

## Article

# Aerodynamic Characteristics Analysis of Floating Wind Turbine Subjected to Different Wind and Platform Movement Directions

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## Abstract

Floating offshore wind turbines (FOWTs) are subjected to complex oceanic environmental loads, which can result in non-collinear wind and wave directions that may not align with the rotor axis, potentially leading to complex variations in aerodynamic characteristics. In this study, the aerodynamic performance and wake of the NREL 5 MW wind turbine under different inflow angles and platform surge motions in various directions were investigated using the actuator line model (ALM) implemented in OpenFOAM. The results demonstrate that an increase in surge amplitude primarily amplifies the cyclic fluctuations in rotor thrust and torque, while the direction of surge motion has a negligible influence. In contrast, yawed inflow leads to a substantial reduction in both the mean and peak values of thrust and torque. Wake analysis further reveals that the mean wake recovery is predominantly governed by the yaw angle. Under aligned inflow conditions, the wake remains nearly symmetric and shows limited sensitivity to platform surge motion. Conversely, yawed inflow induces significant wake deflection with an asymmetric distribution of turbulent kinetic energy and enhanced mixing in the downstream region.

**Keywords:** floating wind turbine; actuator line model; platform surge motion; yawed inflow

## 1. Introduction

With the continuously growing global demand for sustainable energy and the increasingly severe challenge of climate change, wind energy, as a key component of renewable energy, has garnered increasing attention [1–3]. According to the Global Wind Report 2025 [4], offshore wind power has enormous potential, and the global installation capacity has been steadily expanding. By the end of 2024, the cumulative global offshore wind capacity had reached approximately 83 GW. Owing to the abundant wind resources and larger available development areas in deep-water regions, offshore wind power is progressively shifting from fixed-bottom concepts to floating concepts in deep and far offshore locations. Compared with conventional fixed-bottom offshore wind turbines, floating offshore wind turbines (FOWTs) are subjected to more complex environmental loads. Therefore, it is essential to account for the platform's six degrees-of-freedom (DoFs) motions and yawed inflow in FOWT aerodynamic analyses, as these factors directly impact operational reliability, maintenance requirements, and power generation efficiency [5–10].

At present, the primary numerical approaches employed for analyzing wind turbine aerodynamics include blade element momentum (BEM) theory, the free vortex method



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(FVM), and computational fluid dynamics (CFD). The BEM method combines blade element theory with momentum theory by discretizing the blade into independent elements and evaluating the thrust and torque based on both the change in fluid momentum and the aerodynamic characteristics of the airfoil [11]. To improve the accuracy of BEM-based simulations, various correction models have been introduced, including Prandtl's tip-loss correction [12], Glauert's high-thrust correction [13], and dynamic stall corrections.

In the free vortex method (FVM), the continuous vorticity field is discretized into vortex elements whose trajectories are tracked over time, enabling an accurate resolution of the convection and deformation of vorticity in the flow field. Qiu et al. [14] developed a more accurate and efficient wake-vortex model based on FVM to compute the unsteady aerodynamic loads on turbine blades and their wakes under platform motion. This improved method demonstrates high accuracy and efficiency in simulating the variations in unsteady aerodynamic loads and wake evolution during control processes. Wen et al. [15] employed an FVM approach to investigate the influence of platform motion on the aerodynamic characteristics of a spar-type floating wind turbine. Their results indicate that fluctuations in power and thrust are primarily governed by the angle of attack (AOA), and that these variations become more pronounced as the frequency or tip speed ratio increases.

With the rapid advancement of computational power, CFD methods have been widely adopted to investigate wind turbine aerodynamic performance and wake dynamics. By numerically resolving the complex flow around the turbine, CFD provides predictions with significantly higher fidelity. The mainstream CFD approaches currently employed for wind turbine analysis include the actuator disk model (ADM), the actuator line model (ALM), and blade-resolved CFD methods. In ADM, the turbine rotor is idealized as an infinitesimally thin disk, neglecting the actual three-dimensional blade geometry and rotational effects [16,17]. In ALM, each turbine blade is represented as a rotating line along which body forces are distributed, enabling efficient simulation of wake evolution [18,19]. Blade-resolved CFD methods, in contrast, perform full-grid discretization of the true three-dimensional blade geometry and directly solve the flow around it, achieving the highest accuracy at the expense of extremely high computational cost [20]. Tran and Kim [21] employed an overset moving-mesh approach to investigate the effects of platform oscillation frequency and amplitude on thrust, power, and wake characteristics. Ye et al. [22] conducted CFD simulations with fully resolved wind turbine geometries and quantified numerical uncertainties related to discretization errors. Cai et al. [23] and Ji et al. [24] applied blade-resolved CFD methods to study the aerodynamic characteristics of wind turbines under specific operating conditions. Zhou et al. [25] analyzed the influence of turbulent and shear wind on FOWT structures using CFD. Despite the high numerical accuracy of CFD, the associated computational cost remains considerable.

