Authors' final response - "Dynamics of floating wind turbine wakes in a wind tunnel setup"

R. Amaral, F. Houtin-Mongrolle, D. von Terzi, P. Deglaire and A. Viré

May 2026

1 General remarks

The authors thank the reviewer for their valuable feedback and believe that the main concerns have been addressed in the new version of the manuscript. In the author's understanding, the main concerns with the manuscript were: (1) the insufficient number of cases to support generalized conclusions; (2) the lack of contextualization of this manuscript and its novelty within the literature; (3) the lack of literature review pertaining to more recent and relevant work; (4) the simplified nature of the setup (laminar flow, no turbulence, constant rotor speed, scaled-down turbine); (5) the statement that the prescribed motions were realistic; and (6) the use a wind tunnel setup with an asymmetric cross-section and high blockage ratio. All the comments from the reviewer are addressed in this document, and the comments pertaining to the main concerns are addressed first.

This document is structured in the following way:

- RC2 - where all the comments are addressed, starting with the ones perceived as the most critical.
- Additional Changes - the authors highlight further changes to the manuscript, beyond the comments, that they believe improve the quality and readability of the manuscript.

2 RC2

2.1 Comment from referee

In my opinion, the topic itself is interesting; however, I am quite confused about the rationale and motivation for simulating a downscaled turbine in a wind tunnel (with limitations such as confined space and blockage effects) and under such low turbulence intensity conditions. This setup makes the results less relevant to real-world applications. Moreover, the choice of only two sets of dynamic parameter combinations is insufficient to represent wake dynamics or to justify trends within a given parameter range (unless supported by rigorous theoretical arguments). In addition, thorough proofreading is strongly recommended to improve readability and clarity.

2.1.1 Authors' response

The authors agree with the comments from the reviewer. Nevertheless, the authors believe there was value in simulating the turbine in this setup in order to understand what influence the wind tunnel has on floating wind turbine wakes, because most of the experimental data under controlled conditions comes from wind tunnel testing (such as the Politecnico di Milano wind tunnel with the scaled-down version of the DTU 10 MW). Hence, the authors found it a good idea to explore if there had been a sizable impact in the experiment that this study replicates. The study finds that there was likely an impact on wake recovery and the tip-root vortex trail mergers due to the blockage and wind tunnel asymmetry, but that the floating turbine wake fundamentals found in the literature are captured.

The authors added justification of the results and conclusions with references from the literature in the new version.

A thorough language review was performed and the authors believe the language is now suitable for a scientific article.

2.1.2 Authors' changes in manuscript

Overview of the performed cases, data used and analyses: L70-L80.

Novelty in the context of the broader Politecnico di Milano wind tunnel work carried out with the 1:75 scaled-down version of the DTU 10 MW: L81-L98.

Connection to the IEA task OC6 Phase III: L99-L105.

References to support results and conclusions: L284-L295, L321-L330, L335-L344, L350-L361, L370-L374, L396-L402, L404-L413, L426-L432, L441-L450, L467-L478, L486-L495, L505-L509, L579-654.

2.2 Comment from referee

The introduction lacks coverage of recent studies on wind tunnel experiments (e.g., involving single- or multiple-degree-of-freedom motions), as well as numerical or experimental investigations under high-turbulence-intensity or atmospheric boundary layer (ABL) conditions. It should be more comprehensive, given the topic under investigation.

2.2.1 Authors' response

The authors recognize that a large body of literature pertaining to experimental work directly relevant to this study, as well as to the effect of turbulence and prescribed motion direction on the wake was missing from the literature review. These references were now included in the literature review.

2.2.2 Authors' changes in manuscript

References regarding the effect of turbulence: L55-L65.

References regarding cross-stream motion prescription: L66-L69.

Acknowledgment of related work carried out in the Politecnico di Milano wind tunnel: L81-L85.

2.3 Comment from referee

The knowledge gaps are not clearly identified, and the novelty and contributions are not well articulated. The rationale for selecting only two sets of Strouhal number–amplitude (St–A*) combinations, as well as the use of such a low turbulence intensity, is not explained. The definitions of St and A* should also be provided upon first use.

