



A Global POD Comparison of Surge- and Pitch-Induced Wake Dynamics of a Floating Offshore Wind Turbine

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Abstract. The motion of floating offshore wind turbine platforms strongly affects wake development. Consequently, understanding motion-induced wake effects has become a key research topic, with implications for wind farm layout optimization and advanced control strategies. This work investigates the wake dynamics of floating offshore wind turbines operating under realistic atmospheric boundary layer inflow using Large-Eddy Simulations with an actuator line model. A comprehensive dataset including surge and pitch motions over a range of motion frequencies and amplitudes is analysed through a global proper orthogonal decomposition, providing a common modal basis for the consistent comparison of wake dynamics across all cases. The results identify the reduced frequency as the dominant parameter governing platform-induced wake dynamics. Although the time-averaged wake is only marginally affected under the investigated operating conditions, the coherent wake response strongly depends on the reduced frequency. Motions with a reduced frequency of $f_r = 0.2$ produce a negligible coherent contribution, whereas $f_r = 0.5$ generates energetic coherent structures that persist up to approximately 4-5 rotor diameters downstream. In contrast, $f_r = 0.8$ leads to a more localized response confined to the near wake. Motion amplitude primarily influences the intensity of the coherent response, while the reduced frequency controls its spatial evolution. Surge and pitch exhibit similar overall trends, although pitch produces slightly stronger coherent energy in the upper wake close to the rotor. Finally, only a limited number of POD modes are required to reconstruct the coherent response in regions where the platform-induced wake structures remain well organized and spatially coherent, highlighting the potential of the proposed global POD framework for reduced-order modelling of floating offshore wind turbine wakes.

1 Introduction

The Net Zero Emissions by 2050 scenario, outlined in the World Energy Outlook 2025 (International Energy Agency, 2025), requires a rapid expansion of renewable energy capacity, with offshore wind playing a pivotal role in large-scale power sector decarbonization and floating technology enabling deployment in deep water sites. Under the combined action of wind, waves, and currents floating offshore wind turbines (FOWTs) can move in all six degrees of freedom. These motions, occurring at different time scales and amplitudes, affect both the rotor aerodynamics and the wake development. As a result, understanding motion-induced wake effects has become an important research topic, with direct implications for wind farm layout optimization, floater and mooring system design, and advanced control strategies.



25 A numerical study by Kleine et al. (2022), conducted under idealized laminar inflow conditions, investigated the effects of
platform motion on wake behaviour, showing that rotor oscillations can induce instabilities in the near wake. Within this line
of research, other studies performed under laminar or low-turbulence inflow conditions have also reported the development of
coherent flow structures driven by platform motion, both in lateral and fore–aft directions (Fontanella et al., 2025; Messmer
et al., 2024a; Cioni et al., 2026). In particular, Messmer et al. (2024a) experimentally showed that, under laminar inflow
30 conditions, fore–aft (surge) motion can alter wake dynamics, with the response strongly dependent on the reduced frequency
of the imposed platform motion. This leads to different wake regimes, ranging from surge-dominated coherent structures to
more pronounced wake meandering behaviour. However, wakes are also strongly affected by inflow turbulence, both in terms
of magnitude and turbulent scales, which can significantly modify the wake recovery processes (Hodgson et al., 2023; Biswas
and Buxton, 2026). The interplay between inflow turbulence and motion-driven coherent structures has been investigated in
35 recent experimental works (Messmer et al., 2024b, 2025) and high-fidelity numerical studies (Firpo et al., 2026; Pagamonci
et al., 2025; Li et al., 2024; Barile et al., 2026).

Building on these findings, it is also crucial to assess how inflow turbulence interacts with platform motion in more real-
istic atmospheric environments, where shear is present. The presence of an Atmospheric Boundary Layer (ABL) introduces
additional complexity in wake development and evolution. This aspect has been recently addressed through experimental in-
40 vestigations by Hubert et al. (2025) and Schliffke et al. (2024) and numerical studies by Liu et al. (2025) and Li et al. (2022).

To support the physical interpretation of complex wake dynamics, reduced-order modelling techniques have recently been
adopted in the analysis of floating offshore wind turbines. These methods provide a compact representation of complex flow
fields, enabling the identification of dominant coherent structures. Among them, Proper Orthogonal Decomposition (POD) is
a widely used data-driven technique that decomposes turbulent flow fluctuations into orthogonal modes, yielding an optimal
45 representation in terms of variance (Lumley, 1967; Berkooz et al., 1993). POD has been applied to a wide range of flow
problems, and its modes are typically used for two main purposes: first, to provide physical insight into dominant coherent
structures in turbulent flows; and second, to construct reduced-order models (ROMs). In the context of floating wind turbines,
Raibaud et al. (2022) applied POD to the wake of a surging turbine, showing that the temporal coefficients exhibit distinct
peaks at the surge frequency. They also reported an overall increase in low-frequency spectral energy as the surge frequency
50 increases. In a subsequent study, Raibaud et al. (2023) coupled the POD framework with a data-driven inflow reconstruction
methodology to generate realistic turbulent inflow fields for aeroelastic simulations based on wind tunnel measurements. POD
was also employed by Hubert et al. (2026) to investigate the wake of a surging porous disk, clarifying the physical origin of a
sub harmonic signature observed in spectral analyses. More recently, Barile et al. (2026) applied POD to the wake of a surging
actuator disk under laminar, low-turbulence and atmospheric boundary layer inflow conditions. Their analysis showed that the
55 energy associated with the vortex-ring structures decreases with increasing turbulence intensity and reaches a maximum at
intermediate surge frequencies.

Typically, modal bases are derived from and applied to data corresponding to a single flow case, characterized by a specific
inflow condition, turbine operating state, and platform motion. As shown by Hubert et al. (2026), variations in the platform
motion (e.g., different surge frequency) can lead to differences in the resulting spatial modes. This variability makes direct



60 comparison across cases more challenging and may hinder a consistent physical interpretation of the results when different
operating conditions are considered. Recent studies (Andersen and Murcia Leon, 2022, 2023; Fu et al., 2023; Nony et al.,
2023; Buoso et al., 2022) have proposed the use of a single global basis obtained by applying POD to a dataset of multiple flow
cases. While preserving orthogonality and physical interpretability, this strategy allows for a consistent cross-case analysis.
In addition, it paves the way to more robust reduced order models, enabling interpolation in parameter space and enhancing
65 predictive capabilities for unseen flow conditions (Andersen and Murcia Leon, 2022).

Building on these developments, this work aims to advance the understanding of wake dynamics in floating offshore wind
turbines operating under realistic ABL inflow conditions, based on Large-Eddy Simulation (LES) data using an actuator line
model (ALM). In particular, the study investigates how wake behaviour is influenced by surge and pitch motions, which are
generally recognised as the most influential platform degrees of freedom for aerodynamic loading and wake dynamics, as well
70 as by key motion parameters such as frequency and amplitude. To this end, a comprehensive dataset covering multiple surge
and pitch motions over a range of frequencies and amplitudes is analysed using a global POD, i.e. an orthogonal basis built
from all cases in the dataset. By relying on a single global modal basis, this approach enables a consistent comparison across
cases that would otherwise be influenced by basis-dependent variability. Within this framework, the present study pursues two
main objectives: first, to provide a physical interpretation of wake dynamics by analysing the dominant energetic coherent
75 structures governing the flow; and second, to establish a consistent and robust methodology for cross-case comparison of
wake behaviour under varying platform motions and operating conditions. By using a global POD approach, the study aims to
identify the key motion-induced wake mechanisms and to support the development of future reduced order models for floating
wind applications.

2 Methodology

80 2.1 Wind Turbine Modelling

The IEA 22 MW reference wind turbine is considered in this study, featuring a rotor diameter of $D=284\text{m}$ and a rated power
of 22 MW (Zahle et al., 2024a). The turbine is modelled using an in-house Actuator Line Model (Sørensen and Shen, 2002)
implemented within the OpenFOAM CFD framework (Firpo et al., 2026). Only the rotor blades are represented, discretised
as actuator lines, while the surrounding flow field is resolved by the CFD solver. Blade aerodynamics is described using
85 Blade Element Momentum theory. A vortex-based velocity sampling strategy (Sanvito et al., 2024) is employed to accurately
compute the axial and tangential components of the local inflow velocity at each actuator point. The resulting point forces
are then projected onto the mesh using a three-dimensional Gaussian smoothing kernel with a width equal to 2.5 times the
local rotor cell size, ensuring numerical stability (Hodgson et al., 2022). Since the CFD-ALM framework resolves blade
tip vortices directly, no empirical tip-loss corrections are applied. However, secondary effects associated with the reduction
90 of aerodynamic forces due to pressure equalization near the blade tip are not explicitly accounted for; possible correction
strategies (e.g. Meyer Forsting et al. (2019)) are not considered here. Unsteady floating-platform dynamics are included by



prescribing time dependent surge displacement x and pitch angle θ_p according to Equations 1 and 2.

$$x(t) = A_s \sin(2\pi f_s t + \phi_s) \quad (1)$$

$$\theta_p(t) = A_p \sin(2\pi f_p t + \phi_p) \quad (2)$$

95 where $A_{s/p}$ and $f_{s/p}$ denote the motion amplitudes and frequencies of surge and pitch, respectively. The phase shift ϕ is set to zero in all cases, such that the motion is initiated in the leeward direction.

2.2 Simulation set-up

In this work, two distinct sets of simulations are considered, each addressing a specific objective.

- The first set is performed under a uniform laminar inflow condition and considers the turbine in a fixed-bottom configuration. This set is primarily used to assess the accuracy of the ALM in predicting blade loads and to derive an ad-hoc correction that compensates for the absence of a fully coupled aero-servo-elastic solver.
- The second and main set of simulations focuses on wake dynamics under more realistic conditions, employing an ABL inflow. This dataset includes fixed-bottom, surge, and pitch configurations, enabling a systematic investigation of wake behaviour under representative operational conditions.

105 For both simulation sets, second order Crank-Nicolson time integration was employed, while spatial discretization relied on nominally second-order accurate schemes for the gradient, divergence, and Laplacian terms. The pressure-velocity coupling was handled using the PIMPLE algorithm, as implemented in OpenFOAM. The algorithm was configured with two inner corrector iterations to improve convergence within each time step, along with two outer correction loops. All simulations were performed using a time step selected to ensure that the blade tip travelled no more than one grid cell per time step. This choice also resulted in a Courant number consistently below 0.25 throughout the simulations. The simulations employ the Smagorinsky sub-grid scale model for the representation of the unresolved turbulence. Given the different inflow conditions and modelling objectives, the numerical setups of the two simulation sets differ significantly in terms of numerical domain and boundary conditions.

115 Simulations with a uniform laminar inflow are performed on a computational domain of 4260 x 1704 x 1704 m (15D x 6D x 6D). A refined region extends from the inlet to 2272 m (8D) downstream, with a section of 568x568 m (2D x 2D) centred on the domain centreline (Fig. 1). The turbine is positioned 3D downstream of the inlet, within the refined region, where the grid resolution is uniform and equal to $\Delta x = \Delta y = \Delta z = \Delta = R/20$. Although a finer resolution of $R/32$ would be required to fully resolve the tip vortices, the chosen resolution of $R/20$ represents a practical compromise between computational cost and accuracy in predicting both loads and wake development. Previous studies (Hodgson et al., 2021, 2023) have shown that even a resolution of $R/16$ yields a thrust coefficient error below 1% and captures wake dynamics consistent with higher resolution simulations $R/32$. In particular, key flow features, such as vortex sheet roll-up, vortex ring formation, and the transition to small-scale turbulence, are adequately reproduced at this resolution. In addition, Appendix A and B present grid resolution

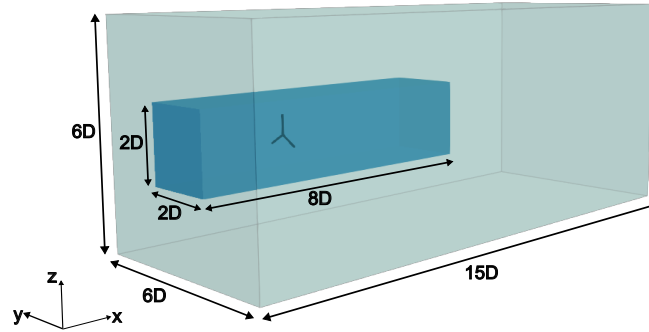


Figure 1. Numerical domain of the simulation with uniform laminar inflow.

sensitivity analyses, demonstrating that a resolution of $R/20$ accurately predicts both rotor loads and wake dynamics under fixed-bottom and floating operating conditions. These results support the adoption of this resolution throughout the present study. Outside the refined region, the grid is progressively coarsened, with cell sizes stretched toward the domain boundaries. A uniform laminar inflow velocity is prescribed at the inlet using a Dirichlet boundary condition, while atmospheric pressure is imposed at the outlet. Slip boundary conditions are applied on the lateral boundaries of the computational domain.

Simulations with a turbulent ABL inflow are performed on a computational domain of $5112 \times 1704 \times 1704$ m ($18D \times 6D \times 6D$). A refined region extends from the inlet to 3976 m ($14D$) downstream, with a lateral extent of 710×710 m ($2.5D \times 2.5D$), centred on the domain centreline and extending vertically from the bottom boundary (Fig. 2). The turbine is posi-

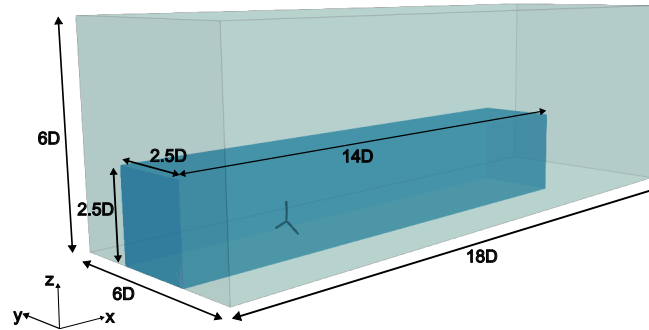


Figure 2. Numerical domain of the simulation with turbulent ABL inflow.

tioned $4D$ downstream of the inlet, within the refined region, where the grid resolution is uniform and equal to $\Delta x = \Delta y = \Delta z = R/20$. This resolution was found to resolve more than 80% of the turbulent kinetic energy, indicating that the energetically relevant turbulent scales are adequately captured. Outside this region, the grid is progressively coarsened, with cell sizes stretched toward the domain boundaries. For this second set of simulations, a conventionally neutral boundary layer (CNBL), generated via a precursor LES, is prescribed at the inlet. Atmospheric pressure is imposed at the outlet, slip con-



ditions are applied at the top boundary, and periodic conditions are used on the lateral boundaries. At the bottom boundary, the boundary conditions available in SOWFA (SOWFA, 2012) were implemented within the present OpenFOAM solver. A Schumann–Grötzbach wall-stress model is employed to prescribe the surface shear stress from the local velocity through a logarithmic rough-wall law using a specified aerodynamic roughness length (Schumann, 1975; Grötzbach, 1987). In addition, the SOWFA `velocityABLWallFunction` is applied to the velocity field to enforce impermeability and extrapolate the resolved tangential velocity gradient to the wall (SOWFA, 2012).

The CNBL was generated in a precursor LES simulation conducted using EllipSys3D, a general purpose multi-block Navier-Stokes solver developed at DTU (Sørensen, 1995; Michelsen, 1992, 1994). The precursor simulation domain size is 10240 m × 10240 m × 3000 m (in streamwise (x), spanwise (y), vertical (z) respectively) with periodic boundary conditions applied on lateral and streamwise faces and a grid resolution of dx = 20 m, dy = 20 m, dz = 5 m. Rayleigh damping is applied above a height of 1000 m (Klemp and Lilly, 1978). The precursor is initialised with the following conditions: temperature profile $dT_0/dz = 288.15$ K until 500 m height, where a temperature difference of 5 K is imposed across the capping inversion, which followed by a linear gradient of $dT_0/dz = 1$ K/km above. Geostrophic wind values $U_G = 7.96$ m s⁻¹ and $V_G = -0.79$ m s⁻¹ are used at the top boundary following Allaerts and Meyers (2015). Conditions constant throughout the precursor are the Coriolis parameter $f_c = 1.1947 \times 10^{-4}$ s⁻¹; wall roughness $z_0 = 0.01$ m; wall temperature $T_{wall} = 288.15$ K; geostrophic wind magnitude $\sqrt{U_G^2 + V_G^2} = 8.0$ m s⁻¹. A wind direction controller is also active, which alters the geostrophic wind components in order to obtain a fully aligned flow (0°) at the turbine hub height of 170 m. The precursor is spun up over of flow time of 20 hrs, over which the boundary layer and turbulence develops. Then, another 5100 s of flow time is run, over which the three velocity components are extracted over a yz-plane spanning the entire domain in vertical and lateral extent.

This data is then used as the inflow to the successor simulation containing the turbine. Figure 3 shows the time and horizontally averaged profiles of the CNBL over the 5400 s used as inflow to the successor simulations. The generated inflow is characterized by a freestream hub height mean wind speed of approximately $U_\infty = 7.5$ m s⁻¹, corresponding to below rated operating conditions, and a turbulence intensity (TI) of 7.3%.

