Reviewer 2

RC2.01) (line 23) In my opinion, a very good abstract manages to communicate the following things:

- Give the context of the present work

- Point to the research question(s)

- Describe the methods

- Mention the most important results

All of which ideally should be done in about 150 words and without the use of acronyms.

If you agree with above criteria, I would then say the present abstract is a tad too long.

As one example. the entire description of the simulations is very detailed and does not necessarily have to ben in the abstract. Instead of giving the code, the type of DLCs and the fact it is 10-minute time series, the first sentence of the second paragraph can almost cover everything you need to mention in an abstract.

That being said, I am not the ultimate expert on the matter and if you say there are so many works out there which use 8 minute time-series and just DLC3.1 and 4.1, than leave everything as is and ignore this comment.

RC2.01) Thank you for this comment. We agree that the abstract was too long. The abstract has been rewritten to approximately 200 words, however, the MDE acronym has been kept as the authors believe it improves the readability (line 1-12):

Abstract. Offshore Wind Turbines are increasingly susceptible to fatigue damage, motivating structure-wide stress monitoring for asset integrity management and life extension. Virtual sensing methodologies, such as multi-band Modal Decomposition and Expansion (MDE), offer a solution to the above by extrapolating measurements from a few sensors at accessible locations to the global structure. However, most MDE studies model the Rotor-Nacelle-Assembly as a lumped mass inertia, thereby ignoring rotor flexibility. This leads to errors in estimated strains or stresses arising from erroneous mode shapes and the omission of relevant rotor modes from the estimates. The present paper quantifies these errors using HAWC2 simulations of the IEA 15-MW Offshore Reference Wind Turbine (RWT). Multi-band MDE estimates of section moments are compared to true responses in terms of Damage Equivalent Loads and Stresses. Long-term estimates show reduced accuracy in the area around the tower top and at ± 15 m around the Mean Sea Level. Furthermore, the error of the MDE estimates exhibits wind speed dependency, which underlines the inherent limitation of the MDE, assuming a linear and time-invariant response. In conclusion, multi-band MDE provides accurate estimates of section moments across most of the IEA 15-MW RWT supporting structure, although improvements are needed to effectively capture the influence from rotor flexibility.

RC2.02) (line 27) The V236 is already installed at least as a prototype and chinese OWT have reached almost 300 m with prototypes (MingYang 20 MW).

RC2.02) Thank you for pointing this out. The section has been edited to reflect the comment (line14-18):

"During recent decades, wind turbines have been consistently growing in size, and modern Offshore Wind Turbines (OWTs) already on the market, such as the Vestas V236-15MW, now have a power production of up to 15 MW and rotor diameters approaching 240 m (Vestas Wind Systems A/S). At the same time, prototypes of the Mingyang MySE18.X-20MW, with a power production of 20 MW and a rotor diameter of up to 292 m, and the Siemens Gamesa SG DD-276, with a power production of 21.5 MW and a rotor diameter of up to 276 m, have also been installed (Ghoshal, 2024; Salas, 2025)."

RC2.03) (line 30) This is just a style issue: I would suggest to rephrase this as the 'recent decades' are already the leading words of the paragraph, so 'at the same time' already incorporates it.
RC2.03) This is a good point, the section has been rephrased (line 21-24):
"The same period has experienced the emergence of Structural Health Monitoring (SHM), where data from sensors installed in a given structure is applied to inform Operation and Maintenance (O&M) strategies, in asset integrity assessments, and lately also for the assessment of potential life-extension through monitoring of strain histories at fatigue critical locations."

RC2.04) (line 34) From the abstract I remember the tower top is the location where the differences between MDE and aero-elastic results are biggest. Then the first statement in the introduction is about locations which are very far away from the top. This might be understood as if the problem you are looking at is not relevant?
RC2.04) This is an understandable comment, and we thank you for raising this concern. In direct relation to the comment, we have added an argument to why the global accuracy is relevant (line 30-32):
"Additionally, virtual sensing has the significant benefit of estimating the response of the structure at any location, hence not limiting the information from the Structural Health Monitoring System (SHMS) to a few predefined sensor locations.
Furthermore, we have added to the abstract a sentence about the error around the mean sea level, to highlight that an improved model might also improve the results here (line 7-9):
"Multi-band MDE estimates of section moments are compared to true responses in terms of Damage Equivalent Loads and Stresses. Long-term estimates show reduced accuracy in the area around the tower top and at ±15 m around the Mean Sea Level.