2.3.1 Authors' response

The three key features of this study are: (1) it compares surge, sway, roll, pitch, and yaw motions; (2) it uses data sampled from radial probes that cover circular two-dimensional sections of the wake at several downstream positions, instead of the commonly used linear probes; and (3) it analyzes the wake in terms of recovery, recovery gradient, turbulence intensity, wake velocity spectral components, morphology, and tip and root vortex trail evolution and merger. The numerical approach (LES-ALM), the motion conditions considered (surge, sway, roll, pitch and yaw), and the pairs of Strouhal number and amplitude are not novel. In terms of wake analysis methodology, the methods used can be found in some form in the literature, although not exactly in the same form and level of detail. The novelty of this study is found when contextualizing the study in the broader Politecnico di Milano wind tunnel work carried out with the 1:75 scaled-down version of the DTU 10 MW. In the context of this work, to the best knowledge of the authors, the simultaneous coverage of points (1), (2), and (3) has not been carried out prior to the current work, especially in terms of the tip and root vortex trail analysis. This is now stated in the "Introduction".

Only two sets of Strouhal number–amplitude combinations were chosen because the goal was to cover a large number of degrees-of-freedom and analyses. This is now mentioned in the "Introduction". The initial number of cases covered was thirteen, corresponding to one fixed-bottom case, two cases for surge, sway, roll, pitch and yaw, and two cases for coupled surge-pitch. The analysis of the coupled surge-pitch cases was removed to reduce the size of the manuscript, and because the number of cases was too small to draw any strong conclusions.

No turbulence was considered to highlight the wake dynamics induced exclusively by the turbine motion, similarly to what was done in other experimental and computational studies in the literature. This is now mentioned in the "Introduction" and "Case Description".

The authors added the definitions at first use.

2.3.2 Authors' changes in manuscript

Overview of the performed cases, data used and analyses: L70-L80.

Novelty in the context of the broader Politecnico di Milano wind tunnel work carried out with the 1:75 scaled-down version of the DTU 10 MW: L81-L98.

Connection to the IEA task OC6 Phase III: L99-L105.

Explained why only two sets of Strouhal numbers were selected: L70-L72.

Explained why no turbulence was included: L104-L105, L179-L183.

Defined the Strouhal number at first use: L49.

Defined the Strouhal number, and amplitude at first use in "Wind turbine model and floating degrees of freedom": L157-L171.

2.4 Comment from referee

Lines 106–107: What is the rationale for using such a low and unrealistic turbulence intensity? Is the inflow sheared? If the goal is to isolate the pure effects of motion, why not use laminar inflow instead?

2.4.1 Authors' response

The inflow was indeed laminar to isolate the pure effects of the motion. Hence, no turbulence was considered to highlight the wake dynamics induced exclusively by the turbine motion, similarly to what was done in other experimental and computational studies in the literature. The inflow was not sheared.

2.4.2 Authors' changes in manuscript

Explained why no turbulence was included: L104-L105, L179-L183.

Created table that includes the details about the free-stream velocity (4 ms^{-1}), type of inflow (laminar, no shear), blade stiffness (rigid), blade pitch (0 deg), rotor speed (Constant, 240 rpm), wall boundary condition (slip wall) and blockage ratio (8.46 %): Table 3.

2.5 Comment from referee

Parameter selection: Why were only two parameter pairs selected for each motion? What representative operating conditions do these pairs correspond to? The selection omits intermediate Strouhal numbers that may lead to different wake dynamics. Moreover, is it realistic for low-frequency motions to be associated with large amplitudes?

2.5.1 Authors' response

The authors recognize that the inclusion of intermediate Strouhal numbers also covered in the IEA task OC6 Phase III would have been informative. Only two sets of Strouhal number–amplitude combinations were chosen because the goal was to cover a large number of degrees-of-freedom and analyses. This is now mentioned in the ”Introduction”. Nevertheless, the wake behavior at the simulated high Strouhal number ($St_{\mathrm{p}} = 1.1905$) is strikingly different from the one at the simulated low Strouhal number ($St_{\mathrm{p}} = 0.0744$), which allowed the authors to identify two different wake regimes (see Figs. 9, 11, 12, 13 and 14, for instance).