2.3 Global Proper Orthogonal Decomposition

Proper orthogonal decomposition is a standard technique for analysing turbulent flows, in which the flow is decomposed into orthogonal spatial modes that optimally capture variance. The velocity field, $\mathbf{V}(y, z, t)$, is expressed as the sum of a mean component, $\bar{\mathbf{V}}(y, z)$, and a fluctuating component, $\mathbf{V}'(y, z, t)$. POD is applied to the fluctuating velocity components, arranging time snapshots as columns of a data matrix $M = [\mathbf{V}'_1, \dots, \mathbf{V}'_{N_t}]$. The auto-covariance of M is then computed and the associated eigenvalue problem is solved, yielding a diagonal matrix of real, positive eigenvalues Λ and a set of orthonormal eigenvectors $G = [g_1, \dots, g_{N_t-1}]$. The resulting spatial modes are ranked by decreasing energy content and form an orthogonal basis for the flow. For each mode, the temporal coefficient $\phi_j(t)$ is obtained by projecting the flow onto the mode using the standard inner product. Subsequently, as shown in Eq. 3, the spatial modes multiplied by their contribution over time can be summed to

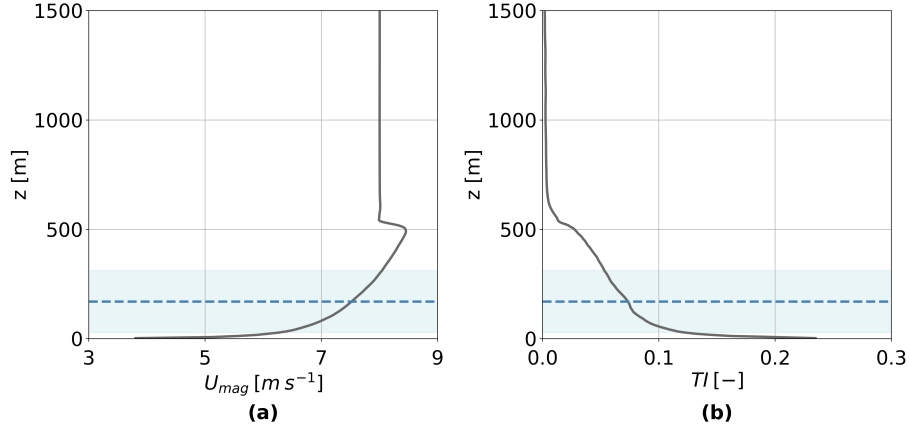


Figure 3. Averaged vertical profiles of the CNBL precursor inflow: (a) velocity magnitude; (b) turbulence intensity (TI), computed using the local mean velocity. The light blue shaded area indicates the turbine rotor extent.

reconstruct the flow including a number of modes $K \leq N_{t-1}$.

$$\mathbf{V}'(y, z, t) \approx \sum_{j=0}^K g_j(y, z) \phi_j(t) \quad (3)$$

While POD is typically applied to individual flow cases, in this work a global POD approach is adopted to enable consistent comparison across different platform motion conditions. As detailed in Andersen and Murcia Leon (2022), rather than constructing a separate modal basis for each dataset, a single global basis is obtained by including q different datasets and adding N_t snapshots from each flow dataset to the matrix M before applying POD (Eq. 4).

$$M = [\mathbf{V}'_{1,1}, \dots, \mathbf{V}'_{1,N_t}, \dots, \mathbf{V}'_{q,1}, \dots, \mathbf{V}'_{q,N_t}] \quad (4)$$

Although the final global basis is suboptimal for any individual dataset, it provides a more consistent representation across the entire ensemble (Céspedes Moreno et al., 2025). In the present study, each dataset corresponds to a transverse plane in the turbine wake. For each simulated condition (fixed-bottom, surge, and pitch), 10 planes are sampled downstream of the rotor, from $x = 1D$ to $x = 10D$, with a spacing of $1D$, where D is the rotor diameter. The global POD basis is constructed using all sampled planes from all simulated cases. Details of the resulting basis are provided in Section 4.3.1. Once the global spatial modes are obtained, the temporal coefficient of each mode for each dataset (i.e., each plane) is computed and analysed to identify the main differences in wake dynamics under varying platform motion conditions.



3 Uniform inflow fixed-bottom simulations

Before performing the wake analysis of the turbine under floating conditions, simulations were first carried out for a fixed-bottom configuration under uniform laminar inflow to verify the accuracy of the predicted blade loads. This preliminary assessment is motivated by the fact that the adopted actuator line model is not coupled with an aero-servo-elastic solver (Hodgson et al., 2021), and therefore cannot account for dynamic aeroelastic response and blade deformations, which are non-negligible for turbines of this scale. The verification was carried out for a fixed-bottom configuration under a uniform inflow velocity of 8 m s^{-1} , comparable to the hub-height wind speed of the CNBL used in the simulations of Section 4. The turbine thus operates in below-rated conditions with a rotational speed of 4.92 rpm and a pitch angle of -0.98° . Rotor performance is compared against steady-state results obtained from the HAWC2 solver (Larsen and Hansen, 2007), available in the repository Zahle et al. (2024b), with gravity and tilt effects neglected. Although coupling the ALM with an aero-servo-elastic solver represents a natural extension of the modelling approach, a different and readily implementable strategy is adopted in this work, applicable to any ALM framework lacking aeroelastic coupling. To account for the altered blade load distribution induced by blade deformation and torsion, a correction to the design twist angle is proposed and applied. The correction is applied to a straight blade representation so as to account for the effects of non-straight geometry arising from both design and operating conditions (e.g. prebend, deflection, and torsion). Figure 4 compares the radial distribution of normal and tangential forces obtained with the aeroelastic solver HAWC2 and the ALM assuming perfectly straight blades (i.e. ALM no correction). As expected, discrepancies, particularly in the normal force, increase toward the blade tip, where prebend, deflection, and torsion effects are more pronounced.

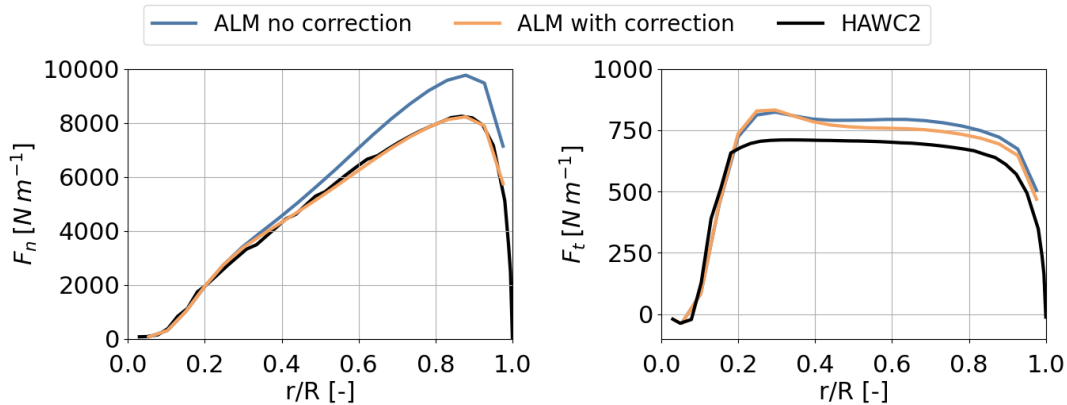


Figure 4. Radial distribution of normal and tangential force. Comparison between HAWC2 aeroelastic results, ALM straight lines without twist correction and ALM with twist correction.

To mitigate these differences, a correction to the twist angle is applied starting from the radial location where deviations become significant ($r/R = 20.6\%$). To capture the increasing discrepancy toward the tip while retaining simplicity, a linear correction profile is adopted, with its magnitude tuned to minimize differences with the HAWC2 load predictions.

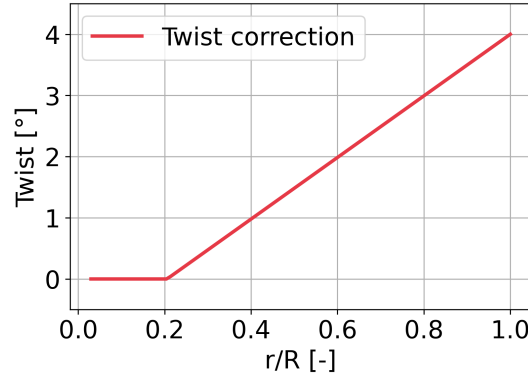


Figure 5. Radial correction applied to the original ALM twist angle.

The applied twist correction is shown in Fig. 5, while the resulting load distributions are reported in Fig. 4 (i.e. ALM with correction). The normal force is satisfactorily corrected, whereas the tangential force appears less sensitive to the adjustment.
 205 The remaining, nearly uniform offset is likely attributable to inherent characteristics of the ALM formulation rather than aeroelastic effects. Finally, Table 1 provides a quantitative comparison of mean thrust and torque between the two models, along with the relative error of the corrected ALM with respect to HAWC2.

Table 1. Thrust and torque comparison between corrected ALM and HAWC2.

	Thrust [MN]	Torque [MNm]
HAWC2	2.024	19.179
ALM	2.026	21.154
% err	+0.10	+10.29

As expected, the corrected ALM accurately predicts the thrust (error of 0.1%), while overestimating the torque by approximately 10% relative to HAWC2. Since the primary objective of this work is the analysis of the wake, it is worth noting that
 210 wake development is predominantly governed by the streamwise momentum deficit, which is directly linked to the thrust coefficient C_T . Consequently, the excellent agreement in thrust is deemed sufficient to ensure an accurate prediction of the wake, despite the observed discrepancy in torque.

To verify the adequacy of the mesh resolution for load estimation, the same twist angle correction was applied in a simulation performed on a uniformly refined grid with $\Delta x = \Delta y = \Delta z = R/32$. A detailed comparison of the two mesh resolutions,
 215 including overall thrust, torque, and span wise load distributions, is presented in Appendix A. Compared with the baseline $R/20$ simulation, the refined mesh yielded a relative difference of 0.59% in the predicted thrust, with consistently small



differences observed for all other load quantities. These results indicate that the $R/20$ mesh provides sufficient accuracy for load prediction.

Since the wake analysis will be carried out under floating conditions involving surge and pitch motions, the inflow velocity experienced by the rotor is not constant and varies around the reference value considered in the fixed-bottom calibration. These variations induce changes in the aerodynamic loading and, consequently, in the effective torsional and deformation state of the blades. As a result, the radial twist correction derived under steady conditions may not remain strictly optimal across all operating states. To assess the robustness of the proposed correction, additional fixed-bottom simulations have been performed for reduced and increased inflow velocities, selected to envelope the range of effective velocities experienced by the rotor during the majority of the surge and pitch motion cases considered in this study. In particular, simulations have been carried out for inflow velocities of 6 m s^{-1} and 10 m s^{-1} . The comparison of thrust with respect to HAWC2 is reported in Table 2. The results indicate that the thrust prediction remains reasonably consistent with HAWC2 across this velocity range, with errors within approximately -6% and +8%. On this basis, the ALM formulation combined with the applied twist correction appears to provide a reasonably consistent representation of the thrust over the investigated operating conditions. This suggests that the approach can be considered a suitable basis for the analysis of wake behaviour under floating conditions, although some residual uncertainty remains due to the absence of a fully aeroelastic coupling in the model.

Table 2. Thrust comparison between corrected ALM and HAWC2 for reduced and increased inflow velocity.

	Thrust [MN]	
	$U_0 = 6 [\text{m s}^{-1}]$	$U_0 = 10 [\text{m s}^{-1}]$
HAWC2	1.164	2.621
ALM	1.097	2.835
% err	-5.74	+8.16

4 CNBL inflow floating simulations

The second, and primary, set of simulations is performed under CNBL inflow conditions and comprises a comprehensive dataset covering multiple surge and pitch motions over a range of frequencies and amplitudes. This dataset is used to investigate wake behaviour under different platform motion conditions.

As described in Section 2.2, all simulations are performed on a uniform Cartesian grid with a resolution of $\Delta x = \Delta y = \Delta z = \Delta = R/20$. Although Appendix A demonstrated that this mesh resolution provides sufficiently accurate load predictions for fixed-bottom simulations under uniform inflow, an additional mesh resolution assessment was carried out for the present dataset of floating conditions. In Appendix B the baseline $R/\Delta = 20$ mesh is compared with a refined mesh of resolution $R/\Delta = 32$ for a representative surge case. The comparison considers both the aerodynamic loads induced by the platform



motion and the resulting wake characteristics, including the mean wake velocity deficit, the magnitude of wake turbulence fluctuations, wake recovery, and the distribution of the coherent energy associated with the platform motion. The results show that the $R/\Delta = 20$ mesh provides sufficiently accurate predictions of both the aerodynamic loads and the wake development, supporting its use throughout the analyses presented in this section.

245 4.1 Platform motion cases

The simulations set considered in this work includes cases with prescribed sinusoidal surge and pitch motions, as defined by Equations 1 and 2. A range of motion frequencies is investigated in order to capture different wake dynamic behaviours. The platform motion frequencies are characterized through the reduced frequency (or Strouhal number), defined as:

$$f_r = \frac{fD}{U_\infty} \quad (5)$$

250 where f is the platform motion frequency, D is the rotor diameter, and U_∞ is the mean inflow velocity at hub height. Focusing first on the surge cases, Messmer et al. (2024a) showed that, under laminar inflow conditions, surge motions with $f_r < 0.2$ and $f_r \approx 1.0$ do not significantly affect the wake dynamics. In contrast, for $f_r \in [0.2, \sim 0.55]$, the wake exhibits pronounced pulsing structures, whereas for $f_r \in [\sim 0.55, 0.9]$, meandering patterns coupled with mild pulsing emerge. Based on these observations, reduced frequencies of $f_r = 0.2, 0.5$, and 0.8 are selected in the present study for the surge motion cases,
255 as they are representative of the different wake behaviour regimes identified in the literature. To further assess the influence of motion amplitude, two different platform motion amplitudes are considered. As reported by Messmer et al. (2024b), floating wind turbines typically operate within a reduced frequency range of $f_r \in [0, 1.5]$. Within this range, two main categories of platform motion can be identified. High-frequency motions ($f_r > 0.5$) are generally characterized by relatively small amplitudes ($A/D \sim 0.01$) and are typically associated with the linear response of the platform to wave excitation. In contrast,
260 lower frequency oscillations ($f_r < 0.3$) exhibit larger amplitudes ($A/D \sim 0.1$) and are mainly related to mooring lines (Hubert et al., 2025; Messmer et al., 2024b). The first amplitude considered in this work, corresponding to $A = 0.05D$, represents a compromise between realistic operating conditions and the requirement for sufficiently pronounced motion-induced wake signatures to enable a meaningful analysis under turbulent inflow conditions. A second amplitude of $A = 0.1D$, is introduced for methodological purposes to enhance wake response to platform motion. This high amplitude case serves as a benchmark
265 to better isolate and interpret the influence of platform dynamics on the wake, supporting a clearer interpretation of the lower amplitude results, where motion-induced effects may be less pronounced.

To additionally provide a comparison between different types of platform motion, pitch cases are also investigated using the same reduced frequencies considered for the surge configurations. For the pitch cases, the amplitudes are selected to match the same hub-height platform velocity amplitude of the corresponding surge motions, thereby ensuring comparable thrust
270 modulation. This approach allows any observed differences in wake behaviour between surge and pitch cases to be attributed primarily to the nature of the platform motion itself, rather than to differences in loads amplitude. The resulting pitch amplitudes are therefore 4.79° and 9.57° . The larger pitch amplitude is likewise introduced primarily as a methodological configuration



aimed at facilitating the interpretation of wake dynamics in a condition where the influence of platform motion is expected to be more clearly observable.

275 Table 3 reports the complete list of simulated cases together with the corresponding mean values and amplitudes of the thrust force. The mean values show good consistency across the different cases, with deviations from the fixed-bottom case below 1% for most simulations. Larger discrepancies are observed for the surge case at the highest frequency and amplitude ($f_r = 0.8$, $A = 0.1D$), where the deviation reaches 2.3%, and for the pitch case at the highest frequency and amplitude ($f_r = 0.8$, $A = 9.57^\circ$), where the deviation increases to 3.5%.

Table 3. Mean thrust, percentage error relative to the fixed-bottom case, and thrust amplitude for all simulated floating cases.

	Mean thrust [MN]	Mean thrust %err	Ampl. thrust [MN]
fixed	1.761	-	-
surge $f_r = 0.2$ $A = 0.05D$	1.761	0	0.20
surge $f_r = 0.5$ $A = 0.05D$	1.758	-0.17	0.49
surge $f_r = 0.8$ $A = 0.05D$	1.751	-0.57	0.77
surge $f_r = 0.2$ $A = 0.1D$	1.759	-0.11	0.39
surge $f_r = 0.5$ $A = 0.1D$	1.746	-0.85	0.96
surge $f_r = 0.8$ $A = 0.1D$	1.720	-2.33	1.47
pitch $f_r = 0.2$ $A = 4.79^\circ$	1.757	-0.22	0.19
pitch $f_r = 0.5$ $A = 4.79^\circ$	1.754	-0.40	0.48
pitch $f_r = 0.8$ $A = 4.79^\circ$	1.747	-0.80	0.76
pitch $f_r = 0.2$ $A = 9.57^\circ$	1.744	-0.97	0.38
pitch $f_r = 0.5$ $A = 9.57^\circ$	1.732	-1.65	0.94
pitch $f_r = 0.8$ $A = 9.57^\circ$	1.699	-3.5	1.42

280 Regarding the thrust force amplitude, the corresponding surge and pitch cases exhibit comparable amplitude levels. Figure 6 shows the filtered thrust evolution over one platform motion period for the surge and pitch cases at $f_r = 0.5$ and for the two considered amplitudes. It can be observed that each corresponding surge and pitch case exhibits the same thrust modulation. This provides a suitable basis for interpreting differences in wake behaviour as a consequence of the platform motion nature, rather than of differences in force amplitude.

