of each segment. We acknowledge that boom vibration is a three-dimensional motion; however, the correction discussed here specifically addresses its effect in the flapwise direction. The correction in the Z-direction, which is used to derive the pitch angle shown in Figure 14, is currently under investigation.
- Thank you for this insightful comment. Indeed, the automotive lidar sensor is equipped with an integrated IMU, and we have analyzed the acceleration data recorded by the lidar's IMU. We found a small difference between the bending angle calculated using the proposed method and that derived from the accelerometer measurements. Nevertheless, further work is needed to accurately characterize the vibration motion of the boom tip, which will be investigated in future studies.

Comment 11

Lines 195ff: I find the order a little confusing here – the following paragraph is the explanation of the sentence in lines 197-199, this should belong together?

Response:

Thank you for this valuable comment. We agree with the reviewer that these two paragraphs are closely connected, and have now combined them into a single paragraph to improve the readability and logical flow of the text in **L223**.

Comment 12

Line 210f: How exactly did you normalize? Maybe even give the formula?

Response:

Thank you for this nice comment. We have implemented this comment into the text by adding "were normalized by subtracting their respective means and scaling by their standard deviations" in **L234**. Now, the new sentence is: 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.

Comment 13

Line 213: Where exactly inside the blade Is the strain gauge embedded?

Response:

Thank you for pointing this out. The compared strain gauge in blade C is installed at a distance of 1.4 m from the rotor's center, which is mentioned in **L238** and newly added paragraph in **L117**, which are 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. and 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. 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 14

Figure 8: Maybe an even shorter time interval would be interesting to look at exemplary for even better comparison? It looks a little like the amplitude of the strain gauge is consistently a little lower?

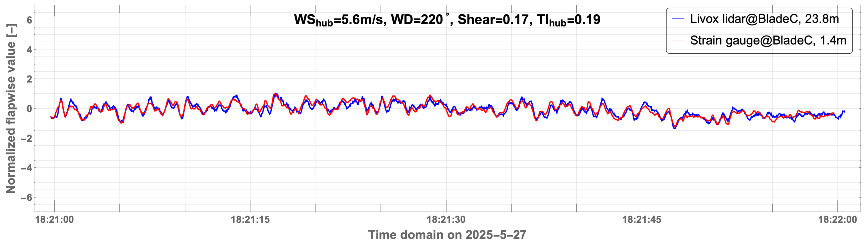
Response:

Thank you for this valuable comment. We agree with the reviewer and have added a new figure showing a comparison over a shorter time interval (one minute) in Figure 9, also as follows. The amplitude of the strain gauge signal is consistently slightly lower than that of the lidar data. This difference can be attributed to the residual effect of boom vibration. Although we applied a correction method to remove the influence of boom vibration by assuming that the rotor segment remains static, this assumption cannot completely eliminate the effect in practice. Consequently, tiny discrepancy still remains between the two signals.

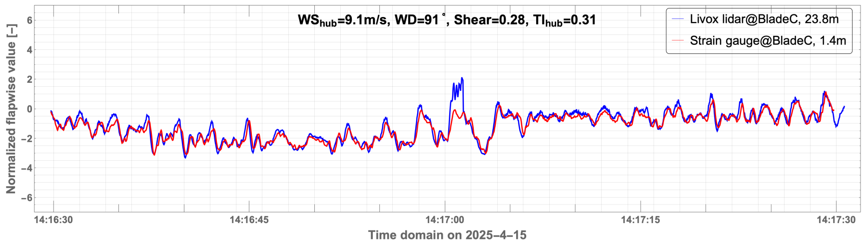
Comment 15

Figure 9: A trend is visible that the higher frequencies identified from the strain measurements are a slightly lower than frequencies identified from the lidar measurements. Is there a possible explanation?

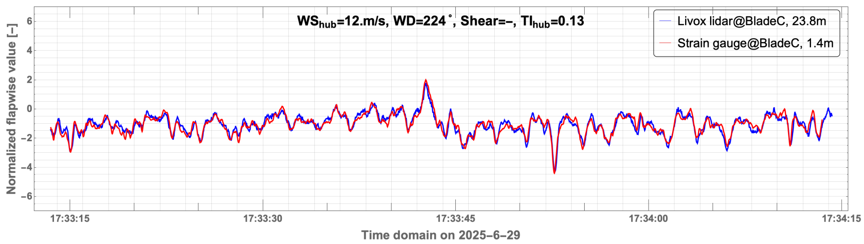
Response:



