Dynamic displacement measurement of a wind turbine tower using accelerometers: tilt error compensation and validation

Answers to the reviewer's comments

The authors would like to thank the editor and reviewer for their time and effort in reviewing the article and their constructive comments. We appreciate the chance to clarify the points that were commented on. The article is revised according to the reviewers' remarks and queries, with detailed responses and explanations of the edits given below. All edits in the manuscript have been highlighted in red colour.

We note that during the revision, the number of lines has been changed. Therefore, in the following paragraphs, we refer to the revised article.

Reviewer

In summary, the proposed tilt error compensation method is interesting and could be very useful to researchers and practitioners alike. However, before granting full acceptance, the following remarks should all be addressed by the Authors

We appreciate your helpful comments. We hope that the revision will significantly improve the understanding of the manuscript.

1) A flowchart of the complete method, building upon the one already reported in Figure 1 for signal preprocessing, could improve the reader's understanding, reporting in a clearer and visual way a step-by-step breakdown of the methodology

We have updated Figure 1 and, in addition to the dynamic displacement determination process, we have also included the laser validation measurement and added visualisations.

2) The authors could provide more context for the amplitude error percentages (e.g., 9% and 95% errors) and how these values impact the practical application of the method. Do these errors have significant consequences in real-world monitoring for daily operations?

Indeed, these amplitude errors significantly impact fatigue life estimation, if they are not accounted for. Therefore, a numerical example using the quoted figures (9% and 95%), which are also shown in Figure 10, was added to the paper to exemplify this relation.

For very low frequencies, Fig. 10 demonstrates, that the correction factor of the highest measuring level drops below 0.05. This means that 95% of the measured acceleration amplitude is due to tilt and only 5% are due to the actual structural acceleration. The impact of these errors can be exemplified for tower fatigue life estimation as a typical application for structural measurements. The fatigue life ratio between the corrected and raw measurement data can be expressed, assuming small deformations, a linear stress-strain relationship and a harmonic acceleration signal, using an equation inspired by the Eurocode 3 (EN 1993-1-9:2005).

$$\frac{N_{corr}}{N_{raw}} = \left(\frac{\Delta\sigma_{raw}}{\Delta\sigma_{corr}}\right)^m = \left(\frac{a_{raw}}{a_{corr}}\right)^m = (c(f))^m, \tag{1}$$

where $m = 3$ *for steel structures and* $\frac{a_{raw}}{a_{corr}}$ *corresponds to the correction factor* $c(f)$*. Under the assumptions outlined above, the ratio between the measured and corrected stresses* $\frac{\Delta\sigma_{raw}}{\Delta\sigma_{corr}}$ *also corresponds to* $c(f)$*. Using the correction factor* $c(f) = 0.91$ *results in* $\frac{N_{corr}}{N_{raw}} = 0.75$*, which means that using the uncorrected data results in 25% reduced fatigue life estimates. Considering* $c(f) = 0.05$ *results in* $\frac{N_{corr}}{N_{raw}} = 0.00013$*, which shows that for very low frequencies, the raw data is essentially unusable for fatigue life estimations.*

3) If this Reviewer understood well the Authors' intended meaning, the "95% overestimation of dynamic displacement amplitude" at low frequencies is quite high. Addressing whether this error can be reduced, or how it might impact the overall results, would strengthen the analysis.

The stated overestimation of the dynamic displacement amplitude is fully compensated by the proposed tilt error compensation approach. The wording was changed to make this clearer.

For quasi-static movements below 0.01 Hz, a 95% overestimation of the dynamic displacement amplitude was observed at the tower head without tilt error compensation, and this error is successfully compensated by using the proposed tilt error compensation approach.

4) It would be useful to further expand on how noise is currently handled in the TLS data and accelerometers, and what further preprocessing techniques can be applied to minimize it.

The best way to reduce noise in the measurement is to use measurement technology with as little noise as possible. Noise can be reduced after the measurement by digital filtering by filtering out frequency components that are not relevant to the measurement task. In this study, only frequency components up to 2 Hz were considered for both measurement methods to avoid high-frequency noise. To clarify this in the manuscript, the following has been added:

The bandpass filter is used to ensure that only frequency components relevant for the evaluation are included in the time signal by reducing measurement noise.

5) Further elaboration on how this tilt compensation method could be integrated with existing structural health monitoring (SHM) systems (e.g., in wind turbines) would be useful. Discussing how feasible the implementation is, whether it requires specific hardware, and any practical challenges would add practical value. In this regard, it can be useful to introduce and mention the recent review works of https://doi.org/10.3390/s22041627, where several technologies and strategies are discussed

Thank you for these valuable hints. The method requires bixaxial acceleration sensors that measure horizontally. These are usually already installed in the nacelle, as the VDI 3834 recommends the use of acceleration sensors for monitoring wind turbines. We have added the following to the introduction in the manuscript:

There are other monitoring approaches using different sensor technology as described by Civera and Surace (2022). However, the VDI 3834 recommends using the nacelle acceleration to estimate the health status using vibration measurements. Accelerometers are therefore already installed in many wind turbines.

6) If this Reviewer understood correctly, the idea of using bi-axial versus tri-axial MEMS accelerometers for tilt error compensation is interesting but underexplored. More details on this comparison and how it might influence future designs would enhance the discussion.