These pairs are considered representative of different FOWT support structures under near-rated conditions based on Bergua et al. [2023]. The authors made the statement about the surge and pitch prescribed motions being realistic based on Bergua et al. [2023], who analyzed the same surge and pitch cases from the experiment addressed in the IEA task OC6 Phase III. The relevant excerpt from Bergua et al. [2023] is the following: ”The platform motion amplitudes shown in Table 4 correspond to oscillations ranging from 0.6 to 9.375 m at a full scale (i.e., from 0.003 to 0.05 rotor diameter). In terms of periods at a full scale, the tests cover the range from 12.5 to 20 s (Mancini et al., 2020). Most FOWT testing is done with Froude-scaled models. However, in the two testing campaigns considered in this study, the scaling was based on the reduced frequency to try to preserve the relationship between the wind and the platform velocity. In this case, the wind velocity was scaled by a factor of 3 and the physical dimensions by 75 (Mancini et al., 2020). These amplitudes and periods are considered representative of different FOWT support structures.”

The isolated frequencies and amplitudes are representative in the sense that they would likely be found in the high-energy region of the response spectrum of a floating wind turbine for different support structures. The language was changed from ”realistic” to ”representative”.

2.5.2 Authors' changes in manuscript

Explained why only two sets of Strouhal numbers were selected: L70-L72.

Supported the statement about the surge and pitch cases being representative of different FOWT support structures with a reference: L201-L204.

2.6 Comment from referee

Line 135: If wall shear and turbulence are present, the inflow profiles of mean velocity and turbulence intensity should be provided. In the experimental setup, the turbine top appears to be very close to the wind tunnel ceiling. How does this proximity affect wake dynamics? Is this effect accounted for in the precursor inflow simulation? Please comment on how representative this setup is compared to more realistic conditions (e.g., absence of a ceiling boundary layer and lower blockage effects).

2.6.1 Authors' response

No wall shear, nor turbulence were present. The inflow was laminar with no shear, hence no precursor inflow simulation was performed. The goal was to reproduce the experiment in order to assess whether the phenomena documented in the literature would still be captured, and what would be the impact of the wind tunnel asymmetry (height much lower than width, and proximity to the top wall), and blockage effect. The study finds that there was likely a reduction in wake recovery due to the blockage, and earlier tip-root vortex trail mergers in the height direction due to the wind tunnel asymmetry, but that the floating turbine wake fundamentals found in the literature for less constrained setups are captured. This impact is discussed in more detail in "Wake recovery", "Tip and root vortex trails", and in the "Discussion".

2.6.2 Authors' changes in manuscript

Discussed potential effect of wind tunnel blockage on wake recovery: L321-L330.

Discussed potential effect of wind tunnel asymmetry on tip-root vortex trail mergers: L571-L577.

Discussed potential effect of wind tunnel blockage and asymmetry in the "Discussion": L647-L654.

2.7 Comment from referee

Line 77: Details of the wind tunnel should be provided.

2.7.1 Authors' response

The dimensions of the wind tunnel were added. The authors believe that the wind tunnel cross-section is the only information from the wind tunnel that is required to reproduce the simulation setup in this study. The remaining dimensions of the simulation domain (which has the same cross-section as the wind tunnel) and the turbine positioning are provided, but were defined by the authors. Is there any other information that should be added?

2.7.2 Authors' changes in manuscript

Sentence reformulated: L210-L212.

2.8 Comment from referee

Line 83: The power coefficient (Cp) and thrust coefficient (Ct) of the turbine model should be reported, along with details of the operational and control strategies applied.

2.8.1 Authors' response

The authors added the coefficients and the details of the operational and control strategies in some tables to make them more easily identifiable.

2.8.2 Authors' changes in manuscript

Added the power and thrust coefficients: Table 1.