285 4.2 LES wake analysis

The analysis first focused on identifying the potential impact of platform motion on the main wake characteristics, starting from the wake velocity profiles and wake recovery. Figure 7 shows the mean stream-wise velocity profiles, normalized by the mean hub height velocity, along horizontal lines at hub height and at different downstream locations. The first row reports the

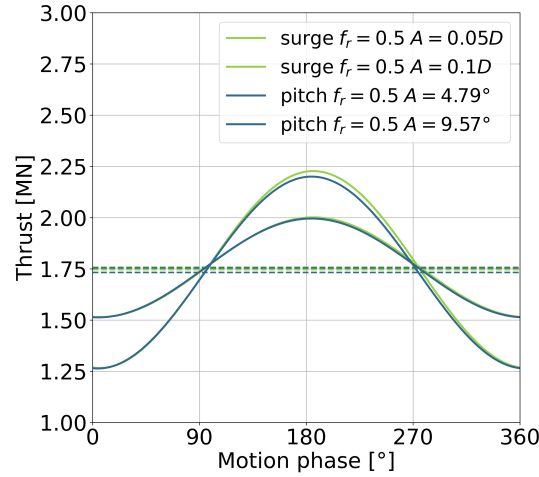


Figure 6. Filtered thrust over one platform motion period for surge and pitch corresponding cases.

results for all simulated surge cases, while the second row presents the pitch cases. Given the non-negligible turbulence level

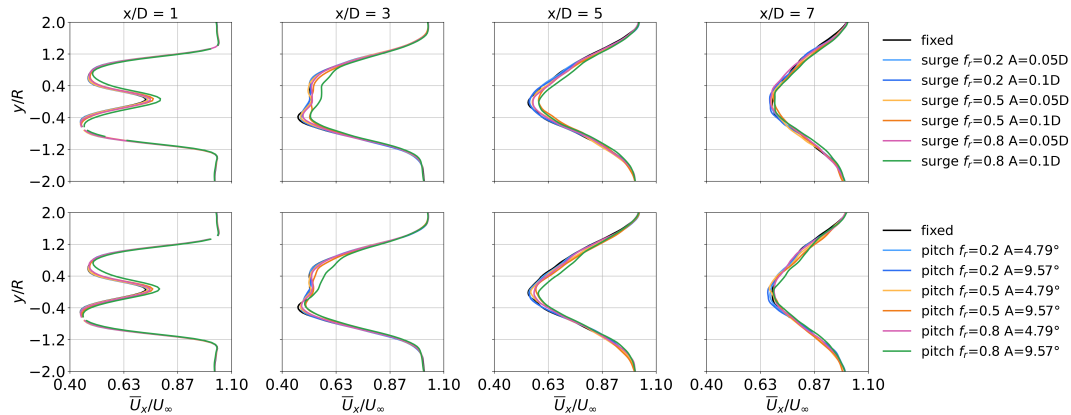


Figure 7. Mean normalized axial velocity over four horizontal lines.

of the inflow, the influence of platform motion on the wake velocity profiles appears to be limited, consistent with the findings of Firpo et al. (2026), Messmer et al. (2025), and Pagamonci et al. (2025). Only a few cases exhibit noticeable differences. In particular, the surge and pitch cases at $f_r = 0.8$ and $A = 0.1D$ and 9.57° show the largest deviations. For these cases, the velocity deficit already appears reduced even at locations very close to the rotor ($1D$). This suggests that the enhanced wake recovery is mainly associated with the lower mean thrust reported in Table 3, rather than with a direct effect of the platform motion itself. No significant differences are observed between the surge and pitch cases. The same analysis is reported in Figure 8 for vertical lines aligned with the hub. The observations discussed above remain valid also in this case. Because of



the different nature of surge and pitch motions, the pitch cases exhibit slightly more asymmetric velocity profiles between the upper and lower portions of the rotor area.

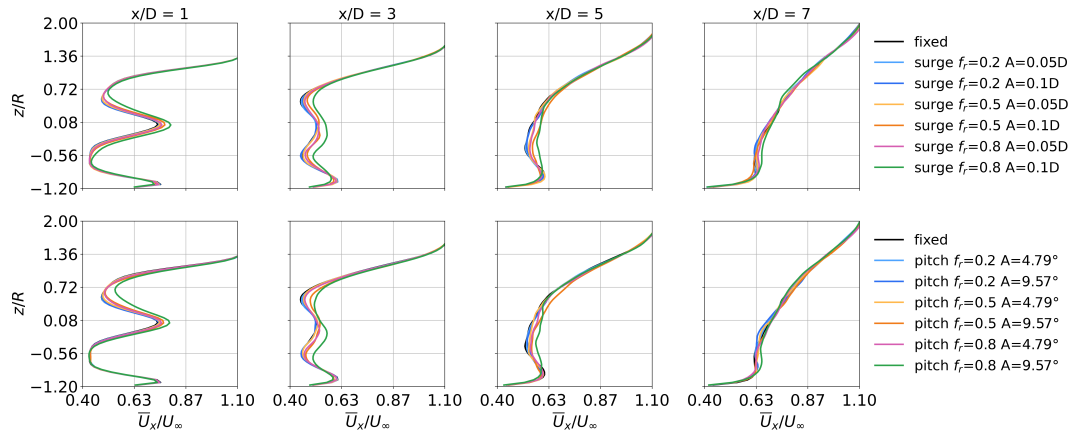


Figure 8. Mean normalized axial velocity over four vertical lines.

To complete the analysis, Figure 9 reports the mean stream-wise velocity averaged over transverse planes spanning the region between $-R$ and $+R$, used here as a global indicator of wake recovery.

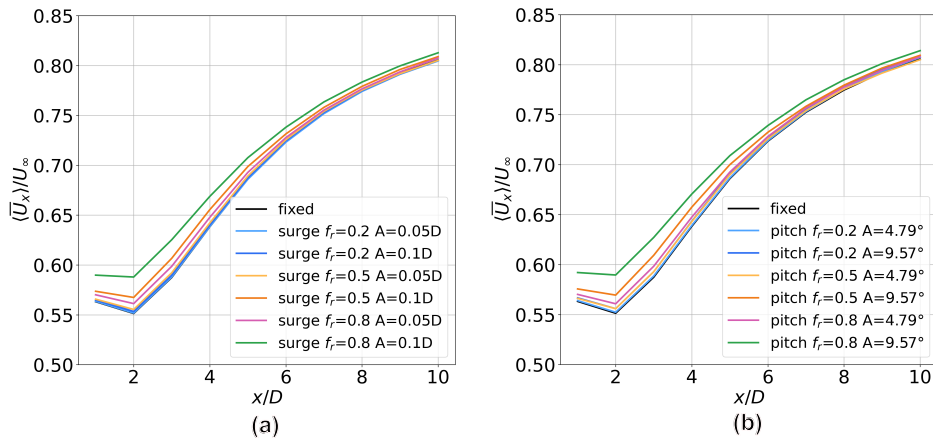


Figure 9. Wake recovery. (a) Surge cases. (b) Pitch cases.

As previously discussed, the surge and pitch cases at $f_r = 0.8$, with amplitudes of $A = 0.1D$ and $A = 9.57^\circ$, respectively, exhibit the strongest wake recovery already at $1D$ downstream. This behaviour is primarily attributable to the lower mean thrust generated under these operating conditions and persists throughout the wake evolution. A similar, although less pronounced, trend is also observed for the remaining cases as platform-motion amplitude and frequency increase. However, given the relatively small differences among the cases, it is difficult to establish a clear contribution of the motion-induced coherent



wake structures to the wake recovery process. Consistent with the previous analyses, no significant differences are observed between the surge and pitch cases.

4.3 Global POD wake analysis

4.3.1 Global POD basis

310 As anticipated in the previous sections, the wake dynamics of the floating cases is investigated through a global POD analysis. The primary objective is to provide a physical interpretation of the wake behaviour by identifying and analysing the dominant energetic structures governing the flow, while establishing a consistent framework for dynamic cross-case comparisons under different platform motions and operating conditions. This work constitutes a preliminary step towards the development of reduced order models for floating wind turbine applications. In particular, the analysis aims to quantify the influence of platform
315 motion on the POD modal decomposition by identifying the modes most affected by the imposed motions and assessing the associated energy. Furthermore, the dependence of the modal energy content on the frequency, amplitude, and type of platform excitation is investigated, providing insights into the mechanisms through which floating dynamics alter wake evolution and coherent flow dynamics.

The global POD basis is constructed by combining all wake planes sampled across the entire set of simulated cases. Specifi-
320 cally, for each case, ten transverse planes, spanning $y \in [-1.37R, 1.37R]$ and $z \in [-1.12R, 1.08R]$, are sampled at stream-wise locations ranging from $x = 1D$ to $x = 10D$ with a spacing of $1D$. Due to a numerical issue related to the velocity sampling at a single point of the plane located at $x = 10D$ in the pitch case with $f_r = 0.8$ and $A = 9.57^\circ$, this plane was excluded from the dataset used to construct the global POD basis and from all subsequent analyses. However, since the plane lies in the far wake region, where the influence of platform motion is significantly reduced, its exclusion does not affect the results nor the
325 conclusions drawn from the subsequent analyses.

Each plane is recorded at a sampling frequency of 1 Hz over a time window of 3600 s. This duration is selected as a compromise between the need for a sufficiently long dataset to ensure a robust POD decomposition and the requirement to include a sufficiently large number of platform-motion cycles to guarantee statistical convergence and stable representation of the wake dynamics.

330 The resulting dataset, comprising 129 wake planes in total, is then used to construct the global POD basis following the procedure described in Section 2.3. The inclusion of all planes from all cases is motivated by the need to obtain a modal basis representative of the complete range of wake dynamics, encompassing both near-wake and far-wake regions as well as the different platform-motion and operating conditions considered. To assess whether the use of the full dataset is strictly necessary and to explore potential reductions in computational cost, an alternative global basis was also generated using only a subset of
335 the available planes. In this approach, one or two planes per case were selected so as to provide a uniform coverage of both the near-wake and far-wake regions. However, the resulting basis was found to be biased towards those cases whose selected planes were located in regions where the influence of platform motion was most pronounced. Consequently, the modal basis failed to provide an equally accurate representation of the wake dynamics across all cases and exhibited reduced reconstruction



capabilities for a significant portion of the dataset. This preliminary assessment highlighted the importance of including all
 340 sampled planes from all cases in the POD formulation, thereby ensuring that the resulting global basis captures the full range
 of coherent structures present in the wake and provides an accurate reconstruction of the complete dataset.

Figure 10 presents the first seven modes of the global POD basis for the three velocity fluctuations components U' , V' ,
 and W' . These global modes represent the most energetic spatial structures contained within the entire dataset and provide a
 compact description of the dominant wake dynamics across all cases considered.

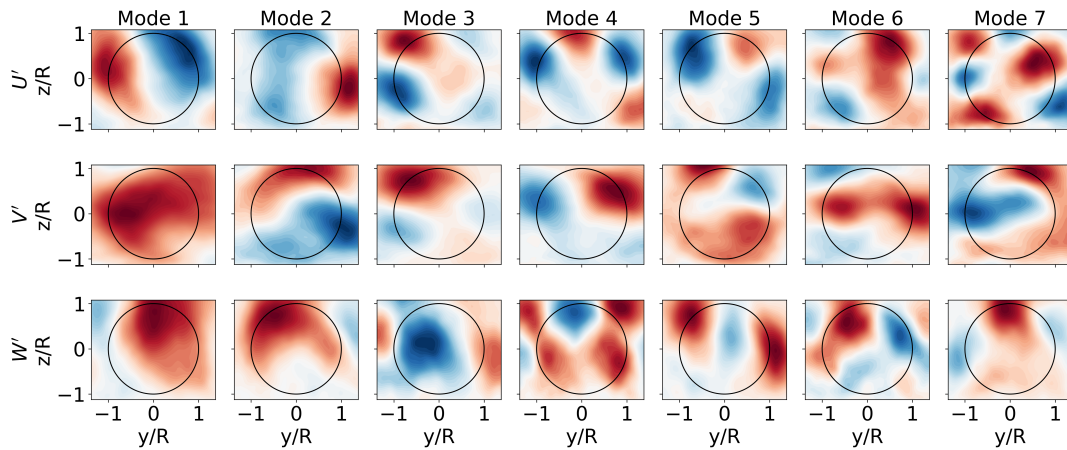


Figure 10. First seven modes of the global POD basis for the three velocity fluctuations components, U' , V' , and W' .

345 Using Eq. 3, the velocity field on any sampled wake plane can be reconstructed. To assess the ability of the proposed basis
 to accurately represent and reconstruct the wake dynamics of the individual cases, Fig. 11 compares the power spectral density
 (PSD) of the streamwise velocity component at a wake location aligned with the turbine hub and positioned at $x = 4D$. Three
 representative cases are considered: the fixed-bottom configuration, a surge case with $f_r = 0.5$ and $A = 0.1D$, and a pitch
 case with $f_r = 0.5$ and $A = 9.57^\circ$. For each case, the PSD is computed from the original LES velocity field (LES) and from
 350 velocity fields reconstructed using the first 50 POD modes (POD 50 modes) and the first 200 POD modes (POD 200 modes).
 As expected, increasing the number of retained modes progressively improves the reconstruction accuracy, enabling a more
 faithful representation of the flow structures. This is reflected in the increasingly close agreement between the reconstructed
 and original spectra. In particular, for both the surge and pitch cases, the reconstruction obtained with 200 modes successfully
 captures the spectral peak associated with the reduced frequency of the platform motion, demonstrating that the global POD
 355 basis retains the key dynamical features introduced by the platform excitation. Overall, the PSD comparison confirms that the
 global POD basis provides an accurate representation of the wake dynamics and is capable of reconstructing the dominant flow
 features across the cases considered in this study.

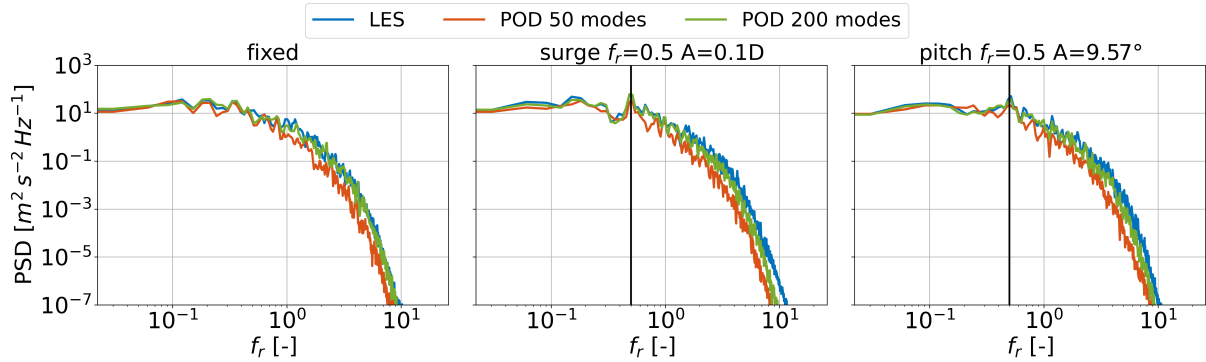


Figure 11. PSD of the streamwise velocity component at hub height and $x=4D$ for the fixed-bottom, surge ($f_r = 0.5$ and $A = 0.1D$), and pitch ($f_r = 0.5$ and $A = 9.57^\circ$) cases. Comparison between the original LES field and POD reconstructions obtained using 50 and 200 global modes.

4.3.2 Analysis of modal energy

Projection of the flow data onto the global POD basis yields the temporal coefficients $\phi_j(t)$ associated with each mode at every sampling plane. These coefficients characterize the temporal evolution of the modal contribution and can be analysed to quantify both the energy content and the spectral characteristics of each mode across the wake. By combining modal energy and spectral analyses, it is possible to identify the modes most affected by platform motion and to characterize the stream-wise evolution of platform-induced perturbations, thereby providing a spatial description of their impact on the wake dynamics.

The first analysis focuses on estimating the energy content of each POD mode at each wake plane. Figure 12 reports, for the first 25 modes, the variance of the temporal coefficient associated with mode j , normalized by the total modal energy of the global system, defined as the sum of the squared singular values λ_j . This quantity can therefore be interpreted as the relative energy contribution of mode j at a given plane with respect to the total energy contained in the modal decomposition, similar to the analysis by Andersen and Murcia Leon (2023). Comparing this quantity between the floating and fixed-bottom configurations allows the identification of the modes most affected by platform motion and the assessment of how their energy content evolves throughout the wake. Figure 12 presents the modal energy distributions at three representative wake locations ($x = 1D$, $x = 4D$, and $x = 9D$). The first row compares the surge cases with identical motion amplitude ($A = 0.1D$) and varying reduced frequency against the fixed-bottom reference, while the second row reports the corresponding comparison for the pitch cases ($A = 9.57^\circ$). Overall, the case with $f_r = 0.2$ exhibits a modal energy distribution closely matching that of the fixed-bottom configuration, suggesting a negligible influence of low frequency platform motion on wake dynamics. For the surge cases, at $x = 1D$ several modes (particularly modes 1, 2, 4, and 7) exhibit enhanced energy content for $f_r = 0.8$. Further downstream, at $x = 4D$, the largest differences are associated with modes 1 and 7, which are more energetic for $f_r = 0.5$. Notably, the fixed case has more energy in mode 3 than the high frequency case. At $x = 9D$, the differences between cases become significantly weaker, indicating a progressive attenuation of platform-motion effects with downstream distance.