Despite the significant progress achieved in the aforementioned studies, key limitations and research gaps persist in high-fidelity numerical simulations of FOWT aerodynamic performance. High-fidelity, blade-resolved CFD approaches (e.g., [21,23,24]) are computationally prohibitive, rendering them impractical for systematic parametric studies across multiple operating conditions or for long-duration dynamic simulations. Conversely, lower-fidelity methods—such as BEM theory or FVM augmented with empirical corrections [14,15]—often lack sufficient accuracy to capture complex unsteady wake structures. The ALM embedded in a CFD framework strikes a favorable balance between computational accuracy and efficiency, making it particularly suitable for simulating large wind farms and complex flow environments. Wang et al. [26] employed an ALM-based CFD approach to simulate the wake of the NREL 5 MW wind turbine under various yaw angles. Their results showed that wake deflection and deformation are primarily governed by a counter-rotating vortex pair induced by the blade tip vortices. Stanly et al. [27] used

large eddy simulation with a filtered actuator line model (FALM) to simulate the NREL Phase VI wind turbine on relatively coarse grids, thereby circumventing the conventional ALM's over-prediction of blade loads and power. Arabgolarcheh et al. [28] applied an ALM-based method to analyze the influence of platform motion on wake structure and aerodynamic performance, demonstrating that ALM can effectively capture the complex vortex dynamics induced by platform motions in floating wind turbines.

With the rapid advancement of floating wind power technology, particular attention must be paid to the influence of platform motions on turbine aerodynamic performance. Unlike fixed-bottom foundations, floating platforms undergo pronounced 6-DoF motions under combined wind–wave–current loading. Cheng et al. [29] employed an unsteady actuator line model (ULAM) to analyze the 6-DoF motions of a floating platform and found that these motions induce periodic fluctuations in turbine thrust and power, with a period identical to that of the incident waves. Wu and Nguyen [30] developed a CFD model coupling rotor rotation with platform surge motion. Their computed results show close agreement with those obtained from the BEM method, while the CFD-based coupled model is able to capture flow details more accurately. Wei et al. [31] investigated the wake dynamics of a FOWT subjected to periodic surge motion and revealed that platform motion excites wake-traveling waves and tip-vortex clustering, and that such unsteady flow behavior accelerates wake recovery.

The influence of yawed inflow on the aerodynamic characteristics of FOWTs is also non-negligible. Unlike aligned inflow, yawed inflow results in a non-uniform distribution of aerodynamic loads along the blades, which in turn affects the power output of the turbine. Zhang et al. [32] examined the evolution of the wake field to assess the impact of yawed inflow on turbine aerodynamic performance. They reported that yawed inflow disrupts the incoming vortex structures and modifies the distribution of turbulent kinetic energy in the wake. Wang et al. [33] analyzed the variations in blade AOA, aerodynamic loads, and torque during both static and dynamic yaw motions. Their results indicated that yawed inflow induces periodic fluctuations in AOA primarily through the combined effects of advancing and retreating blade motion and the asymmetry between the upwind and downwind sides of the rotor. Howland et al. [34] employed an analytical model calibrated against historical data to quantify the influence of yaw misalignment on turbine aerodynamic performance and demonstrated that yaw steering control can significantly enhance the total power output of a wind farm under specific inflow directions.

In real-world operations, FOWTs are subjected to complex environmental loads characterized by misaligned wind and wave conditions, including yawed inflow and oblique wave incidence. Hildebrandt et al. [35] quantified the occurrence and correlation of wind–wave misalignment and demonstrated that non-collinearity between wind and waves primarily leads to increased motion response amplitudes of FOWTs. Li et al. [36] simulated the dynamic responses under various combinations of yaw misalignment and wind–wave offset conditions. Their results indicated that yaw misalignment is mainly influenced by power production efficiency and power fluctuations, whereas wind–wave misalignment has a pronounced effect on platform motions and on the structural loads at the tower base and yaw bearing. Ali et al. [37] evaluated the combined effects of regular waves, above-rated wind, multi-directional currents, and wind–wave misalignment on platform stability and structural loads. Their findings show that wind–wave misalignment significantly alters the dynamic response, leading to a reversal of the tower base bending moment and a reduction in thrust.

