Reviewer 1

RC1.01) Clarify the novelty of your approach compared to existing studies, highlighting specific contributions and advances.

RC1.01) Thank you for pointing this out. The novel contributions of this paper are summarised below:

- This work shows how the structure-wide performance of multi-band MDE is limited by the lumped inertia RNA model. It specifically shows how errors are associated with erroneous second and third tower bending modes, given the omission of rotor modes coupled to tower excitation.
- This work proposes using a simple time-invariant load distribution for the wave load Ritz vector, which has not been explicitly defined in the considered existing studies dealing with OWTs on monopile foundations.
- Finally, this work is the first to utilise the comprehensive dataset from the IEA-15-MW-RWT-Monopile Database Pedersen et al. (2025). This dataset (1) facilitates cross-institute benchmarking of virtual sensing algorithms, as it provides an unrestricted range of sensor locations and quantities, and (2) enables validation of predicted response in the complete OWT, including monopile tower and blades.

This justification has been added to the paper as (line 84-91):

"The novel contributions of this paper are summarised as follows. This paper demonstrates how the structure-wide performance of multi-band MDE is limited by the lumped inertia RNA model. It specifically shows how errors are associated with erroneous second and third tower bending modes and the omission of rotor modes coupled to tower excitation. Additionally, this paper proposes a simple time-invariant load distribution for the wave load Ritz vector, which, to the best of the author's knowledge, has not been explicitly defined in existing studies dealing with virtual sensing in OWTs on monopile foundations. Finally, this is the first work to utilise the dataset (Pedersen et al., 2025). This dataset facilitates cross-institute benchmarking of virtual sensing algorithms, as it provides an unrestricted range of sensor locations and associated output channels. Furthermore, it enables validation of the predicted response in the entire OWT, including the monopile, tower, and blades."

RC1.02) Consider shortening the Data section, moving detailed information to an appendix to maintain focus on virtual sensing

RC1.02) Thank you for the comment. The authors recognise that the data section is long. To meet this point of critique, the Data section has been split into two sections: "2 Data" (line 99-110), which briefly lists the key information regarding the dataset (Pedersen et al., 2025), and "3 IEA 15-MW RWT performance and relative damage assessment" (line 111-229), which collects the former sections "2.4 Performance of the IEA 15-MW RWT" and "2.5 Relative lifetime damage results". The authors are of the opinion that section 3 is necessary context to fully interpret the MDE results and support the paper's conclusions. However, the former sections "2.1 IEA Wind 15-Megawatt Offshore Reference Wind Turbine", "2.2 Modelling", and "2.3 Load cases" have been collected in Appendix A.

RC1.03) Provide a rationale for the multi-band approach boundaries in Table 6, indicating if they are standard or proposed by the authors.

RC1.03) Thank you for this suggestion, it has resulted in significant improvements in the revised manuscript. A rationale for the frequency bands' boundaries has been added to the paper, and Figure 11 (previously 6), presenting the bands, has been moved to this section of the paper.

Furthermore, based on this comment and RC1.05 and RC1.06, we looked into the band separation and performed an extensive analysis. Based on the results, we changed the boundaries of B1 to include the 3P effects in this band and represent this with the Ritz vector obtained from the nodal moment. The altered text in the paper is presented here (line 434-459):
"The rationale for the band separation depends on case-specific factors, including the frequency distribution of the external loads, the dynamic properties of the considered structure, and the properties of the sensors available in the monitoring system. Thus, the frequency bands should be selected such that the response is predicted accurately without exceeding the inherent sensor limitations of the MDE. The justification of the present band separation is given below for the MDE configuration summarised in Table 3:

– B1 is defined with an upper limit of 0.05 Hz. According to Toftekær et al. (2023), accurate displacements cannot be obtained from measured accelerations at frequencies below 0.05 Hz. Hence, the measured DOFs in Φm are defined in terms of rotations in B1, and the boundary represents a practical limitation of the sensors. B1 represents the quasi-static domain of the response, primarily driven by turbulence. Thus, the Ritz vectors included for the prediction in this band are obtained from the nodal force and moment in Figure 8(a,b). Furthermore, the wind is assumed to act as a distributed load across the tower, whereby the first tower bending mode shapes in Figure 7(a) are also included in the MDE.