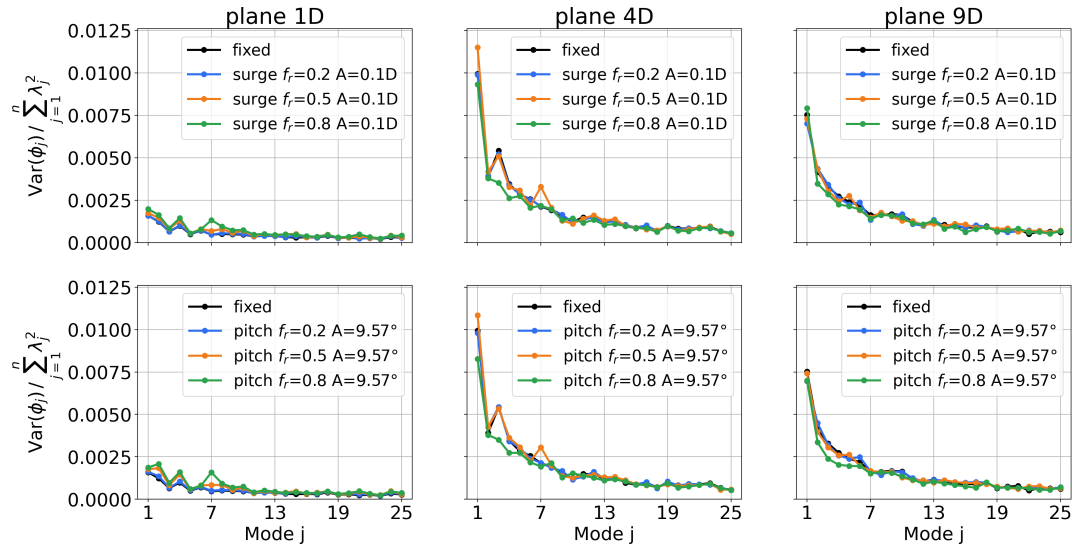


Figure 12. Relative energy contribution of the first 25 POD modes at selected wake locations ($x = 1D$, $x = 4D$, and $x = 9D$). Comparison between the fixed-bottom configuration and the surge and pitch cases at the largest motion amplitude.

The pitch cases exhibit trends consistent with those observed for surge. This preliminary analysis highlights that platform motion selectively excites specific modes, with the degree of activation depending on both the motion frequency and the wake location. For clarity, Figure 12 only reports the cases with the highest motion amplitudes, where the effects are most evident. The corresponding results for the lower amplitude cases are provided in Appendix C and display the same qualitative behaviour, although with reduced intensity.

To provide a more comprehensive view of the modes influenced by platform motion and their spatial distribution within the wake, Figure 13 presents a heat map of the difference in modal energy between each surge case and the fixed-bottom reference. This representation allows direct identification of the wake regions where the surge motion increases the energy content of specific modes. Results for all surge cases, including both amplitudes and all three reduced frequencies, are summarized to provide an overall picture of the influence of platform motion parameters. For $f_r = 0.2$, differences relative to the fixed-bottom case remain negligible for both amplitudes, confirming the limited impact of low frequency surge motion on wake dynamics. At $f_r = 0.5$ and $A = 0.1D$, a more pronounced increase in modal energy is observed throughout the wake region extending approximately from $x = 1D$ to $x = 6D$. In particular, modes 1 and 7 exhibit strong amplification, with maximum differences concentrated around $x = 3D$ and $x = 5D$. A similar spatial distribution, although with lower intensity, is observed for the corresponding lower-amplitude case ($A = 0.05D$). This provides a first indication that the motion amplitude primarily affects the magnitude of the response while preserving its overall spatial structure. For $f_r = 0.8$, the effect of surge motion becomes more localized within the near wake. The largest modal energy increases occur between $x = 1D$ and $x = 3D$, with modes 1 and 7 showing strong activation at $x = 1D$ and $x = 2D$, followed by a rapid downstream decay. The same behaviour is observed for the lower amplitude case, albeit with reduced intensity. These results provide initial evidence that different platform motion

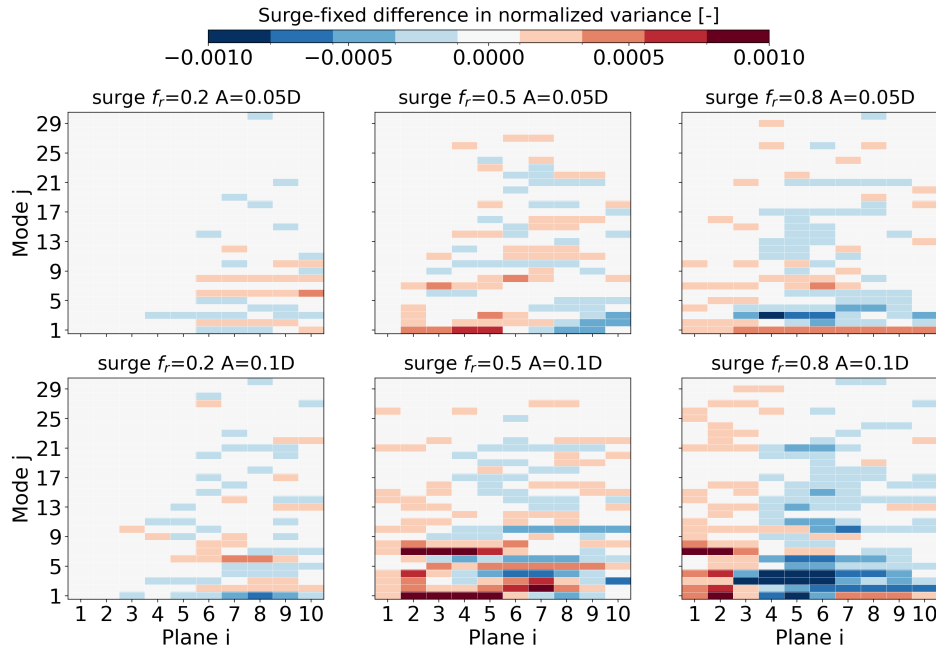


Figure 13. Difference in relative energy contribution between the surge cases and the fixed-bottom reference. Results are shown for the first 30 POD modes across all wake planes.

frequencies affect different regions of the wake. In particular, $f_r = 0.5$ appears to exert a stronger influence within the mid wake region ($x \approx 4D$), whereas $f_r = 0.8$ primarily affects the near wake ($x \approx 2D$). The following analyses will quantify these observations more rigorously.

In general, platform motion predominantly affects the lowest order modes, while its influence progressively decreases with increasing mode number. Figure 14 reports the corresponding analysis for the pitch cases. Overall, the same trends observed for surge are recovered, with the same modes exhibiting the largest energy increase. The main difference is found at $x = 1D$, where pitch motion activates a larger number of modes and with greater intensity. This behaviour is consistent with the expectation that the strongest differences associated with the specific type of platform motion occur immediately downstream of the rotor.

The previous analysis identified modes 1 and 7 as the most strongly affected by platform motion for both $f_r = 0.5$ and $f_r = 0.8$. To further investigate their dynamics, Figure 15 presents the PSD of their temporal coefficients at three wake locations ($x = 2D$, $x = 4D$, and $x = 9D$). Results are shown for the fixed-bottom configuration together with the surge cases at $A = 0.1D$. Before discussing the effects of platform motion, it is useful to examine the spectral content of the fixed-bottom case. Mode 1 exhibits a clear low frequency peak around $f_r \approx 0.24$. Although relatively weak at $x = 2D$, this contribution becomes more pronounced further downstream and remains clearly visible at both $x = 4D$ and $x = 9D$. Considering both the frequency range and the spatial structure of mode 1 shown in Fig. 10, this peak can reasonably be associated with wake meandering, whose characteristic frequencies are reported within a similar range in the literature ((Andersen et al., 2013; Yang and Sotiropoulos,

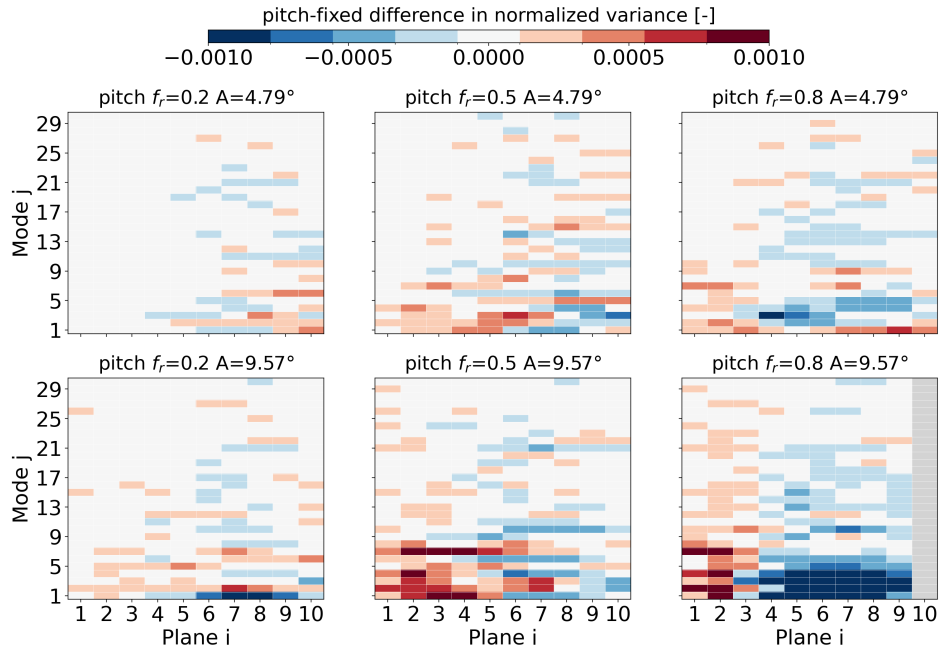


Figure 14. Difference in relative energy contribution between the pitch cases and the fixed-bottom reference. Results are shown for the first 30 POD modes across all wake planes.

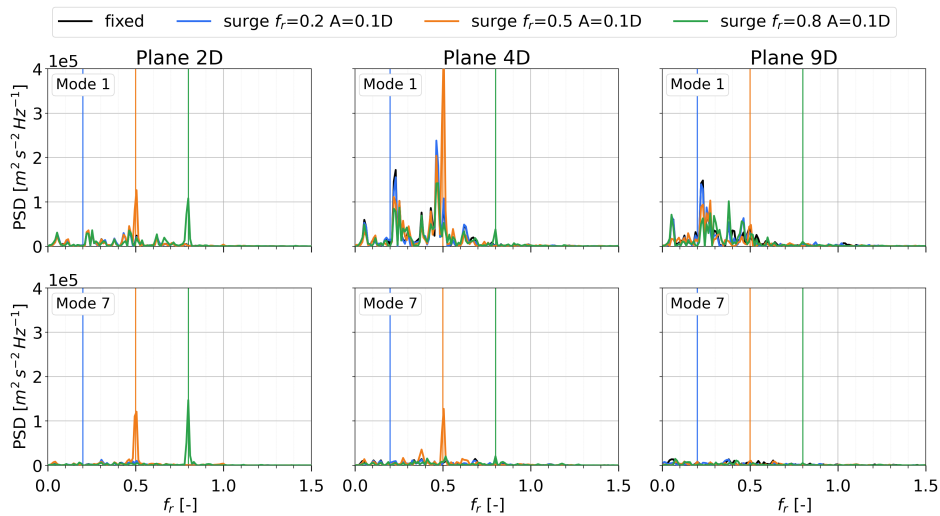


Figure 15. PSD of temporal coefficients of modes 1 and 7 at selected wake locations ($x = 2D$, $x = 4D$, and $x = 9D$). Comparison between the fixed-bottom configuration and the surge cases at the largest motion amplitude. The vertical lines indicate the forcing frequencies.



2019; Messmer et al., 2024b; Li et al., 2022)). At $x = 4D$, a second peak corresponding to the second harmonic of the dominant wake-meandering frequency is also evident, together with several minor contributions in the surrounding frequency range.

For the surge cases, the spectra corresponding to $f_r = 0.2$ remain nearly indistinguishable from the fixed-bottom reference for both modes 1 and 7 at all wake locations. No distinct spectral peak emerges at the forcing frequency, further supporting the conclusion that low frequency platform motion has a negligible influence on wake dynamics.

For $f_r = 0.5$, a clear peak appears at the platform-motion frequency. For mode 1, this contribution is already visible at $x = 2D$, reaches its maximum intensity at $x = 4D$, and substantially decreases by $x = 9D$. This indicates that the platform motion introduces a coherent contribution that is sufficiently energetic to be clearly distinguished in the modal spectrum. At $x = 4D$, the platform-induced peak is located near the second harmonic of the wake meandering frequency and within the frequency range where several minor contributions are present. This suggests that, for $f_r = 0.5$, nonlinear interactions between the platform-induced forcing and the intrinsic wake dynamics may enhance the spectral signature associated with the platform motion. For Mode 7, the platform induced contribution appears as a distinct and isolated peak, maintaining a comparable energy level between $x = 2D$ and $x = 4D$ before becoming negligible at $x = 9D$. This behaviour demonstrates that different modes respond differently to the same platform forcing and exhibit distinct downstream evolutions.

For $f_r = 0.8$, the platform-forcing frequency is well separated from the frequency range associated with wake meandering, enabling a clearer identification of the platform-induced contribution. For both Modes 1 and 7, the energy associated with the forcing frequency is maximum at $x = 2D$ and rapidly decreases downstream, becoming only weakly visible at $x = 4D$. These spectral results therefore confirm the different wake dynamics associated with different surge frequencies, with $f_r = 0.5$ producing a more spatially extended response and $f_r = 0.8$ generating a stronger but more localized near-wake effect.

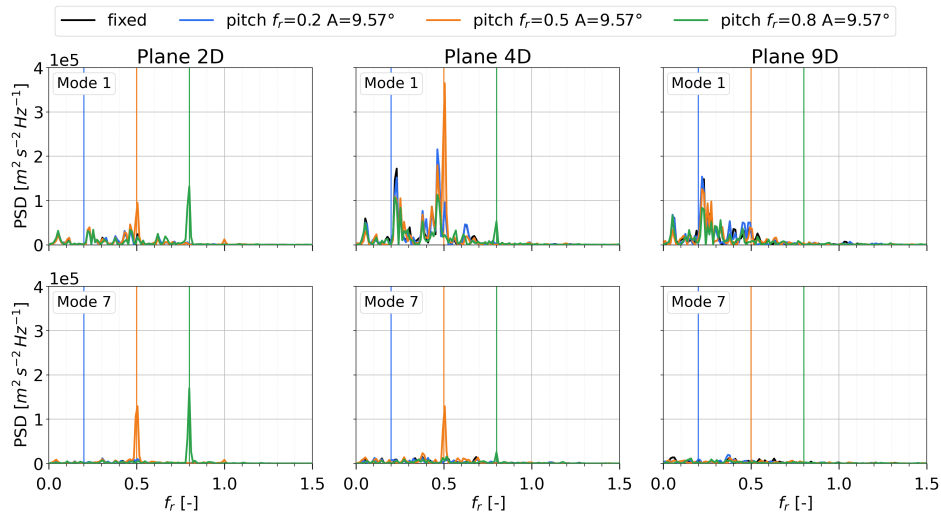


Figure 16. PSD of temporal coefficients of modes 1 and 7 at selected wake locations ($x = 2D$, $x = 4D$, and $x = 9D$). Comparison between the fixed-bottom configuration and the pitch cases at the largest motion amplitude. The vertical lines indicate the forcing frequencies.



Figure 16 reports the corresponding analysis for the pitch cases at $A = 9.57^\circ$. Overall, the same qualitative behaviour is observed, with only minor differences in the relative magnitude of the dominant peaks. For brevity, the equivalent figures for the lower amplitude cases are reported in the Appendix C. As expected, the same trends are recovered, although with reduced spectral amplitudes.

4.3.3 Analysis of modal energy coherent with platform motion

The previous analysis showed that several POD modes exhibit a clear and distinguishable energetic contribution at the platform motion frequency. The objective of this section is therefore to quantify the modal energy that can be directly attributed to the imposed platform motion. To this end, the power spectral density of each modal coefficient, $S_{\phi_j}(f)$, is computed for every mode and wake plane and used to evaluate the energy associated with the platform-induced response. Specifically, the energy contribution of mode j related to the platform motion is estimated by integrating the spectrum over a narrow frequency band centered on the imposed platform frequency, f_{plt} . This quantity is denoted the coherent energy estimate:

$$E_j^{coh} = \int_{f_{plt}-\Delta f}^{f_{plt}+\Delta f} S_{\phi_j}(f) df \quad (6)$$

where Δf is selected according to the spectral resolution, ensuring that the full energy content of the spectral peak at the platform motion frequency is included. Beyond the modal interpretation of the wake dynamics, this analysis provides a quantitative measure of the POD energy directly induced by the platform motion. By evaluating this quantity across operating conditions characterized by different platform amplitudes and frequencies, the aim is to investigate whether systematic relationships exist between the forcing parameters and the resulting coherent modal energy. Such information could potentially support the development of reduced order models for floating wind turbine wakes.