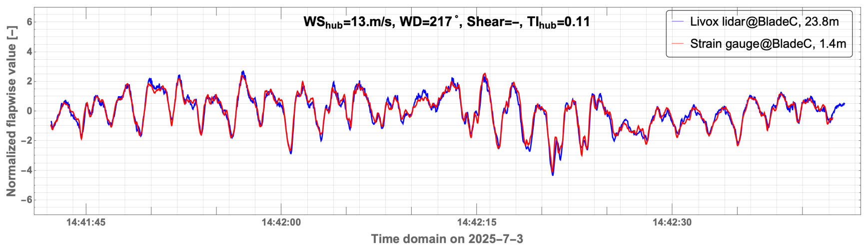
(a)



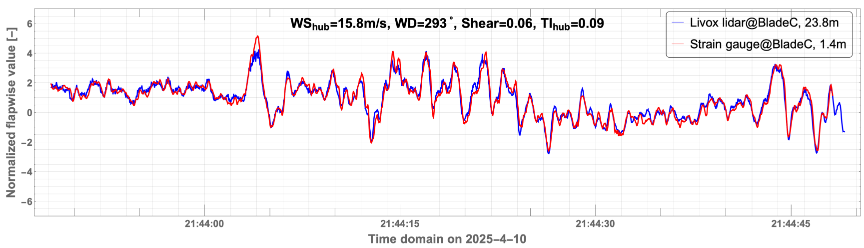
(b)



(c)



(d)



(e)

Figure 2: Validation of normalized flapwise deflection over one-minute measurements under different wind conditions.

Thank you for this valuable comment. We identified that an incorrect frequency value had been used during the data analysis. After correcting this value and reprocessing the data, the discrepancy observed in the spectra was resolved, as shown in Figure 3.

Comment 16

I believe a short summary (maybe in bullet points) of the findings and observations would be nice at the end - just a suggestion.

Response:

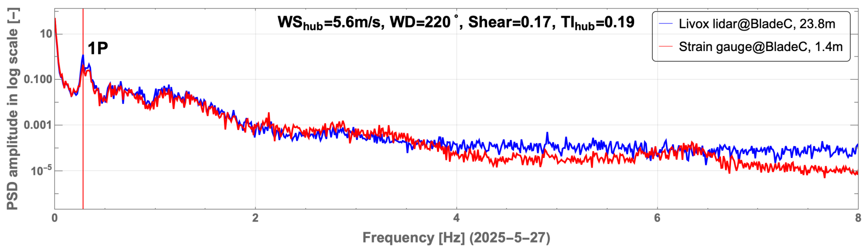
Thank you for this valuable suggestion. We appreciate the reviewer's point that a short summary of the main findings could provide a concise overview for the reader. In the revised manuscript, however, we have retained the current detailed Conclusion section, which already synthesizes the key findings and observations and discusses their implications and future research directions. We consider the existing structure to provide a sufficiently clear summary while avoiding repetition that could arise from adding a separate bullet-point summary. Therefore, we have decided not to introduce an additional summary at the end of the Conclusion section.

Comment 17

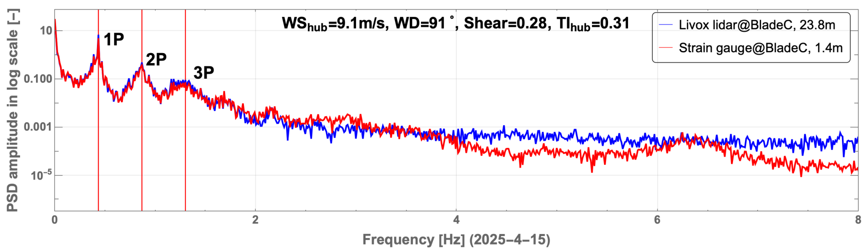
Also the last sentences could be a nice benefit of this approach – consider mentioning this also earlier on, maybe even in the introduction as I believe this is an advantage.