RC2.05) (line 35) I was a bit in doubt reading this absolute statement of inaccessibility of the inside of the monopile post/erection. I have then asked someone who is dealing with OWTs more than I do and they confirmed there is a hatch which should then allow to access the monopile. So perhaps it makes sense to rephrase this along the lines of 'only accessible with significant efforts'?
RC2.05) Thank you for this comment. We agree that it is possible to access the sensors in the monopile above the mud line. However, we believe that significant efforts would be made to avoid it. In a scenario where, for example, a fibre Bragg strain sensor needs to be replaced, it must be glued or welded on the inside of a submerged monopile with great accuracy. We are not entirely certain whether that is, in fact, possible or at least affordable.
The section has been modified to reflect the comment (line 24-26):
"However, for offshore structures, these critical locations are often sub-sea, where the strain sensors are only accessible with significant efforts, or sub-soil, where strain sensors cannot be installed or maintained in practice, post-erection."

RC2.6) (line 36) What about fibre brag sensors for strain monitoring? I agree the strain gauges have a drift and get damaged over the years, though.
RC2.6) Fibre Bragg sensors would, as you mention, not have the problem with drift or damage over time. However, for monitoring of strains/stresses in the monopile, the sensor would have to

be installed before the erection, thus making it vulnerable to damage during the installation. As the sensors are located sub-soil or sub-sea for this purpose, they are at least complicated and expensive to replace, and at worst, it is not possible.

RC2.7) (line 38) I wonder why this paper does not appear here: 10.1088/1742-6596/3025/1/012011 - isn't that very related?
RC2.7) Thank you for guiding our attention towards this paper. It does deal with virtual sensing, but the approach is data-driven, and it requires training data from strain gauges at the locations of the predicted response. This is very practical in case a critical sensor fails, however, it does not serve as a global monitoring strategy, which makes it less relevant for the case considered in the present paper. That being said, it is a good example of how machine learning can be used in virtual sensing and does add value in terms of background knowledge. Therefore, it has been added in the literature review in the introduction, in the section dealing with machine learning (line 38-41):
"Lately, the use of neural networks has also entered the field of virtual sensing, e.g. when physics-guided learning from SCADA data and 10-minute acceleration statistics are used to estimate damage equivalent moments (de N Santos et al., 2023), or when virtual sensors are trained based on strain sensors for gap-filling in strain histories in case of sensor failure (Faria et al.,2025)."

RC2.8) (line 91) Besides the tiny remarks in the first paragraph, I find the rest of the introduction to be a very pleasant and easy-to-understand read. Good work!
RC2.8) Thank you for the nice comment.

RC2.9) (line 173) Again, a well written and understandable section without any comments.
RC2.9) Thank you for the nice comment.

RC2.10) (Figure 2) The generator torque seems to have the maximum values in blue and the minimum values in red, or am I mistaken?
RC2.11) (Figure 2) Just for the sake of beauty and clarity of the figures you might consider putting in rated wind speed as a vertical (dashed?) line. This is just optional and more a question of personal taste.
RC2.10+RC2.11) Thank you for bringing this to our attention. Figure 2 has been corrected accordingly, and so has Figure 3.

RC2.12) (Figure 4) Again, and similar to above, it might be nice to have the eigenmodes present as vertical lines in the plots.
RC2.12) Thank you for bringing this to our attention. We have included the first natural frequency of the first eigenmode in the figure 4(b), as this is the focus in the discussion of the figure.

RC2.13) (Figure 5) That is a beautiful figure!
RC2.14) Thank you for the nice comment.

RC2.14) (line 342) No comments to this section
RC2.14) Thank you for the nice comment.

RC2.15) (Figure 8 (now 7)) Would it make sense to include the height of the TP as a horizontal line here?
RC2.15) Thank you for this comment. We have not included a horizontal line at the TP, but we have included the MSL and mud line as in similar figures in the paper.

RC2.16) (Figure 8 (now 7)) This poor x-axis would love a label.
RC2.16) Thank you for bringing this to our attention. The figure has been corrected accordingly.

RC2.17) (line 432) A tiny remark on language here: The use of 'while' seems a bit out of place as it insinuates a timely connection or insinuates a contradiction and perhaps a split in two sentences as "… Ritz vectors. Similar methods…" is a simpler and more elegant solution.
RC2.17) Thank you for bringing this to our attention. The suggested correction has been made (line 374-375):
"Similar methods are applied in Iliopoulos et al. (2017), Augustyn et al. (2021), and Toftekær et al. (2023)."