Figure 17 presents the coherent energy estimate, E_j^{coh} , for the first ten modes at each downstream location for all the surge cases considered. The first row reports the cases with surge amplitude $A = 0.05D$ as the excitation frequency increases, whereas the second row shows the corresponding cases with $A = 0.1D$. To assess the capability of the proposed methodology to isolate the energetic contribution exclusively associated with platform motion, the E_j^{coh} calculation is also applied to the fixed-bottom case using the same three excitation frequencies considered for the platform motions. Since no platform motion is present in the fixed-bottom configuration, negligible values of E_j^{coh} are expected. Any non-zero coherent energy identified in this case would suggest that the estimation procedure captures additional contributions that cannot be directly attributed to platform motion. Therefore, the fixed-bottom results provide a useful baseline for the interpretation of the coherent energy levels obtained in the floating cases.

For the cases with $f_r = 0.2$ (both $A = 0.05D$ and $A = 0.1D$), the coherent energy remains very limited and is essentially independent of motion amplitude, and is fully comparable to the fixed-bottom reference. This confirms the negligible influence of this excitation frequency on the wake dynamics, as also confirmed by Messmer et al. (2024a).

In contrast, the cases with $f_r = 0.5$ exhibit clearly identifiable coherent energy levels with characteristic spatial trends. Different modes, associated with distinct spatial structures, display markedly different downstream evolutions of coherent

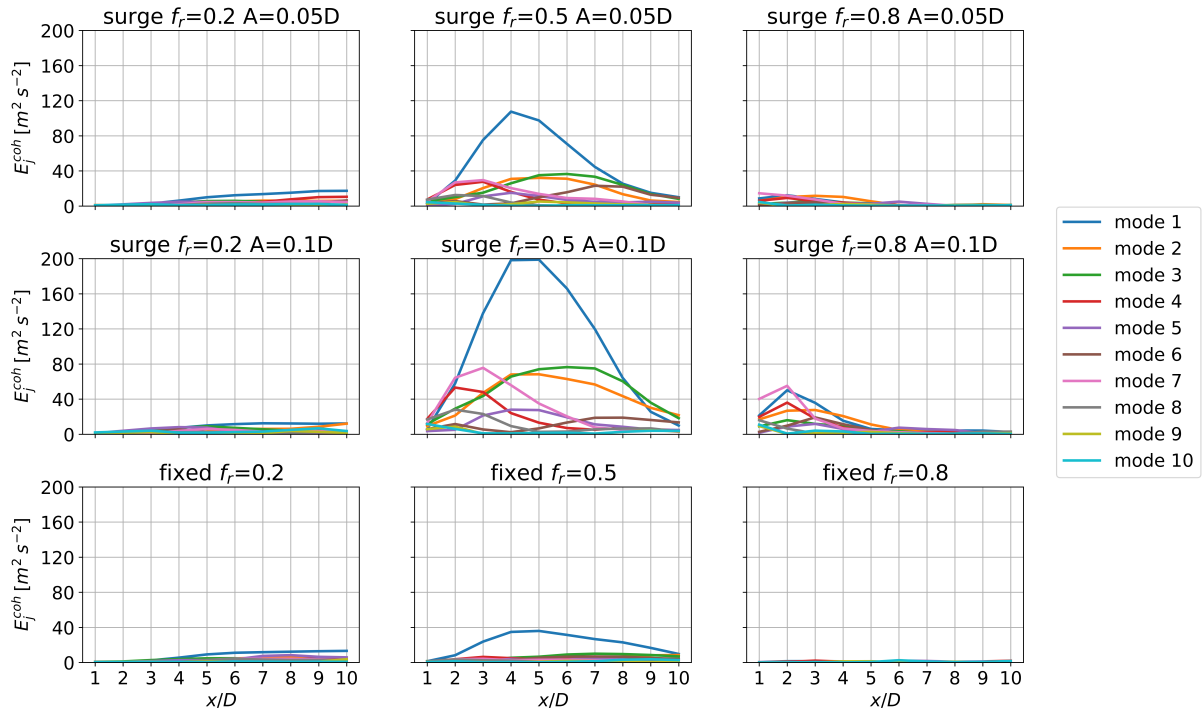


Figure 17. Platform-motion coherent energy of the first 10 modes for all surge cases. The same approach is also applied to the fixed-bottom case as baseline case.

energy. Increasing the surge amplitude leads to higher energy levels across the modes, while the overall spatial distribution remains unchanged, indicating that the wake dynamics is preserved despite the increase in forcing amplitude. For these $f_r = 0.5$ cases, it is particularly informative to examine the fixed-bottom reference. As shown in Figure 17, mode 1 is the only mode exhibiting a non-negligible coherent energy level. This behaviour can be attributed to the small spectral peaks located around the second harmonic of the wake meandering frequency identified in Figure 15. Because the platform excitation frequency ($f_r = 0.5$) falls within a frequency range where these secondary contributions are present, they are not entirely filtered out by the coherent energy estimation procedure. As a result, mode 1 exhibits a non-zero value of E_j^{coh} even in the absence of platform motion. This observation indicates that the coherent energy estimated for the surge cases also contains a contribution from these secondary spectral components. However, the fixed-bottom reference case provides a reasonable estimate of their magnitude. Even after conceptually removing this contribution from the surge cases, mode 1 would still remain the dominant energetic mode, with a clear maximum located approximately between $x = 4D$ and $x = 5D$. The cases with $f_r = 0.8$ exhibit a substantially different wake response. In this case, the coherent energy is concentrated in the near-wake region close to the rotor for all modes considered. As observed for $f_r = 0.5$, the overall spatial distribution remains similar when the surge amplitude increases, while the fixed-bottom case again yields negligible coherent energy values, further supporting the validity of the methodology. Overall, these results indicate that, for a given platform motion, different modes exhibit distinct downstream



480 evolutions of the energy associated with the platform excitation. The amount of transferred energy depends strongly on the motion amplitude, whereas the spatial dynamics remain largely unaffected. The same analysis is reported in Appendix D for the pitch cases, where comparable trends are observed and the same conclusions apply. Taken together, these results show that changing the excitation frequency while keeping the motion amplitude fixed leads to significantly different wake responses in terms of coherent energy content. Conversely, varying the motion amplitude at a fixed frequency has only an effect on the
485 intensity of the coherent energy.

4.3.4 Analysis of velocity field energy coherent with platform motion

The final analysis aims to isolate the effect of platform motion, previously identified through the POD modal analysis, on the reconstructed wake flow field. This investigation is useful for determining the number of modes effectively required to reconstruct the platform-induced contribution and for understanding how the coherent energy is spatially distributed on each
490 plane. For brevity, only the surge and pitch cases at $f_r = 0.5$ and $f_r = 0.8$ are presented, as these conditions exhibited the most pronounced impact of platform motion. The first step of the reconstruction procedure consists of identifying the POD modes that are effectively required to recover the coherent energy associated with the platform-motion frequency. To isolate the dominant modes to this energetic content, the following procedure is applied:

1. For each wake plane, the total coherent energy E^{coh} is computed by summing the contribution of all POD modes.
- 495 2. The modes are ranked in descending order according to their coherent energy contribution.
3. For each plane, only the first $N_{modes,90\%}$ modes are retained, corresponding to the minimum number of modes required to recover 90% of the total coherent energy.

As a result, the reconstructed velocity field contains the minimum set of modes necessary to adequately represent the platform-induced coherent contribution within the wake. It is worth emphasizing that the selected modes are not ordered according to their position within the global POD basis but according to their coherent energy content; consequently, the retained
500 modes are not necessarily consecutive.

Figure 18 reports the number of modes $N_{modes,90\%}$ required to recover 90% of the coherent energy for all surge cases (Fig. 18(a)) and pitch cases (Fig. 18(b)), considering both oscillation amplitudes and reduced frequencies. Focusing first on the surge cases, the number of modes required to reconstruct the phenomenon is lower in the wake regions where coherent
505 structures were previously shown to be strongest. At $f_r = 0.5$, the coherent energy persists farther downstream; consequently, the number of modes required to recover 90% of the coherent energy remains relatively small throughout the wake, reaching a minimum of approximately 10-20 modes around $x = 4D - 5D$, where most of the energy is concentrated within the leading modes. Conversely, at $f_r = 0.8$, coherent structures are more localized near the rotor, resulting in a minimum of approximately 30-35 modes around $x = 2D - 3D$. As the wake progressively loses coherence, an increasing number of modes becomes
510 necessary to reconstruct the decreasing coherent energy contribution. Interestingly, a similar behaviour is observed for cases characterized by the same reduced frequency but different oscillation amplitudes, further confirming the existence of analogous

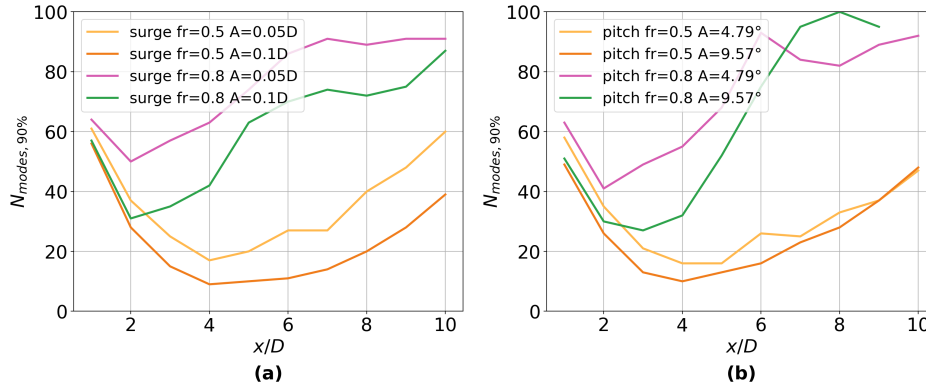


Figure 18. Number of modes required to recover 90% of the coherent energy. (a) surge cases. (b) pitch cases.

wake dynamics. Similar observations also apply to the pitch cases. Overall, these results are fully consistent with the previous modal-energy analysis and highlight that, even in the presence of well defined coherent structures, more than 10-15 modes are generally required to adequately describe the platform-induced dynamics, confirming the intrinsically complex nature of the wake and the involvement of multiple spatial structures.

One of the main advantages of POD is its ability to reduce the dimensionality of the problem while facilitating the interpretation of the dominant flow dynamics. The coherent energy associated with the platform motion can be quantified for each POD mode at each wake plane. However, the modal decomposition does not directly reveal how the coherent energy is distributed within the wake planes. This information can only be recovered by reconstructing the velocity field through the superposition of the POD modes. The reconstructed field therefore enables the spatial distribution of the coherent energy to be analysed.

The objective of this analysis remains the quantification of the wake energy directly attributable to platform motion. For this purpose, the velocity fluctuation field was reconstructed using only the modes identified in Fig. 18, thereby obtaining a flow field primarily containing the platform-induced contribution. For each wake plane, the fluctuating velocity components U' , V' , and W' are reconstructed in both space (y, z) and time. To estimate the energy content directly correlated with platform motion, the same procedure described in Eq. 6 is applied to each velocity component at every spatial location. Accordingly, for a generic point (y, z), the coherent energy associated with the stream-wise velocity fluctuation U' is computed through:

$$E_{U'_{yz}}^{coh} = \int_{f_{plt}-\Delta f}^{f_{plt}+\Delta f} S_{U'_{yz}}(f) df \quad (7)$$

The coherent energy integrated over the entire plane is then obtained as:

$$E_{U'}^{coh} = \frac{1}{A_{plane}} \iint_{\Omega} E_{U'_{yz}}^{coh} dy dz \quad (8)$$



530 Where A_{plane} is the area of the planes. The same procedure is applied to the transverse and vertical velocity components. The total coherent energy associated with a given wake plane is therefore defined as:

$$E^{coh} = E_{U'}^{coh} + E_{V'}^{coh} + E_{W'}^{coh} \quad (9)$$

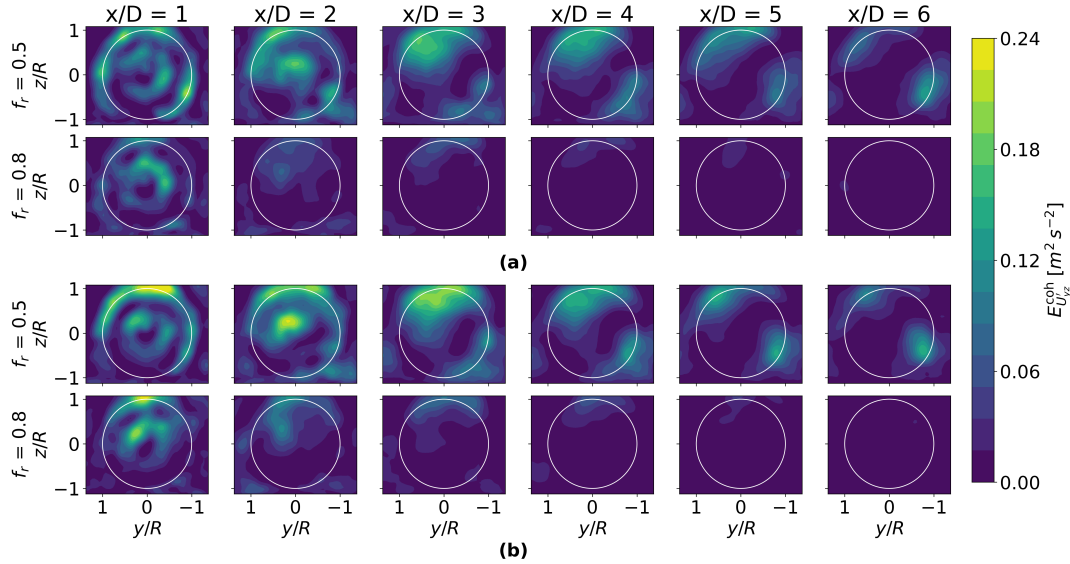


Figure 19. Platform-motion coherent energy of the stream-wise velocity fluctuations, evaluated on the first six wake planes. **(a)** Surge cases with $A = 0.1D$ at $f_r = 0.5$ and $f_r = 0.8$. **(b)** Pitch cases with $A = 9.57^\circ$ at $f_r = 0.5$ and $f_r = 0.8$.

Figure 19 presents the coherent energy distribution of the stream-wise velocity component U' for the first six wake planes downstream of the rotor for the surge (Fig. 19(a)) and pitch (Fig. 19(b)) cases at $f_r = 0.5$ and $f_r = 0.8$, considering the largest
 535 oscillation amplitude. For both motion types, a region of elevated coherent energy is initially observed near the blades tips at the $x = 1D$ plane. Further downstream, this energetic region progressively evolves and becomes concentrated in the upper portion of the rotor wake. The energy distribution is asymmetric on the vertical plane owing to the influence of the ABL and the lower boundary of the numerical domain. Differences between the two reduced frequencies are clearly visible. The $f_r = 0.5$ cases exhibit coherent energy distributions extending farther downstream, with detectable signatures still present at $x = 6D$.
 540 In contrast, the $f_r = 0.8$ cases display a stronger influence in the near wake ($x = 1D - 2D$) followed by a more rapid decay. Comparing surge and pitch motions, noticeable differences emerge within the first three wake planes, where pitch generates a stronger contribution in the upper part of the rotor wake, consistent with the larger displacement experienced by the upper rotor region during pitching motion.

The same analysis is reported in Fig. 20 for the transverse velocity component V' . For both motion types, the coherent
 545 energy is organized into two horizontally distributed lobes, representing the wake pulsation pattern. These structures are again more visible in the upper wake region due to the effects of the ABL and the lower domain boundary. Similar to the stream-wise component, the $f_r = 0.5$ cases exhibit coherent energy extending farther downstream, with a maximum around $x = 4D - 5D$,

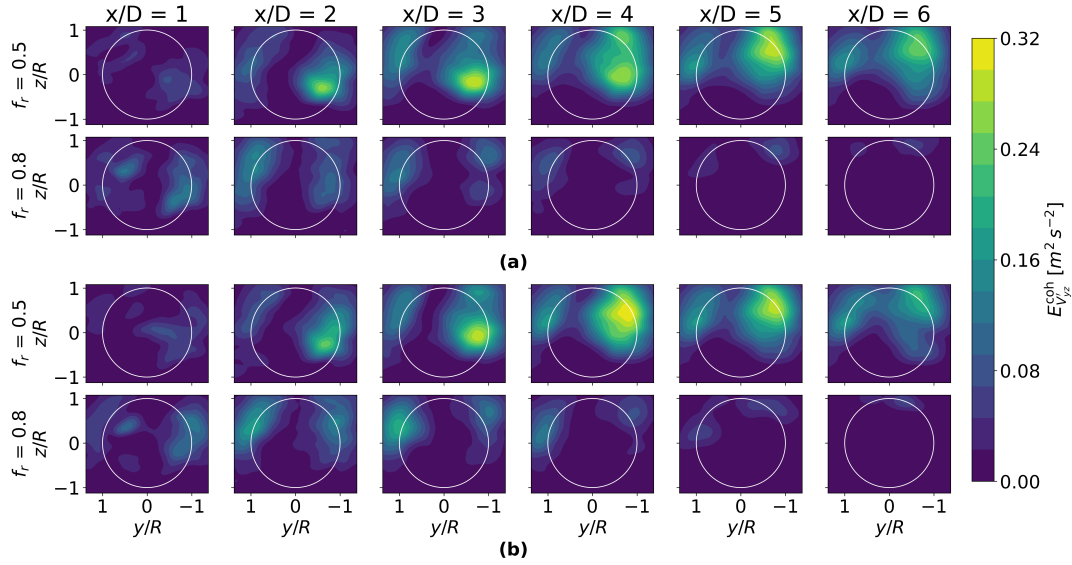


Figure 20. Platform-motion coherent energy of the transverse velocity fluctuations, evaluated on the first six wake planes. **(a)** Surge cases with $A = 0.1D$ at $f_r = 0.5$ and $f_r = 0.8$. **(b)** Pitch cases with $A = 9.57^\circ$ at $f_r = 0.5$ and $f_r = 0.8$.

whereas the $f_r = 0.8$ cases show a more localized peak around $x = 2D$. No significant differences between surge and pitch are observed for this velocity component.