Created table that includes the details about the free-stream velocity (4 ms^{-1}), type of inflow (laminar, no shear), blade stiffness (rigid), blade pitch (0 deg), rotor speed (Constant, 240 rpm), wall boundary condition (slip wall) and blockage ratio (8.46 %): Table 3.

The details about the operating conditions are addressed in "Case definition": L175-L190.

2.9 Comment from referee

Line 155: How is the rotational speed regulated? Is it dynamically adjusted or kept constant? How realistic is this approach?

2.9.1 Authors' response

The rotor speed was kept constant for all cases with the goal of isolating the effect of the prescribed motion only. This was also the approach in the wind tunnel experiment. The approximation should not be too far off from reality, since the turbine operated near rated conditions. This is now mentioned in "Case definition".

2.9.2 Authors' changes in manuscript

Added rotor speed: Table 3.

Addressed the constant rotor speed simplification: L175-L179.

2.10 Comment from referee

Lines 179–183: Can the authors provide a physical interpretation of the observed behavior?

2.10.1 Authors' response

Based on the frequency-dependent wake response identified in the literature review, the authors associate the higher destabilization of the wake with the excitation of the wake at more favorable frequencies, i.e., frequencies that the wake tends to amplify, leading to coherent structures and, therefore, more destabilization. Although the Strouhal number of the high-St/low-A^* cases falls outside of the most favorable range identified in the literature (0.1-0.9), the authors show in "Frequency contents" that this frequency still falls inside the range of frequencies that the fixed-bottom turbine naturally develops, which are arguably its natural modes. Hence, exciting the wake at this Strouhal number should lead to higher amplification and wake destabilization.

As for the higher wake destabilization for motions in the cross-stream directions, Messmer et al. [2025] finds that the cross-stream wake modes, when excited, are more energetic than the streamwise modes and lead to higher increases in the Reynolds stresses that entrain momentum in the wake.

All these considerations are now discussed in "Wake recovery".

2.10.2 Authors' changes in manuscript

Noted the frequency-dependent behavior and cross-stream preference": L287-L295.

Justified cross-stream preference: L335-L341.

Justified the frequency-dependent behavior: L441-L450.

2.11 Comment from referee

Lines 201–202: What explains the significant difference observed at x* = 3? Is this consistent with findings reported in the literature? Could this discrepancy be due to domain confinement in the wind tunnel and the absence of a fully developed wake region in the simulations?

2.11.1 Authors' response

The literature suggests that motions with a cross-stream component are more beneficial to the wake recovery [Fontanella et al., 2024, 2025, Messmer et al., 2025]. Messmer et al. [2024] shows that the prescribed motion accelerates the recovery by shifting the position where the recovery gradient increases sharply. Hence, based on the literature, the cases showing a stronger wake recovery are expected to have an earlier onset of the wake recovery, due to the earlier sharp increase in recovery gradient. This is indeed what is observed for the SwHS and RoHS cases. The authors believe it is unlikely that the discrepancy arises from the domain confinement, since the domain was confined in all cases. The authors also believe there was a fully developed wake region in the simulations, as evidenced by Fig. 10, where the slope of average wake spectra is approaching -5/3 at $x^* = x/D = 6$. The distance from the turbine position to the outlet was $14D$, giving the wake a further $8D$ of distance to fully develop from $x^* = 6$.

2.11.2 Authors' changes in manuscript

Addressed the wake recovery onset discrepancy: L341-L344.

2.12 Comment from referee

Line 220: What is meant by "destabilization of the inner jet"? How reliable is it to explain wake recovery based on instantaneous wake velocity alone? What role does ambient turbulence play in this context?