RC2.18) (line 450) Is the thrust wind load on the tower negligible?
RC2.18) Thank you for this comment. The thrust wind load on the tower is likely not negligible, but its importance has not been assessed in detail. Instead (as described in section 5.1 (previously 4.1)), the 1st tower bending modes are included to represent the distributed wind load on the tower. We acknowledge the confusion of not mentioning this where the Ritz vectors are presented and have added a sentence in Section 4.3.2 (previously 3.3.2) referring to section 5.1 (previously 4.1) (line 392-394):
"A Ritz vector for the distributed wind load on the tower has not been established in the present work. However, as presented in Table 6, the first tower bending mode shapes are used to represent the quasi-static response resulting from this load."

RC2.19) (Figure 9 (now 8)) This looks a bit like a linear, tilted line from bottom to sea level, is this supposed to look like it or should it look more like the non-linear shapes of the first two load cases.
RC2.19) Thank you for this comment. With the loading from the waves, which only acts on the submerged part of the monopile, the curvature of the beam elements is rather small. The deflected shapes in Figures 8 and 9 (previously 9 and 10) are in fact a correct representation of the deflected shape caused by the wave load.

RC2.20) (Figure 10 (now 9)) Same as above, horizontal lines indicating important levels might add to the beauty of the Figure.
RC2.20) Thank you for this comment. We have included the MSL and mud line as in similar figures in the paper.

RC2.21) (Figure 10 (now 9)) Albeit a normalized axis, this poor fella would really love to have a label as well.
RC2.21) Thank you for bringing this to our attention. The figure has been corrected accordingly.

RC2.22) (Figure 11 now (10)) This is the point where I have to admit I am truly no expert in the area. It escapes me how we can get a large error of the MDE at the tower top when the part of the matrices that is measured is at the tower top? Maybe I am just very clueless and/or overlooked the explanation on this, but if there *is* a sensor this goes into the n_m array of measured values?
RC2.22) This is a valid comment, thank you. There is a sensor at the tower top, and it does go into the n_m array (in terms of a measured rotation for f <0.05 Hz and a measured displacement for f>0.05 Hz). However, we estimate section moments based on nodal displacements and nodal rotations at both end nodes of the 3d beam element. This means that the measured DOFs only represent 2 out of the 8 (2 axial and 2 torsional, not important) DOFs that are used to calculate the section moment in the beam element. The structural response in the remaining 10

DOFs is obtained by modal expansion. At the tower top, the main contribution to the error comes from the frequency range *f*>0.05, hence, the large error arises because the relation between the measured displacement and the curvature of the mode shapes (particularly the 2nd and 3rd tower bending modes) does not match that of the IEA 15-MW RWT. We hope this reply clarifies why an error can occur at a measured location.

RC2.23) (Figure 14) As per the introduction of the paper, the levels below MSL might be the ones with difficult accessibility and thus the ones where MDE might be more useful. However, in this figure, the large error at TT cloud the understanding of the errors at lower levels. Would it make sense to split the figure to allow two x-axes?
RC2.23) Thank you for bringing this to our attention. It is indeed difficult to assess the errors at lower levels, and a good idea to split the figure. The figure has been corrected according to this comment as:

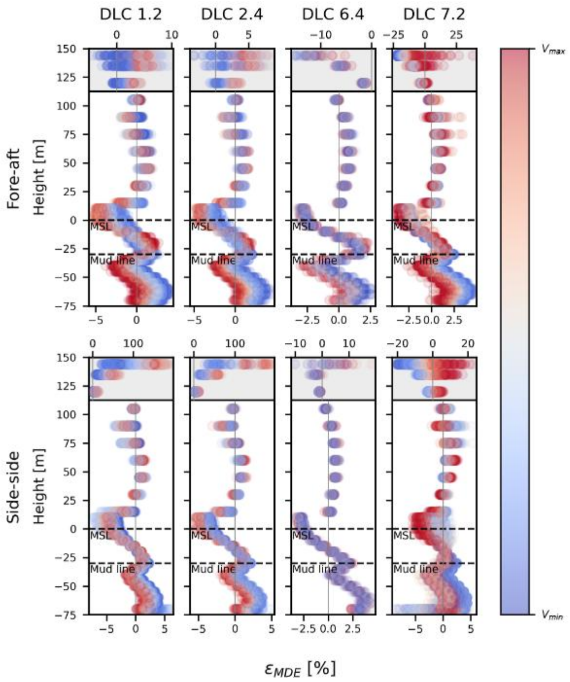

Figure 14. Error ε_{MDE} of DESs for the MDE predicted section moment load histories in the FA (top) and SS (bottom) direction of the IEA 15-MW RWT from the individual HAWC2 simulation s, as presented in (32). Color gradient represents the mean wind speed at the hub V_{hub} for the considered simulation s. Two separate x-axes are used to present ε_{MDE} (illustrated with white and grey background colour).