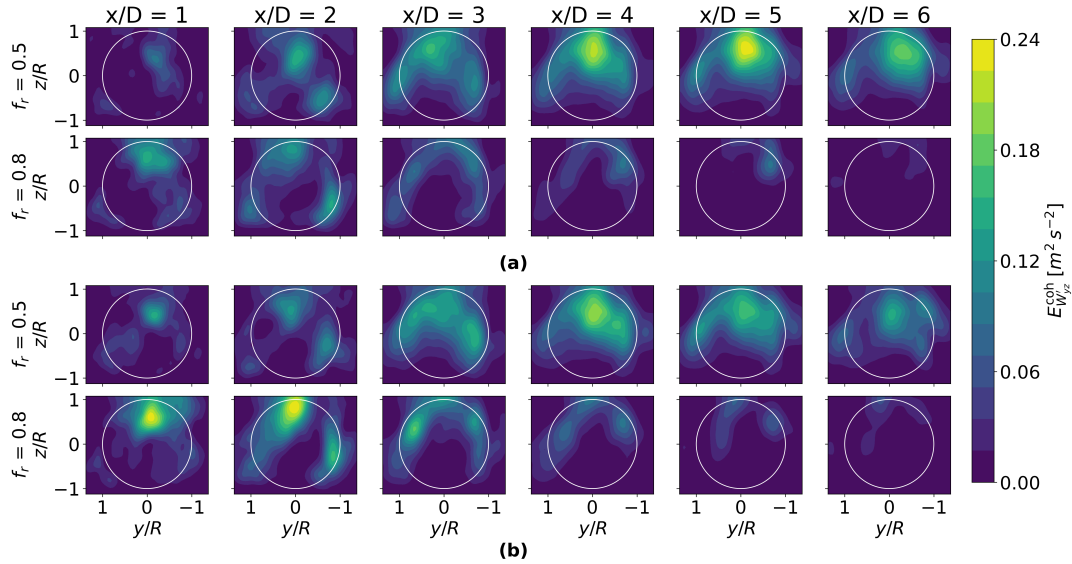


Figure 21. Platform-motion coherent energy of the vertical velocity fluctuations, evaluated on the first six wake planes. **(a)** Surge cases with $A = 0.1D$ at $f_r = 0.5$ and $f_r = 0.8$. **(b)** Pitch cases with $A = 9.57^\circ$ at $f_r = 0.5$ and $f_r = 0.8$.



550 Finally, Fig. 21 presents the coherent energy distribution associated with the vertical velocity component W' . In this case, the coherent energy is concentrated within a single lobe located in the upper part of the rotor wake, while the lower portion is significantly attenuated by the ABL and the lower boundary effects. As observed for the transverse component, the $f_r = 0.5$ cases exhibit a downstream energy maximum around $x = 4D - 5D$, whereas the $f_r = 0.8$ cases reach their maximum around $x = 2D$ and decay more rapidly afterward. Consistent with the nature of the imposed platform motion, pitching tends to amplify the coherent energy in the upper wake region, particularly for $x \leq 3D$ and especially for the $f_r = 0.8$ condition.

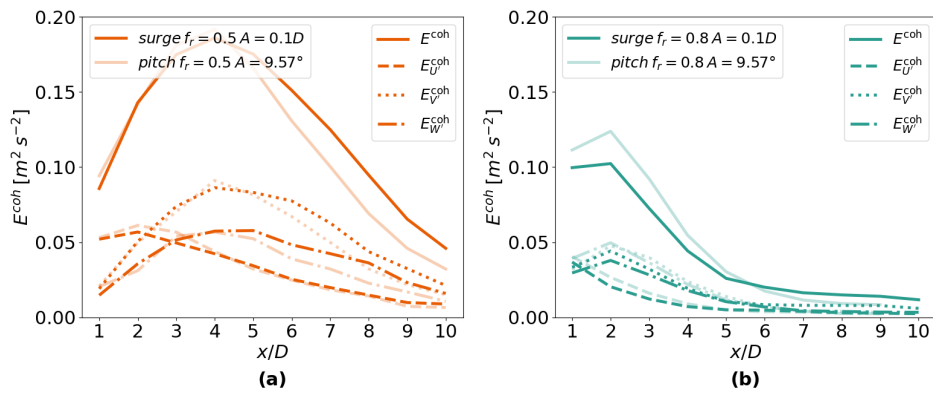


Figure 22. Plane-integrated coherent energy associated with platform motion for the three velocity fluctuation components and the total field. (a) Surge and pitch cases at $f_r = 0.5$. (b) Surge and pitch cases at $f_r = 0.8$.

To summarize the coherent energy evolution of the three velocity components along the wake and to facilitate a direct comparison between surge and pitch motions, Fig. 22 reports the integrated coherent energy for each velocity component as well as the total coherent energy. Results for $f_r = 0.5$ are shown in Fig. 22(a), while those for $f_r = 0.8$ are reported in Fig. 22(b), both considering the largest oscillation amplitude. Consistent with the modal energy analysis, the $f_r = 0.5$ cases display a coherent energy distribution that extends farther downstream, with maxima occurring around $x = 4D - 5D$, particularly for the transverse and vertical velocity components. As discussed previously, this extended downstream persistence, most evident in the transverse and vertical velocity components, is likely to the proximity of the platform-motion frequency to the second harmonic of the wake-meandering frequency, suggesting a combined effect between the platform-induced forcing and the intrinsic wake dynamics. Within the near wake, where differences between surge and pitch would be expected to be most pronounced, only limited discrepancies are observed, apart from a modest increase in the stream-wise coherent energy for the pitch cases, consistent with the observations of Fig. 19. For $f_r = 0.8$, the platform-induced effect remains predominantly confined to the near wake. Under these conditions, pitching motion systematically amplifies the coherent contribution across all velocity components, resulting in a larger total coherent energy compared with surge motion. For completeness, the corresponding results for the lower-amplitude cases are reported in Appendix E. Nevertheless, the same trends and conclusions remain valid, further confirming the similarity of the wake dynamics. Overall, the analysis of the reconstructed velocity field confirms the wake behaviour previously identified through the POD modal-energy analysis while providing additional insight into the spatial dis-



tribution of the platform-induced coherent energy and its influence on the different velocity components. These results enrich and complement the overall characterization of the wake dynamics under floating platform motion.

5 Discussion

575 The present work provides insights that may support the development of analytical and engineering wake models for floating offshore wind turbines. The present LES analysis indicates that, under the investigated sinusoidal surge and pitch motions, platform motion has a limited influence on the time-averaged wake. With the exception of the cases characterized by the largest motion amplitudes and frequencies, the mean thrust remained close to that of the fixed-bottom reference case, and no clear modification of the overall wake recovery rate was identified. This suggests that, under operating conditions comparable to
580 those investigated in this work, steady-state engineering wake models originally developed for fixed-bottom turbines may also remain applicable to floating turbines when the quantity of interest is limited to the time-averaged velocity deficit. However, the global POD analysis revealed clear coherent contributions at the excitation frequency, whose energy and downstream evolution depended strongly on the reduced frequency and on the motion amplitude. Consequently, steady-state engineering models are inherently unable to reproduce these motion-induced unsteady wake features. This limitation may become relevant
585 when the unsteady inflow experienced by downstream turbines and the resulting dynamic or fatigue loads are of interest. These findings also have implications for dynamic engineering wake models. While several analytical wake models have recently been proposed for floating wind turbines (Wang et al., 2022; Zhang et al., 2024; Huanqiang et al., 2024; Wenfeng et al., 2025), most remain based on simplified descriptions of the platform-induced wake dynamics. The POD analysis shows how the coherent wake response varies with platform-motion frequency and amplitude. This information could support the
590 development, calibration, and validation of future dynamic engineering wake models for floating wind turbines, which are still at an early stage of development.

The results are also relevant for Dynamic Wake Meandering (DWM) models. In their conventional formulation, DWM models generally represent the wake as a passive tracer with meandering governed by large atmospheric turbulent structures. The present analysis demonstrates that platform motion generates an additional coherent contribution to the wake dynamics. The
595 spectral analysis further suggests that this contribution may interact with the intrinsic wake dynamics under certain operating conditions. Although the underlying mechanisms remain to be fully understood, these observations indicate that platform-induced dynamics may need to be considered when extending DWM formulations to floating wind turbines.

In addition to its implications for wake modelling, the proposed global POD framework offers a robust methodology for analysing and comparing wake dynamics across different operating conditions. Unlike conventional POD analyses, where
600 each case is decomposed independently, all cases are projected onto the same modal basis. This enables direct quantitative comparisons of modal energy, reconstruction efficiency, and wake complexity across different platform motions, amplitudes, frequencies, and downstream locations. In this sense, the global POD provides a consistent framework for comparing spatio-temporal wake dynamics, whereas previous POD studies have generally relied on qualitative comparisons between modes obtained from separate decompositions.



605 The current study also highlights the importance of constructing the global modal basis from a sufficiently diverse dataset. A preliminary basis generated using only a subset of the available wake planes showed that, although reducing the number of planes lowers the computational cost of the decomposition, it may also biases the basis towards the wake structures that are most strongly represented in the selected data. As a result, the reconstruction accuracy decreases for operating conditions that are less well represented. Including all sampled wake planes from all cases therefore produces a more balanced modal basis
610 that captures the complete range of coherent wake dynamics and enables meaningful quantitative comparisons across different operating conditions.

The global POD analysis also provides useful insights for the development of reduced-order models (ROMs) of floating wind turbine wakes. In regions where the platform-induced wake structures remain well organized and spatially coherent, fewer POD modes are required to reconstruct the coherent response. As these structures progressively lose coherence downstream, additional modes are needed to recover the same fraction of coherent energy. This indicates that coherent platform-induced wake
615 dynamics admit a compact low-dimensional representation. However, the wake response cannot be regarded as an extremely low-order process. More than 10-15 modes are generally required to recover 90% of the coherent energy, indicating that several interacting spatial structures contribute to the wake dynamics. Nevertheless, the concentration of coherent energy within a relatively limited number of modes suggests that the dominant platform-induced response can be represented in a reduced-
620 dimensional space. These observations provide a promising basis for future ROM development. Rather than resolving the full turbulent flow field, future models could exploit the common global POD basis and predict only the temporal evolution of the dominant modal coefficients as a function of the platform motion similar to the prediction of PS-ROM Andersen and Murcia Leon (2022). Such an approach could bridge the gap between high-fidelity LES and engineering wake models, providing computationally efficient predictions of the coherent wake dynamics.

625 **6 Limitations and future works**

The conclusions of this study should be interpreted within the range of operating conditions investigated. The analysis considered isolated sinusoidal surge and pitch motions under a conventionally neutral atmospheric boundary layer. Although surge and pitch produced qualitatively similar trends in the coherent wake dynamics, this behaviour cannot be assumed to hold for other platform degrees of freedom or for coupled six-degree-of-freedom motions representative of realistic floating off-
630 shore wind turbines. In particular, irregular wave-induced platform motions exhibit a broader spectral content than the periodic excitations considered here. Such motions may lead to more complex wake dynamics reducing the coherence of the platform-induced wake structures identified in this work. Extending the present analysis to realistic sea states therefore represents an important direction for future research.

A second limitation concerns the absence of a fully coupled aero-servo-elastic solver. Aeroelastic blade deformations were
635 not considered, although they may play a relevant role for large, flexible turbines such as the IEA 22 MW reference turbine. While the twist correction adopted in this work improves the agreement with the fixed-bottom aeroelastic reference solution, it does not account for the changes in blade deformation induced by platform motion. Although this simplification is not expected



to alter the main conclusions of the present wake analysis, future work including a fully coupled aeroelastic model would allow its influence on the wake dynamics to be quantified.

640 Finally, the present simulations do not include an active turbine controller. The rotor speed was prescribed and therefore did not respond to the variations in apparent wind velocity induced by platform motion. In a real floating wind turbine, generator torque and blade-pitch control may therefore influence both the aerodynamic loading and the resulting wake dynamics. Future work including fully coupled aero-servo-elastic simulations would be valuable to quantify the influence of turbine control on platform-induced wake dynamics.

645 7 Conclusions

This work investigated the wake dynamics of a floating offshore wind turbine operating under realistic atmospheric boundary layer inflow conditions using large-eddy simulations coupled with an actuator line model. A global POD framework was employed to identify and compare the coherent wake response generated by different platform motion conditions.

The results demonstrate that the reduced frequency is the primary parameter governing the platform-induced wake dynam-
650 ics. While the time-averaged wake remains largely unaffected by platform motion under the investigated operating conditions, the coherent wake response exhibits distinct behaviours. Cases with a reduced frequency of $f_r = 0.2$ promote a negligible contribution in the wake dynamics. Cases with a reduced frequency of $f_r = 0.5$ are characterised by a platform-induced contribution that lies within a frequency range influenced by wake-meandering dynamics and generate coherent structures that persist farther downstream, with their strongest influence occurring approximately between 4D and 5D downstream of the ro-
655 tor. In contrast, cases with $f_r = 0.8$ produce a more localized response, mainly confined until 2D downstream the rotor. These conclusions are consistently supported by all analyses performed, including the modal-energy distribution, the coherent modal energy analysis, and the POD wake reconstruction.

Platform-motion amplitude mainly affects the intensity of the coherent response, whereas the reduced frequency determines its spatial evolution. Surge and pitch motions produce similar overall trends, although pitch generates higher coherent energy
660 in the upper part of the wake within the first downstream planes.

Beyond these physical findings, this work demonstrates that a common global POD basis provides a robust framework for analysing and comparing wake dynamics across a wide range of operating conditions. The proposed methodology enables consistent quantitative comparisons between different working conditions and provides a reduced-dimensional representation of the dominant coherent wake dynamics. These characteristics make it a promising foundation for future reduced-order
665 modelling of floating wind turbine wakes. Future work should extend the analysis to realistic six-degree-of-freedom platform motions and fully coupled aero-servo-elastic simulations, while further investigating the interaction between platform-induced coherent structures and other wake phenomena, such as wake meandering and energy transfer across different frequency ranges.



Code availability. The ALM code has been developed in-house and, although it is implemented on an open-source platform, the modeling developments presented in this paper are not publicly available as open source.

670 *Data availability.* Numerical data used in this study are available from the corresponding author upon request.

Appendix A: Mesh resolution assessment for load prediction in fixed-bottom simulations under uniform inflow

This appendix compares the aerodynamic loads obtained using two mesh resolutions to assess the sensitivity of both the load prediction and the twist-angle correction to the mesh resolution. Two uniformly refined Cartesian grids are considered: the baseline mesh adopted throughout this study, with $\Delta x = \Delta y = \Delta z = \Delta = R/20$, and a finer mesh with $\Delta x = \Delta y = \Delta z =$
 675 $\Delta = R/32$.

Table A1 compares the predicted thrust and torque for the two mesh resolutions. The relative differences are computed using the $R/\Delta = 20$ simulation as the reference solution.

Table A1. Comparison of thrust and torque for the $R/\Delta = 20$ and $R/\Delta = 32$ mesh resolutions.

	Thrust [MN]	Torque [MNm]
$R/\Delta = 20$	2.026	21.154
$R/\Delta = 32$	2.014	20.829
% err	-0.59	-1.53

The differences between the two mesh resolutions remain limited, with relative deviations of 0.59% for thrust and 1.53% for torque. Since thrust is the primary load governing wake development, the small discrepancy observed confirms that the
 680 baseline mesh resolution of $R/\Delta = 20$ provides sufficient accuracy for the objectives of this study.

To further evaluate the influence of mesh resolution on the span wise load distribution, Fig. A1 compares the corrected normal and tangential forces predicted by the ALM on the $R/\Delta = 20$ and $R/\Delta = 32$ meshes against the corresponding HAWC2 predictions. Overall, the span wise load distributions exhibit good agreement across the two mesh resolutions, confirming that mesh refinement has only a limited impact on the predicted aerodynamic loads once the twist-angle correction is applied.