2.12.1 Authors' response

"Destabilization of the inner jet" means the oscillation or meandering of the high velocity region at the wake axis. The authors use the instantaneous plots in order to visualize the wake structures that develop, otherwise it would be difficult to see them and identify the cause of the hindered wake recovery. Despite being instantaneous, these contours were extracted at the last instant of the simulation $t = 64$ s, long after the convergence was achieved, and should represent periodic structures that repeat in time, making them informative for the wake velocity. Messmer et al. [2024] and Messmer et al. [2025] identify different wake structures for surge (pulsating) and sway (meandering). Messmer et al. [2025] then demonstrate that the sway meandering structures are more energetic and lead to sharper Reynolds shear stress gradients, which ultimately drive a stronger wake recovery. Although Messmer et al. [2024, 2025] do not observe deterioration of wake recovery in surge, Li et al. [2022] observes this deterioration for a sway case, suggesting that there may be combinations of St and A^* that can hamper the wake recovery.

While no ambient turbulence was present in the simulations, the literature suggests that ambient turbulence intensity as little as 1.5% accelerates wake recovery, and contributes as much as or more to the far-wake transition as the prescribed motion for higher turbulence intensity values. From $I > 5\%$, ambient turbulence should be the sole driver of wake recovery [Messmer et al., 2025].

2.12.2 Authors' changes in manuscript

Explained hampered recovery and supported the hypothesis with more references: L350-L361.

The effect of turbulence is addressed in the "Introduction" and "Discussion": L55-L65, L640-L643.

2.13 Comment from referee

Lines 247–249: This sentence is difficult to follow and should be clarified.

2.13.1 Authors' response

The sentence was reformulated significantly for clarity.

2.13.2 Authors' changes in manuscript

Sentence reformulated: L404-L413.

2.14 Comment from referee

Section 3.5 (Wake meandering): Can the authors comment on how wake meandering might differ under realistic atmospheric boundary layer conditions?

2.14.1 Authors' response

The wake meandering analysis was removed from the manuscript to reduce the size of the manuscript, and because it did not add anything beyond what the velocity amplification factors added.

2.14.2 Authors' changes in manuscript

Wake meandering results and discussion were removed.

2.15 Comment from referee

These sections should explicitly identify the limitations of the present study and discuss how the results might differ under realistic inflow conditions and across a broader range of dynamic parameters.

2.15.1 Authors' response

The "Discussion" and "Conclusions" sections were updated to discuss the points highlighted by the reviewer.

2.15.2 Authors' changes in manuscript

Discussed limitations, results under realistic inflow conditions, and results under broader dynamic parameters in the "Discussion": L638-L654.

Discussed limitations, results under realistic inflow conditions, and results under broader dynamic parameters in the "Conclusions": L686-L694.

3 Additional Changes

In addition to replying to reviewers' comments , the authors took advantage of the opportunity provided by the review of this manuscript to make further changes that they believe improved the quality and readability of the manuscript. These include:

- Due to the manuscript size increase as a result of the review, content related to wake meandering (sections "Wake meandering" and "Appendix D: Instantaneous wake center") was removed because it added little information beyond what the cross-stream velocity amplification factors were already showing. Likewise, content related to the coupled surge-pitch cases was removed because these cases were too few to be able to draw any conclusions.

- The abstract, "Discussion" and "Conclusions" sections underwent significant revisions.

- Ω is now used for the rotor speed expressed in rpm, whereas ω is used for the rotor speed expressed in rad/s.
- Removed mentions of "normalized" but indicated in L170 that "All the quantities used in the study are normalized, i.e., made non-dimensional, unless otherwise indicated. Hence, the adjective "normalized" will be dropped after the quantity is defined, to avoid unnecessary repetitions."

- The high-St_{p}/low-A_{p}^* pitch case was added to Fig. 5, to further highlight the effect of cross-stream perturbations.

- Figure 6 (a) was changed to include the wake recovery of all cases, and the plot was zoomed in to show the different recovery onset positions. In Fig. 6 (c), the wake recovery gradient increments of the low-St_{p}/high-A_{p}^* cases are much lower and steadier compared to those of the high-St_{p}/low-A_{p}^* cases. Since this can be assessed from Fig. 6 (b), the low-St_{p}/high-A_{p}^* cases were removed from Fig. 6 (c) to highlight the high-St_{p}/low-A_{p}^* cases.