The presented tilt error compensation approach requires only measurement data in the horizontal directions. Three-axis sensors are therefore not required in principle. However, for practical applications, it is still beneficial to install three-axis sensors, since the additional measurement axis provides valuable data on sensor misalignment and also enables plausibility checks due to redundancy. We have added the following to the summary and outlook Section:

From a practical point of view, it remains an open question whether a tri-axial MEMS, which is more useful in the approach presented in this study, particularly for compensating for misalignment, or whether the cost savings of a bi-axial MEMS outweigh the disadvantages.

7) It would be beneficial to include error bars or confidence intervals for the measurements, providing a more robust quantification of uncertainty. Also visualizing these C.I.s would be useful.

Thank you for this hint. We decided to not show confidence intervals or error bars in the time series analysis, as the uncertainty intervals of the amplitude and phase shift are frequency-dependent. However, for the TLS measurement and acceleration sensor calibration, uncertainty analyses for the measurement methods were carried out in preliminary work (Helming et al., 2023 and Jonscher et al., 2022b). And to get a better impression of the effectiveness of the method and the similarity of the signals, we have added the Table 4 and the following paragraph:

A comparison based on the Pearson correlation coefficient and the normalised mean square error (nMSE), given by:

$$nMSE = \frac{1}{N\sigma^2_{w_{laser}}} = \sum_{i=1}^{N} \left(w_{laser,i} - w_{accel,i}\right)^2, \tag{2}$$

is listed for all three measurements in Table 4 for the case with and without the presented tilt error compensation of the acceleration measurement. A Pearson correlation coefficient closer to 1 indicates that the signals are correlated, with a value close to 0 the signals are uncorrelated. Tilt error compensation makes the signals - with the exception of measurement two in radial direction - significant more correlated. However, this metric cannot provide any information about an amplitude error. The nMSE is used for this purpose. It is clearly evident that the error is greatly reduced by the proposed tilt error compensation method.

In the outlook, we have also made the missing uncertainty analysis even clearer:

However, discrepancies still remain, and a precise investigation of the deviations and uncertainties should therefore be carried out in further studies on the basis of previous uncertainty analysis for TLS (Helming et al., 2023) and accelerometers (Jonscher et al., 2022b). In particular, the uncertainty analysis for the tilt error compensation method is still missing and should be carried out by means of in-depth laboratory experiments.

8) The Conclusions are a bit lengthy and could be shortened.

The conclusion was shortened and some content was moved to the newly created section on benefits and limitations.

9) The conclusions touch on some potential limitations (e.g., inaccuracies in the laser and accelerometer positioning, deviations from the FE model). These could be highlighted more explicitly as limitations in the paper, so readers understand the scope and limitations of the proposed method.

The remarks on the limitations of the measurement setups and modelling were moved to the newly created section on benefits and limitations:

The results of this study show that using the presented tilt error compensation approach, the different measurement technologies can be successfully aligned. By using a frequency-dependent correction, the accelerometer data is employed for accurate displacement estimations in a significantly expanded low frequency range. Comparisons in the time domain show that residual deviations still remain, which may be attributed to inaccuracies in the positioning of the laser and the accelerometers. Furthermore, inaccuracies in the FE model used to calculate the static bending line and in the algorithm used to extract displacements from the laser measurements contribute to the deviations.

A major benefit of the presented approach is that it can be applied in the monitoring of many slender structures, such as chimneys, offshore wind energy turbine towers or television towers. Similarly to the onshore wind turbine discussed in this paper, these structures exhibit significant structural flexibility and are thus prone to large-amplitude low-frequency motions. The application of the presented approach requires relatively minimal technical equipment, since a two-axis accelerometer measurement system suffices. In addition, only a simple beam model of the structure is required to obtain the static bending line, which is used to parameterise the correction function. Considering the usage of IEPE sensors, a drawback is the high-pass behaviour inherent to the measurement principle, which prevents the estimation of static displacements.

Considering the significant noise level of the contactless TLS-based measurements makes them well-suited for applications where large displacements occur and the measurement noise is not an issue. This is particularly true, e.g., for measuring low frequency displacements, such as those that occur at rotor blades (Helming et al., 2023), where the attachment of a sensor to the measurement object is undesirable. In contrast, accelerometers are preferable for monitoring wind turbine tower dynamics as they have a much lower noise level in the range of the first bending natural frequency and at higher frequencies.

10) The conclusions suggest that the method works well for wind turbine tower dynamics but could be expanded to other applications (e.g., rotor blades or other low-frequency displacement measurements). Providing a clearer discussion on the method's scalability to other structures or conditions would add value to the paper.

A remark on the transferability to different structures was added to the newly created section on benefits and limitations. See in the changes of remark number 9.

11) The applicability of the method for different frequencies and measurement environments (such as offshore wind turbines) could also be discussed in more detail.

As the eigenfrequencies of onshore and offshore turbines only differ around a factor of two, there are no major obstacles to the application of the proposed approach to offshore turbines. Wave spectra rarely possess significant components below 0.1 Hz, hence tower movements due to wave interaction are expected to be captured well. Offshore wind turbines were therefore added to the revised section references in remark number 9.