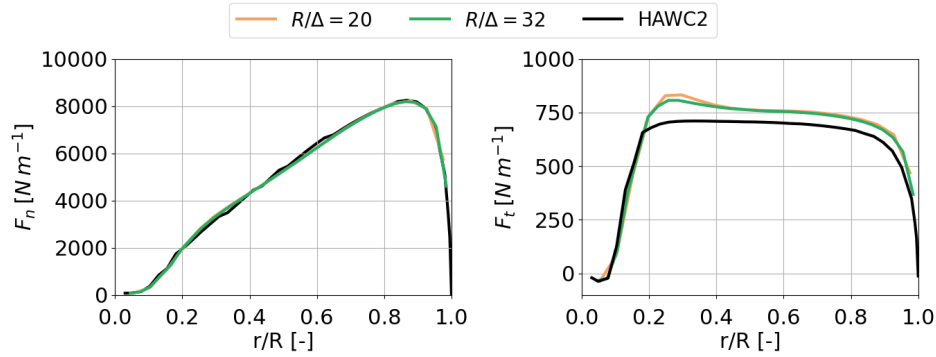


Figure A1. Radial distribution of normal and tangential force. Comparison between HAWC2 aeroelastic results, corrected ALM on $R/\Delta = 20$ mesh and corrected ALM on $R/\Delta = 32$ mesh.

685 Appendix B: Mesh resolution assessment for load prediction and wake dynamics in surge case under CNBL

This section investigates the effect of mesh resolution on the prediction of rotor loads and wake characteristics under platform motion. Among the simulated cases, a single surge condition is selected as a representative test case. Specifically, the surge case with $f_r = 0.5$ and $A = 0.1D$ is simulated using two different meshes: the baseline mesh adopted throughout this study, with $\Delta x = \Delta y = \Delta z = \Delta = R/20$, and a finer mesh with $\Delta x = \Delta y = \Delta z = \Delta = R/32$.

690 The first comparison focuses on the prediction of the global rotor loads in order to assess whether the baseline mesh remains adequate also under floating operating conditions. Figure B1 shows the filtered thrust and torque signals obtained with the two mesh resolutions over one complete surge cycle. An excellent agreement is observed between the two simulations, indicating that mesh resolution has only a minor influence on the prediction of the global loads. This result is consistent with the conclusions previously obtained for the fixed-bottom laminar cases.

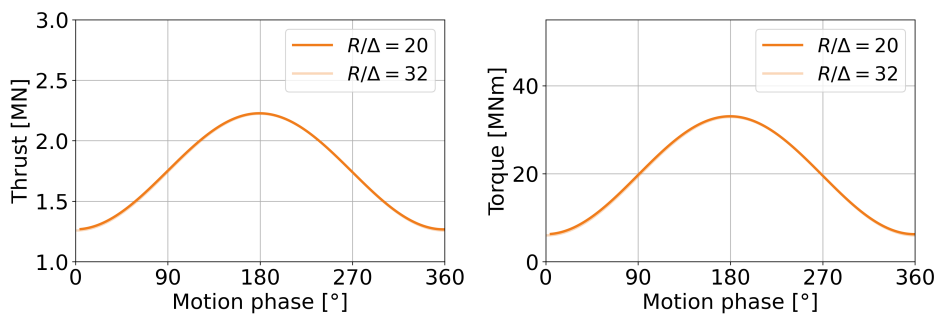


Figure B1. Filtered thrust and torque over one platform-motion period for the surge case computed on the $R/\Delta = 20$ and $R/\Delta = 32$ meshes.



695 The influence of mesh resolution on the wake is then assessed by comparing the velocity fields obtained with the two meshes. Figure B2 presents horizontal profiles at hub height for several downstream locations. The first row reports the mean stream wise velocity normalized by the mean hub-height inflow velocity, while the second row shows the wake turbulent fluctuations intensity, quantified as the standard deviation of the stochastic stream wise velocity fluctuations.

Following Messmer et al. (2025), the stream wise velocity is decomposed as

$$700 \quad U = \bar{U} + U' = \bar{U} + \tilde{U} + U'' \quad (\text{B1})$$

where $\bar{U}$ is the time-averaged velocity, U' denotes the total velocity fluctuations, $\tilde{U}$ represents the deterministic component induced by the periodic platform motion, and U'' is the stochastic turbulent contribution. The deterministic component $\tilde{U}$ is obtained by phase-averaging the velocity over successive surge cycles. As shown in Fig. B2, the mean velocity profiles obtained with the two meshes are in excellent agreement. The only noticeable differences appear in the profiles of the turbulent fluctuation intensity at $x = 1D$, in correspondence with the hub and tip vortices, where the finer mesh provides a better resolution of the vortex structures. Nevertheless, these discrepancies remain confined to $x = 1D$, while the overall wake development is reproduced consistently by both simulations. This indicates that the baseline mesh with $R/\Delta = 20$ is sufficient to accurately capture the wake evolution.

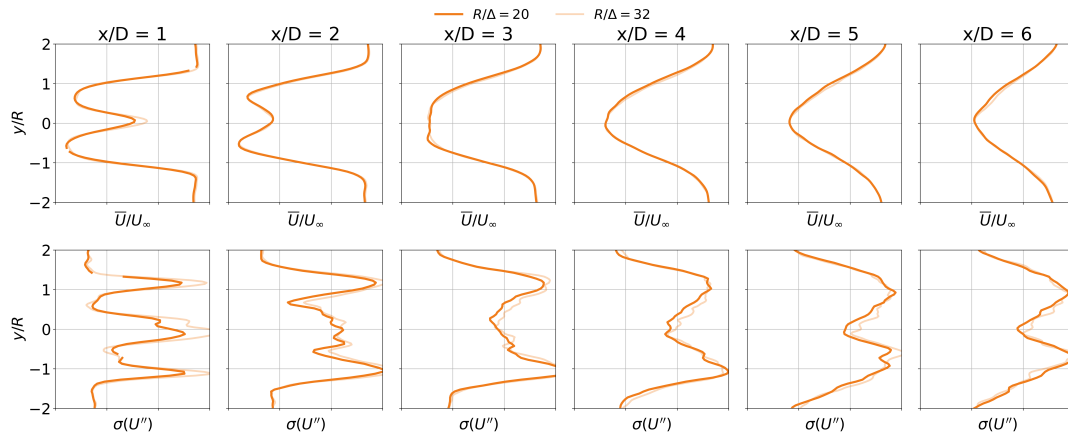


Figure B2. Mean stream wise velocity profiles and standard deviation of the turbulent velocity fluctuations. Comparison between the $R/\Delta = 20$ and $R/\Delta = 32$ meshes.

The same conclusion can be drawn from Fig. B3, which reports the mean streamwise velocity averaged over transverse planes spanning the region between $-R$ and $+R$, providing a global indicator of wake recovery. Apart from negligible differences, both simulations predict comparable wake recovery trends over the entire downstream distance.

Since the main objective of this work is to characterize the downstream evolution of the coherent energy associated with platform motion, it is important to verify that the adopted mesh resolution does not significantly affect its prediction. To this

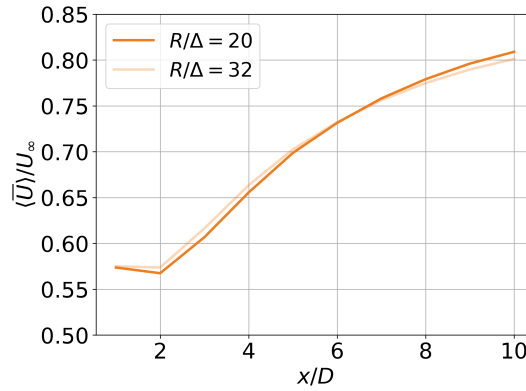


Figure B3. Wake recovery comparison between the $R/\Delta = 20$ and $R/\Delta = 32$ meshes.

end, the coherent energy associated with the platform-motion frequency is evaluated on each transverse plane employed for the POD analysis presented in Section 4.3. The analysis is performed on the total velocity fluctuations of the three velocity components, U' , V' , and W' , directly sampled from the original LES field. The coherent energy is computed at each point of the plane following the procedure described in Eq. 7 and subsequently integrated over the entire plane according to Eq. 8.

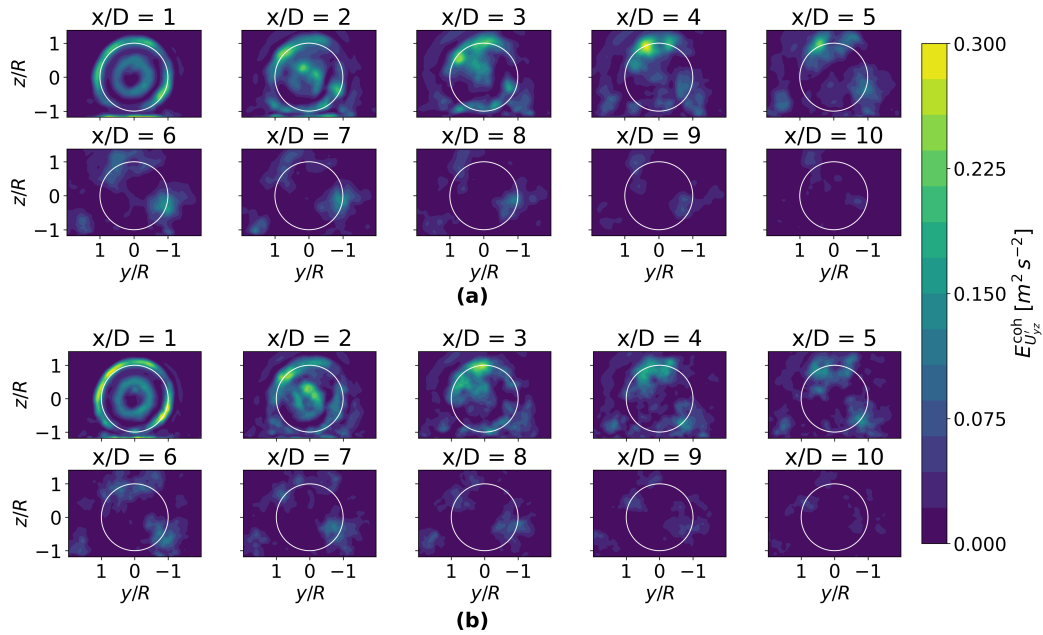


Figure B4. Platform-motion coherent energy of the stream wise velocity fluctuations, evaluated on the ten wake planes. (a) Mesh $R/\Delta = 20$. (b) Mesh $R/\Delta = 32$.



Figure B4 compares the spatial distribution of the coherent energy associated with the streamwise velocity fluctuations U' over the ten wake planes downstream of the rotor for the $R/\Delta = 20$ (Fig. B4(a)) and $R/\Delta = 32$ meshes (Fig. B4(b)). The two simulations exhibit good agreement in both the spatial distribution and the magnitude of the coherent energy. Similar observations can be made for the transverse and vertical velocity components, whose coherent energy distributions are reported in Figs. B5 and B6, respectively.

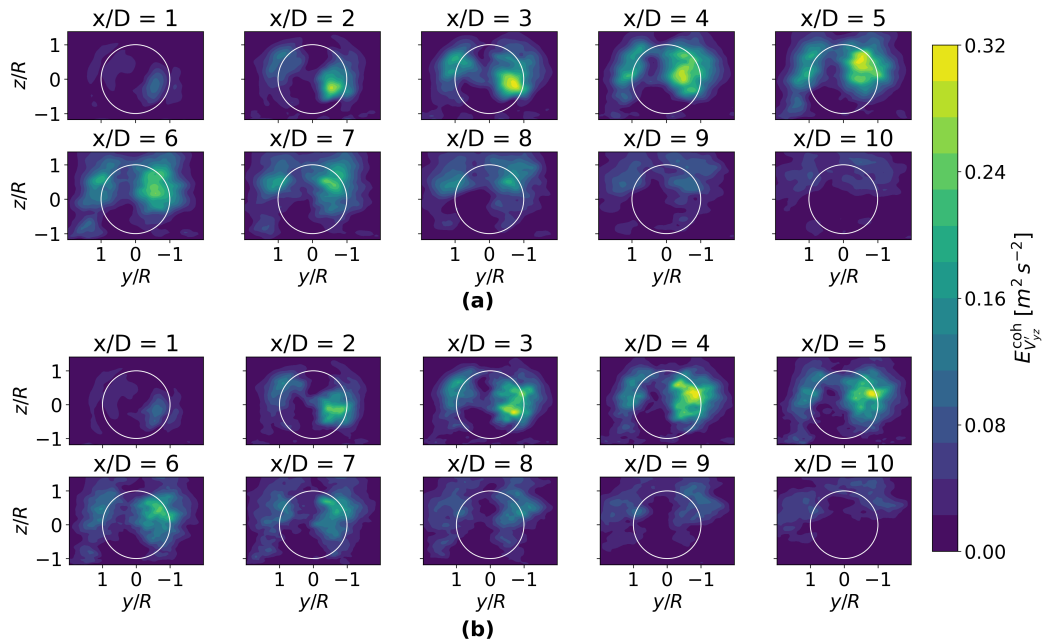


Figure B5. Platform-motion coherent energy of the transverse velocity fluctuations, evaluated on the ten wake planes. **(a)** Mesh $R/\Delta = 20$. **(b)** Mesh $R/\Delta = 32$.

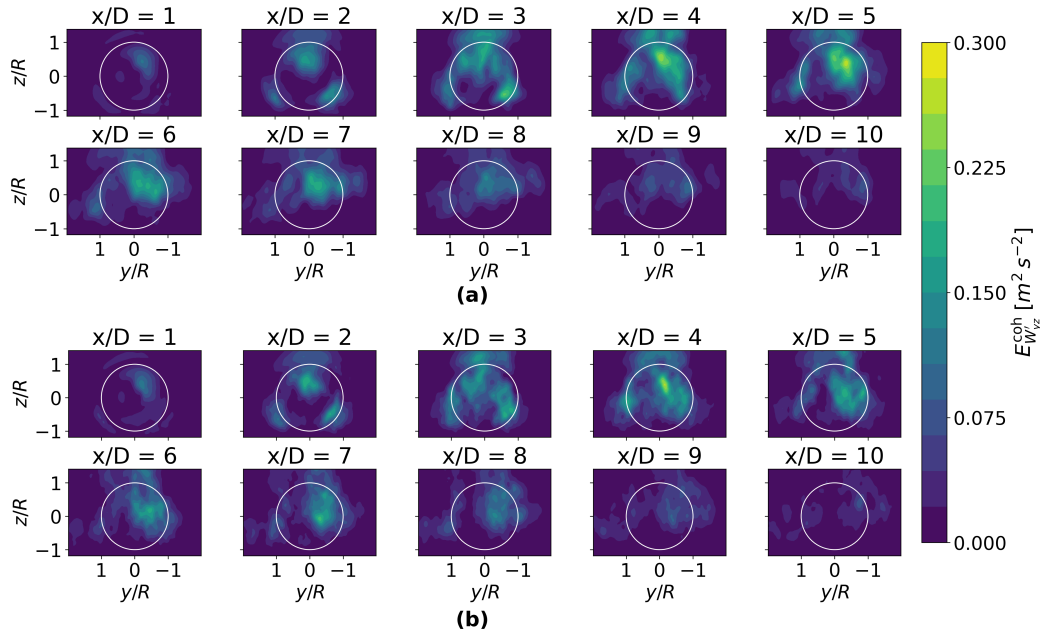


Figure B6. Platform-motion coherent energy of the vertical velocity fluctuations, evaluated on the ten wake planes. **(a)** Mesh $R/\Delta = 20$. **(b)** Mesh $R/\Delta = 32$.

To summarize the downstream evolution of the coherent energy, Fig. B7 reports the plane-integrated coherent energy of the three velocity components. The two mesh resolutions produce comparable trends for all three components, with only minor
 725 quantitative differences. These results demonstrate that the baseline mesh with $R/\Delta = 20$ provides an accurate prediction not only of the global rotor loads and wake statistics but also of the coherent structures associated with platform motion. It therefore represents an effective compromise between computational cost and accuracy for floating wind turbine simulations.

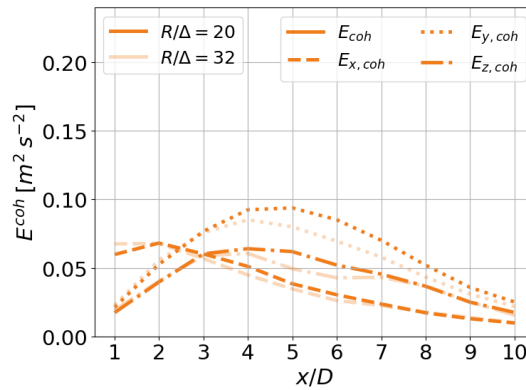


Figure B7. Plane-integrated coherent energy associated with platform motion for the three velocity fluctuation components.