- In the legend of Figs. 6, 9, 11 and 15, the high-St_{p}/low-A_{p}^* cases are now shown as solid lines, while the low-St_{p}/high-A_{p}^* cases are shown as dashed lines. No markers were used.

- The cases shown in Figs. 8 and 12 were changed to match those of Fig. 5, to allow for a more direct comparison between all the figures.

- Added an intermediate step in Equation 12.

- Added the Q-criterion surface for the YaHS case in Fig. 13 and discussed it in L507-L509.

- In ”Tip and root vortex trails”, the tip vortex trail mergers (L560-L577) are now discussed after the comparison between the tip vortex trail thickness and the average cross-stream velocity spectrum (L546-L559).

- While the conclusions throughout the whole manuscript did not change, a thorough language review was performed in order to better frame the findings, and to include more comparisons with some of the references proposed by the reviewers.

- In ”Appendix A: Prescribed motion validation”, the relative error symbol was changed from ϵ to RE (L713-L714), not to overlap with the smearing length scale. In Table A2, A_{pb} was changed to A_{pp}, where ”pp” stands for ”prescribed point”.

- In ”Appendix B: Flow field convergence”, the streamwise flow field convergence study of the SwHS case was added (Fig. B2).

- In ”Appendix C: Experimental comparison”, the symbol of the difference relative to the experimental value was changed from ϵ to RE (L773), not to overlap with the smearing length scale.

References

R Bergua, A Robertson, J Jonkman, E Branlard, A Fontanella, M Belloli, P Schito, A Zasso, G Persico, A Sanvito, E Amet, C Brun, G Campaña-Alonso, R Martín-San-Román, R Cai, J Cai, Q Qian, W Maoshi, A Beardsell, G Pirrung, N Ramos-García, W Shi, J Fu, R Corniglion, A Lovera, J Galván, T. A Nygaard, C. R dos Santos, P Gilbert, P.-A Joulin, F Blondel, E Frickel, P Chen, Z Hu, R Boisard, K Yil-mazlar, A Croce, V Harnois, L Zhang, Y Li, A Aristondo, I Mendikoa Alonso, S Mancini, K Boorsma, F Savenije, D Marten, R Soto-Valle, C. W Schulz, S Netzband, A Bianchini, F Papi, S Cioni, P Trubat, D Alarcon, C Molins, M Cormier, K Brüker, T Lutz, Q Xiao, Z Deng, F Haudin, , and A Goveas. Oc6 project phase iii: validation of the aerodynamic loading on a wind turbine rotor undergoing large motion caused by a floating support structure. *Wind Energ. Sci.*, 8:465–485, 2023. doi: 10.5194/wes-8-465-2023.

Alessandro Fontanella, Alberto Fusetti, Stefano Cioni, Francesco Papi, Sara Muggiasca, Giacomo Persico, Vincenzo Dossena, Alessandro Bianchini, and Marco Belloli. Wake development in floating wind turbines: New insights and open dataset from wind tunnel experiments. *Wind Energy Science Discussions*, 2024:1–23, 2024.

Alessandro Fontanella, Stefano Cioni, Francesco Papi, Sara Muggiasca, Alessandro Bianchini, and Marco Belloli. Experimental investigation of the effects of floating wind turbine motion on a downstream turbine performance and loads. *Wind Energy Science Discussions*, 2025:1–29, 2025.

Z Li, G Dong, and X Yang. Onset of wake meandering for a floating offshore wind turbine under side-to-side motion. *J. Fluid Mech.*, 934(A29), 2022. doi: 10.1017/jfm.2021.1147.

T Messmer, M Hölling, and J Peinke. Enhanced recovery caused by nonlinear dynamics in the wake of a floating offshore wind turbine. *J. Fluid Mech.*, 984 (A66), 2024. doi: 10.1017/jfm.2024.175.

Thomas Messmer, Joachim Peinke, Alessandro Croce, and Michael Hölling. The role of motion-excited coherent structures in improved wake recovery of a floating wind turbine. *Journal of Fluid Mechanics*, 1018:A23, 2025.