Response:

Thank you for pointing this out. We agree with you. Actually, we have already mentioned this in the introduction section in **L96**. The original sentence is <u>Furthermore, the proposed system offers strong potential for real-time structural health monitoring. Combined with advanced pitch control strategies, direct lidar-based deformation measurements could improve power generation, reduce the risk of blade–tower collisions, and enhance overall operational safety for both onshore and offshore wind turbines.</u>



(a)



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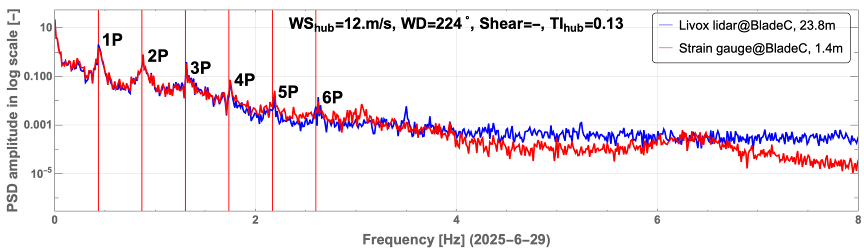

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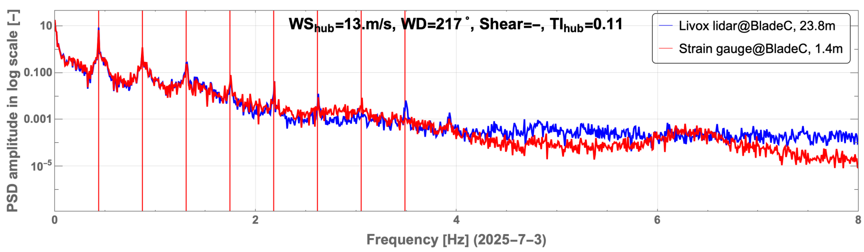

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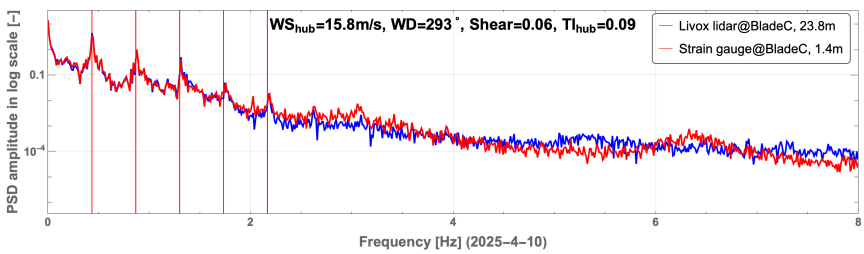

(e)

Figure 3: Spectral validation of normalized flapwise deflection: Livox Avia lidar vs. strain gauge data under different wind conditions.

Comment 18

How can I get to the mentioned video supplements? I don't see it anywhere in the files.

Response:

Thank you for this great comment. We have contacted with Copernicus Publications and they replied that we will be able to attach our videos as assets with the next file upload request.

Comment 19

Some additional (minor) comments:

Line 14: You probably mean monitoring of the structural dynamics of wind turbine rotor blades (and not the whole wind turbine)?

Response:

Thank you for pointing this out. Yes, you are right. We have corrected this sentence in **L14** to These findings highlight the potential of cost-effective automotive-grade lidar sensors for reliable, high-resolution monitoring of turbine blade dynamics under challenging field conditions.

Comment 20

Line 166: However, . . .

Response:

Thank you for this comment. We have change "." to "," in the manuscript.

Comment 21

Line 186: Maybe give a (numbered) equation here?

Response:

Thank you for this helpful comment. We have numbered this equation to (2) in the **L208**.

Comment 22

Line 194: You write denoted as “0” – but in Table 2, it is denoted as “-“.

Response:

Thank you for pointing this out. We use the “–” symbols in Table 2 and the corresponding figures to ensure consistency throughout the manuscript.

Comment 23

Line 242f: Number of equation missing

Response:

Thank you for this helpful comment. To improve the clarity of the discussion and avoid implying a direct relationship between wind speed and flapwise deflection, we have removed the equation from the revised manuscript.

Comment 24

Line 261: time-stamp

Response:

Thank you for pointing this out. This is because the automotive change of the text. We have implemented this comment to change "using" to "with" in **L289**. Now the new sentence is These scans are recorded with high-accuracy timestamps synchronized to the external GPS, thereby providing a temporal reference corresponding to a rotor azimuth angle of 180°, i.e., when the blade is directly in front of the tower.

Comment 25

Line 262: I guess the word “that” is too much in this sentence.

Response:

Thank you for this great comment. Yes, you are right. We have removed the word "that" in **L290** and the new sentence is These scans are recorded with high-accuracy timestamps synchronized to the external GPS, thereby providing a temporal reference corresponding to a rotor azimuth angle of 180°, i.e., when the blade is directly in front of the tower.

References

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