– B2 is defined within the frequency range 0.05 to 0.13 Hz. The upper limit is chosen as the boundary between the thrust-dominated and the resonant parts of the response, dominated by the first tower bending modes. B2 is governed by wave loading with a wave frequency of 1/Tp = 0.068 Hz at V = 35 m/s and 1/Tp = 0.18 Hz at V = 4 m/s for the given site conditions. Furthermore, the wind load also contributes significantly to the response in this frequency band, whereby all three pairs of Ritz vectors in Figure 9 are included in the MDE for this band.

– B3 is defined within the frequency range 0.13 to 0.45 Hz. The upper limit is defined as the boundary between the 3P frequency and the frequency of the first flapwise blade mode. B3 is governed by the first tower bending modes along with the wave loads and the 3P excitation. Hence, the first tower bending mode shapes in Figure 7(a) and the Ritz vectors from wave loading in Figure 8(c) are included in the MDE. As the 3P excitation is driven primarily by uneven thrust loading on the rotor, it is well represented by the Ritz vector obtained from a nodal moment in Figure 8(b), hence, the Ritz vector in Figure 9(b) is also included in B3 for the MDE.

– B4 is defined within the frequency range 0.45 to 50 Hz. This frequency band represents a part of the response where the external loads are of minor influence. Hence, B4 includes the higher-order dynamics and rotor harmonics. Here, the first three pairs of tower bending modes in Figure 7 are included in the MDE, while the first tower torsion mode is omitted as it is considered less significant for estimating bending stresses."

RC1.04) Consider conducting a direct comparison between models with and without accurately modelled RNA, including rotor blades, to isolate error sources.
RC1.04) We thank the reviewer for this comment. The authors agree that including an accurately modelled RNA would indeed help to isolate the cause of the MDE error, and the authors intend to pursue this in future research. This is highlighted in the text in the conclusion (line 622-625):
"In future work, the authors suggest investigating the effects of including a flexible rotor in the FE model used to obtain the mode shapes used in the MDE. The knowledge obtained from the present work will serve as a basis for updating the RNA model to include blade flexibility, and

subsequently to include operational and environmental variability in the RNA modelling, e.g. by using individual RNA models for various wind speeds."

However, the authors consider this to be beyond the scope of the present paper. With the improvements made to the paper by implementing the revisions based on RC1.05 and RC1.06, the authors believe that the present paper provides sufficient argumentation for why a flexible rotor model should be included in the prediction FE model.

RC1.05) Offer a sample time series of strain data and analyse where discrepancies originate, enhancing the understanding of the study's context.
RC1.06) Investigate errors in the frequency domain to offer deeper insights into their origins and behaviour.
RC1.05+RC1.06) Thank you for this good suggestion for improving our work. To meet these points of critique, the following changes/additions have been made to the paper:

1) An Appendix C with selected sample moment time histories and their associated normalised power spectral density (PSD) has been added to the paper.
2) The PSD plots in Appendix C also include the PSD of the MDE error, the wind speed and the wave amplitude for a more qualified interpretation of the errors shown in the MDE error plots (Figures 12, 13, and 14).
3) The discussion in the results Section 5.2 (previously 4.2) (line 490-585) has been adjusted to include the results shown in the appendix.
4) The conclusions regarding the effects of disregarding blade flexibility from the FE model used in the MDE have been backed up by a statement in the introduction (line 66-70): "This is demonstrated by (Reinhardt et al., 2024) which shows that ignoring blade flexibility in the RNA model significantly impacts the natural frequency and mode shape of the second tower bending modes. Additionally, rotor modes, which, given the inherent coupling between the tower and the blades, also affect the tower vibrations, are omitted from the MDE, as these cannot be represented using a lumped inertia RNA model. These simplifications can therefore introduce errors in the strains or stresses estimated in the supporting structure."

References

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