RC2.24) (line 650)
RC2.24) thank you for the elaborate comments. We have replied to the individual comments below the respective sections:

This work is a well-written and understandable read with precise Figures. The reviewer congratulates the authors for its high level.
Thank you for this nice comment.

The only major point of critics concerns the motivation and relevance of the overall concept. The authors argue MDE is applied at positions not accessible for sensor application and than later show the significant errors to be close to the tower top. This position, however, seems rather easy to access and equip with sensors (as also mentioned by the authors and displayed in Figure 11). This contradiction seems unresolved to the reviewer and I ask the authors to comment on this.

Thank you for commenting on this. This is a valid concern, and the authors have attempted to clarify below:

- The multi-band MDE is a global monitoring approach, and thus it should perform accurately structure-wide, ideally, removing the need for location-specific sensors. In the reply to comment RC2.04, the global monitoring approach has been emphasised, and the error around the MWL is added to the argumentation for the need to include blade flexibility. Furthermore, the discussion has been extended with PSD plots of the MDE error around the MWL, which show that the error is related to erroneous tower mode shapes.
- Poor performance anywhere in the structure, broadly speaking, means that the mode shapes used in the MDE do not reflect the mode shapes of the actual structure. This can, in theory, lead to errors anywhere in the structure depending on the measured degrees of freedom.
- In a real-world scenario, it is often relevant to calibrate an FE model to measurement data. If the FE model disregards important parameters (such as blade flexibility), tuning parameters such as the soil stiffness are likely misinterpreted. The error in the natural frequency of the tower modes resulting from disregarding blade flexibility is discussed in (Reinhardt et al., 2024) which has also been included in the present paper (see RC1.06).

The authors hope that this reply satisfies the review comment and solves the contradiction.

Another aspect which might merit some additional explanation in writing: **1)** According to my understanding, DLC4.1 as per IEC61400 does not include turbulence. **2)** It's frequency in the standard also is significantly lower than its practical occurrence, mostly due to curtailment of power output as a function of energy trading. Recent presentations on the WESC 25 mentioned up to 50 turbine stops per day and also claimed this to be critical as they happen also under unfavorable operating conditions. I fully understand this cannot be covered with the present work, but I think a word or two in the conclusions to mention the possibility of DLC4.1 playing a much more significant role in real-world turbines would add value to it.
1) It is correct that DLC 4.1 does not include turbulence. However, in the simulations performed for the dataset (Pedersen et al., 2025), it was chosen to include turbulence and stochastic waves to obtain a more realistic time series response for this DLC (as well as for DLC 4.1). This is also explained in the documentation in (Pedersen et al., 2025).
2) A comment has been added in Section 3.2 (previously 2.5) regarding the duration of DLC 4.1 (line 222-224):
"However, in a real operating scenario, shut-down and start-up may have a larger influence on the lifetime damage, as they occur more frequently than described by IEC (2019b) due to, for example, curtailment. This has not been accounted for in the present paper."
and in the conclusion (line 598-600):
"The damage associated with start-up and particularly shut-down in normal conditions (DLCs 3.1 and 4.1) might be significantly underestimated in the present paper, as the durations specified by IEC (2019b) for these DLCs do not necessarily reflect a real operation scenario, where start-up and shut-down can occur for many reasons, including curtailment."

One last thing that escaped my understanding and where I merely ask for a layman's explanation is the seemingly contradiction of the tower top sensor being there and the huge error of MDE at tower top (also pointed to in a dedicated comment).
We have replied to this under comment **RC2.22.**

Ghoshal, A. (2024). *Colossal 20-MW wind turbine is the largest on the planet (for now)*. https://newatlas.com/energy/world-largest-offshore-wind-turbine-20-mw-mingyang/

Pedersen, M. G., Rinker, J., Høgsberg, J., & Farreras, I. A. (2025). *IEA-15MW-RWT-Monopile HAWC2 Response Database*. Technical University of Denmark. https://doi.org/10.11583/DTU.24460090.v3

Reinhardt, T., Sastre Jurado, C., Weijtjens, W., & Devriendt, C. (2024). On the influence of rotor nacelle assembly modelling on the computed eigenfrequencies of offshore wind turbines. *Journal of Physics: Conference Series*, *2767*(5). https://doi.org/10.1088/1742-6596/2767/5/052034

Salas, J. (2025). *Another turbine world record set – but not by China this time*. https://newatlas.com/energy/siemens-gamesa-sg-dd-276-turbine/