Appendix C: Supplementary POD Wake Analysis - Analysis of modal energy

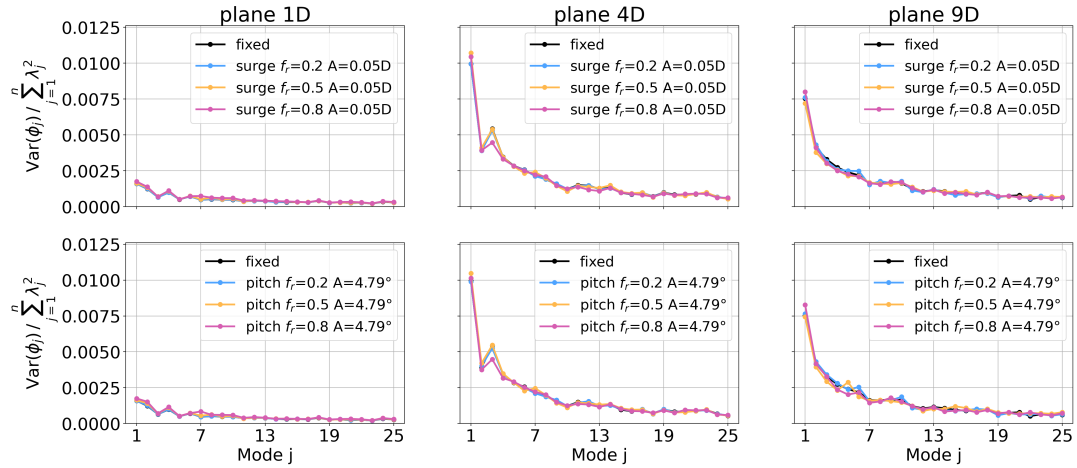


Figure C1. Relative energy contribution of the first 25 POD modes at selected wake locations ($x = 1D$, $x = 4D$, and $x = 9D$). Comparison between the fixed-bottom configuration and the surge and pitch cases at the smallest motion amplitude.

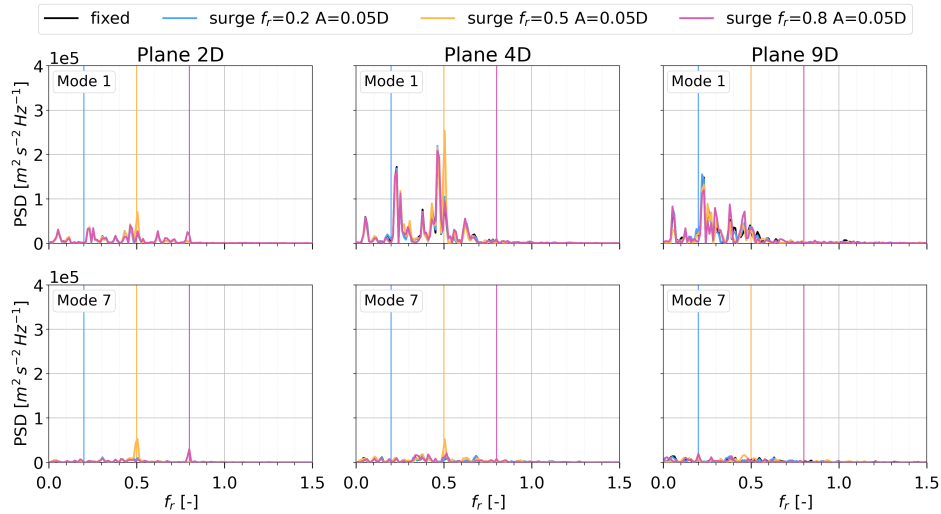


Figure C2. PSD of temporal coefficients of modes 1 and 7 at selected wake locations ($x = 2D$, $x = 4D$, and $x = 9D$). Comparison between the fixed-bottom configuration and the surge cases at the smallest motion amplitude..

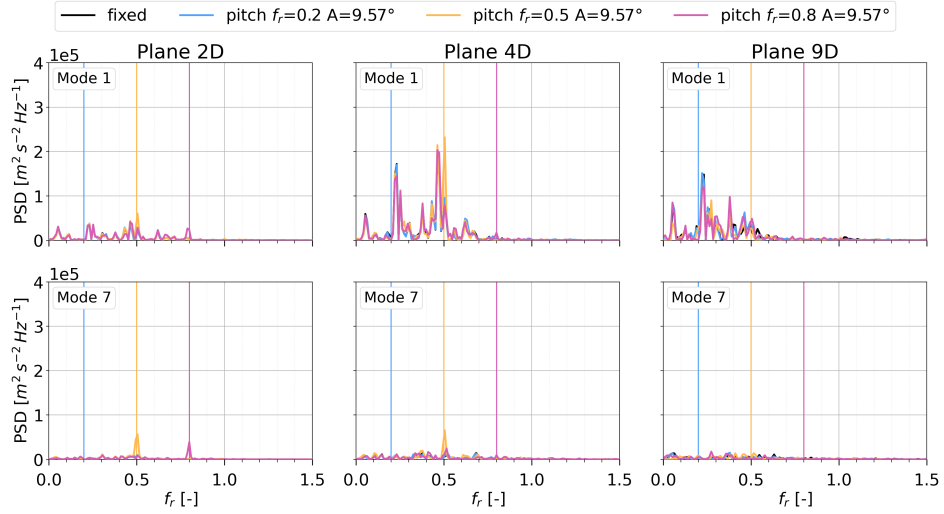


Figure C3. PSD of temporal coefficients of modes 1 and 7 at selected wake locations ($x = 2D$, $x = 4D$, and $x = 9D$). Comparison between the fixed-bottom configuration and the pitch cases at the smallest motion amplitude.

Appendix D: Supplementary POD Wake Analysis - Analysis of modal energy coherent with platform motion

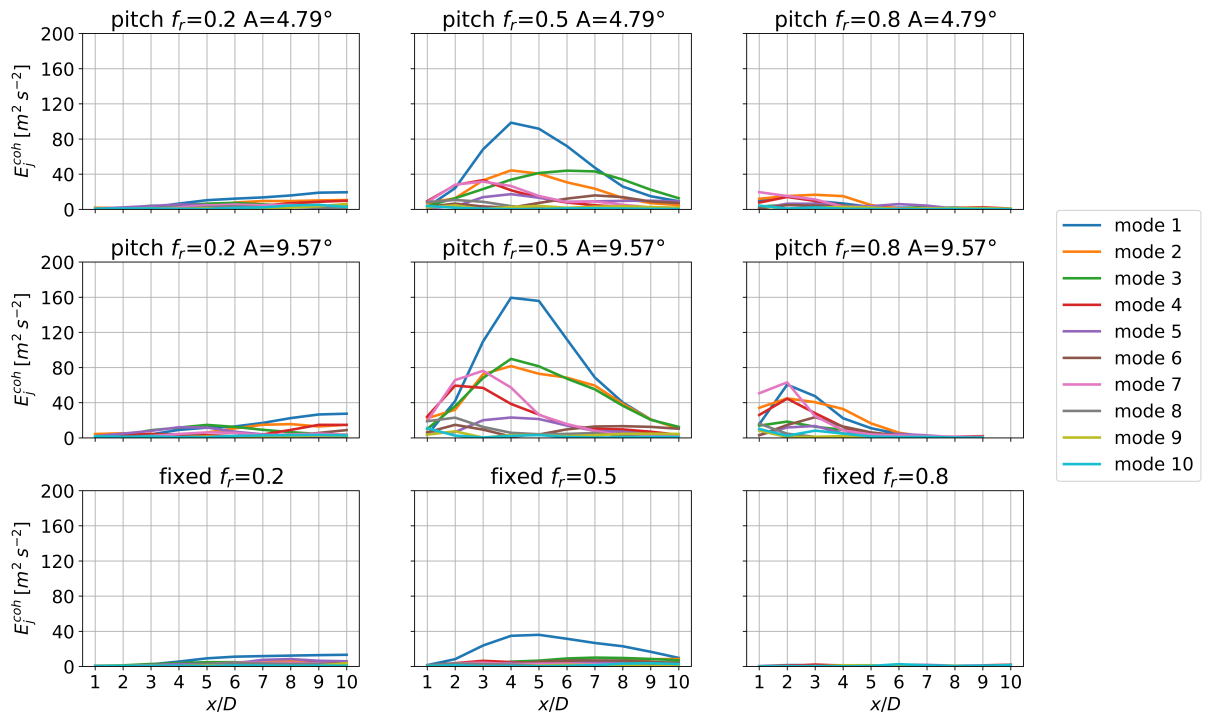


Figure D1. Platform-motion coherent energy of the first 10 modes for all pitch cases.



730 **Appendix E: Supplementary POD Wake Analysis - Analysis of velocity field energy coherent with platform motion**

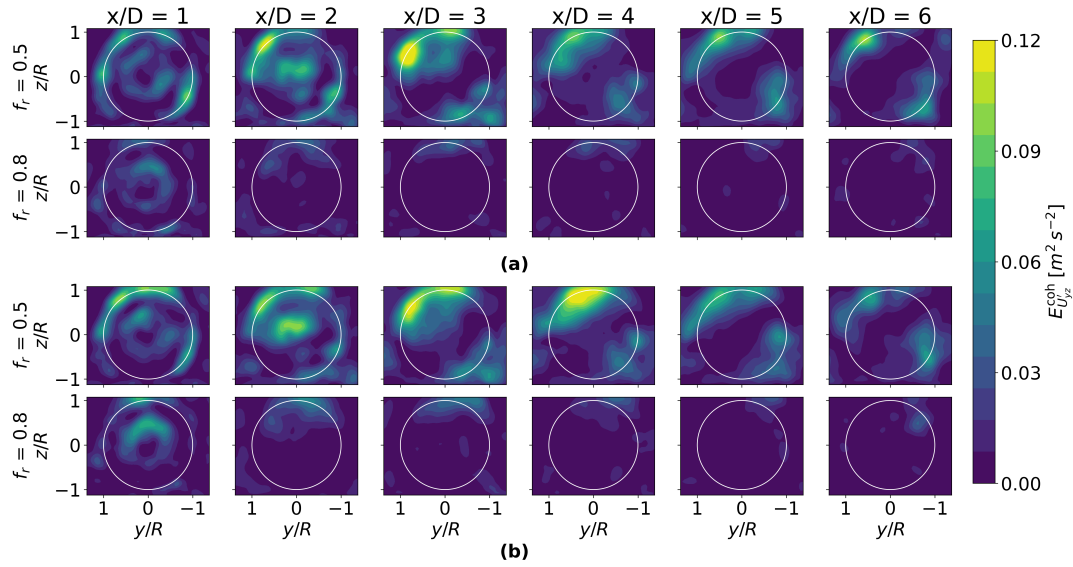


Figure E1. Platform-motion coherent energy of the stream-wise velocity fluctuations, evaluated on the first six wake planes. **(a)** Surge cases with $A = 0.05D$ at $f_r = 0.5$ and $f_r = 0.8$. **(b)** Pitch cases with $A = 4.79^\circ$ at $f_r = 0.5$ and $f_r = 0.8$.

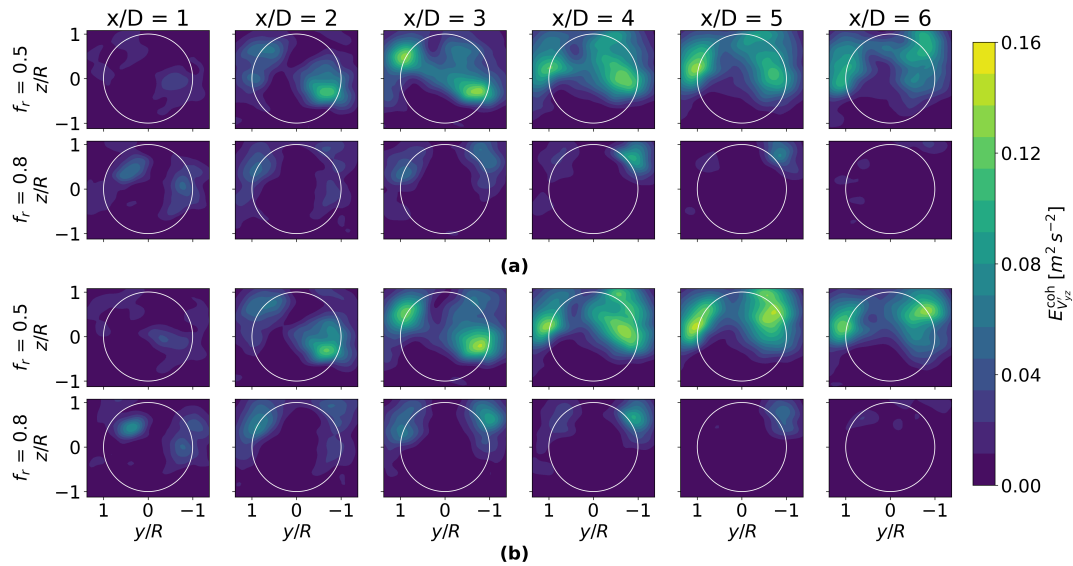


Figure E2. Platform-motion coherent energy of the transverse velocity fluctuations, evaluated on the first six wake planes. **(a)** Surge cases with $A = 0.05D$ at $f_r = 0.5$ and $f_r = 0.8$. **(b)** Pitch cases with $A = 4.79^\circ$ at $f_r = 0.5$ and $f_r = 0.8$.

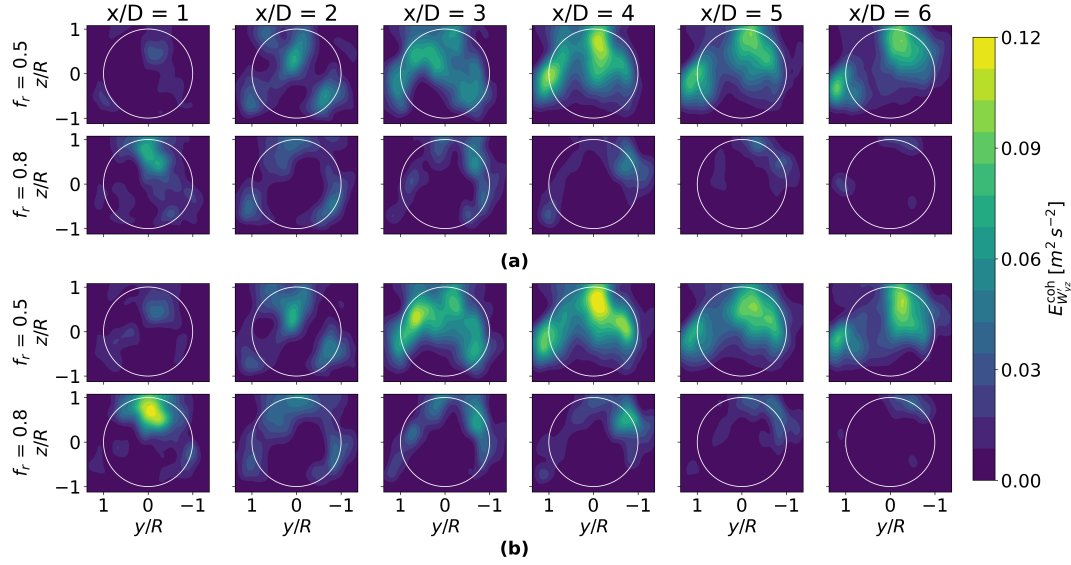


Figure E3. Platform-motion coherent energy of the vertical velocity fluctuations, evaluated on the first six wake planes. **(a)** Surge cases with $A = 0.05D$ at $f_r = 0.5$ and $f_r = 0.8$. **(b)** Pitch cases with $A = 4.79^\circ$ at $f_r = 0.5$ and $f_r = 0.8$.

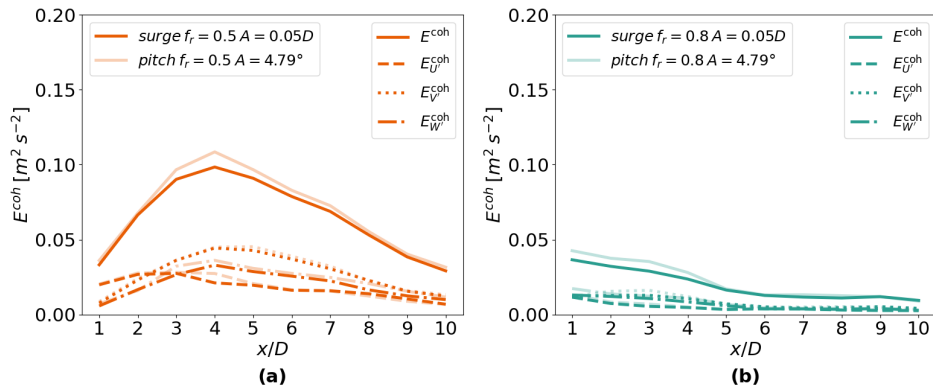


Figure E4. Plane-integrated coherent energy associated with platform motion for the three velocity fluctuation components and the total field. **(a)** Surge and pitch cases at $f_r = 0.5$. **(b)** Surge and pitch cases at $f_r = 0.8$.

Author contributions. AF performed the simulations, carried out the post-processing, data analysis, and results visualization, and wrote the first draft of the manuscript. SJA supervised the work, performed the precursor simulation and the global POD computation, and contributed to the study conceptualization, methodology, and interpretation of the results. GP supervised the work, contributed to the interpretation of the results, and supported the manuscript preparation and revision. All authors reviewed and contributed to the final manuscript.



735 *Competing interests.* The contact author declares that none of the authors has any competing interests.

Acknowledgements. This study was carried out within the NEST - Network 4 Energy Sustainable Transition (D.D. 1243 02/08/2022, PE00000021) and received funding under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3, funded from the European Union - NextGenerationEU. This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them. Computational resources have been provided by the DTU cluster Sophia DTU Computing Center (2021) and the DTU contributions has been funded by the INF4INiTY project (<https://inf4inity.com/>) with grant agreement no. 101136087 under the European Union's Horizon 2020 research and innovation programme.

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