Existing research has often been limited to the investigation of isolated physical factors. For instance, some studies have focused exclusively on aerodynamic responses [30,31] or wake evolution [29] under platform motion, without adequately accounting for the more

complex influences of varying wind directions encountered in real marine environments. Other works have separately examined the effects of yawed inflow [32–34] or treated wind–wave misalignment as an integrated load condition for structural response analysis [35–37]. These studies have yet to systematically isolate and quantify the independent and coupled effects of the two core controlling factors—platform motion and turbine yaw—on aerodynamic performance and wake characteristics. Notably, even when platform motion is represented by a single DoF, coupling it with yaw conditions remains essential for a deeper understanding of their interaction—an aspect that remains underexplored in the current literature.

Building on the above discussion, this study employs a CFD-based ALM to investigate the aerodynamic behavior of a FOWT under the combined effects of platform motion and yawed inflow. Specifically, the coupled influences of platform motion and yaw misalignment on aerodynamic loads and wake characteristics are systematically quantified, and the underlying physical mechanisms governing wake deformation and velocity deficit recovery under these combined conditions are analyzed in detail.

## 2. Theoretical Methods

### 2.1. Governing Equations of CFD Method

In this study, the open-source software OpenFOAM was employed to perform CFD simulations aimed at analyzing the transient behavior of incompressible viscous fluids. The Reynolds time-averaged Navier–Stokes (RANS) equation is expressed as follows:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j} (\bar{u}_j \bar{u}_i) = \bar{f}_i - \frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} [2\nu \bar{s}_{ij} - \overline{u'_j u'_i}], \quad (2)$$

where  $-\overline{u'_j u'_i}$  is the Reynolds stress tensor

The mean strain rate tensor is given as

$$\bar{s}_{ij} = \frac{1}{2} \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right). \quad (3)$$

In the Navier–Stokes equation, the presence of the Reynolds stress term introduces additional unknowns, resulting in an incomplete control equation. To achieve closure in this system of equations, the Boussinesq vorticity approximation method is frequently employed. This approach establishes a relationship between the Reynolds stress and the mean velocity constant.

$$-\overline{u'_j u'_i} = 2\nu_T \bar{s}_{ij} - \frac{2}{3} k \delta_{ij} \quad (4)$$

where  $k$  represents the turbulence kinetic energy,  $\nu_T$  denotes eddy viscosity.

To achieve closure of the control equations, this study employs the  $k - \omega$  SST turbulence model. This model integrates the benefits of the  $k - \omega$  model and the  $k - \varepsilon$  model to formulate a unified approximate expression for eddy viscosity. It automatically transitions to the  $k - \omega$  form in the near-wall region and reverts to the  $k - \varepsilon$  form in the far-field region, thus facilitating an effective simulation of turbulence characteristics.

### 2.2. Actuator Line Model

The ALM is a medium-complexity approach that has gained significant traction in the aerodynamic and wake simulations of wind turbines in recent years. This method simplifies the three-dimensional blade representation into an “actuator line” that is dis-

tributed along the spanwise. It applies the force source term to the flow field using the local two-dimensional lift–drag coefficient, thereby circumventing the need for direct analysis of the blade geometry. The lift and drag forces for each blade element are calculated using the following formula:

$$L = \frac{1}{2} C_l(\alpha) \rho_{air} U_{rel}^2 c dr \quad (5)$$

$$D = \frac{1}{2} C_d(\alpha) \rho_{air} U_{rel}^2 c dr \quad (6)$$

where  $C_l(\alpha)$  and  $C_d(\alpha)$  are the lift and drag coefficients,  $\alpha$  is the local angle of attack,  $\rho_{air}$  represents the air density,  $U_{rel}$  denotes relative velocity at the blade section,  $c$  is the chord length and  $dr$  is the blade width. Figure 1 shows the velocity components in the blade section.

$$U_{rel} = U_{in} - \Omega \times r + U_{rot} + U_M \quad (7)$$

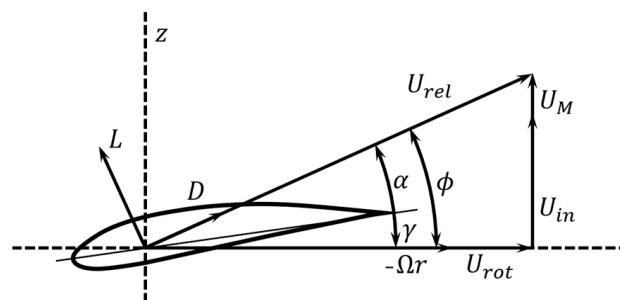
where  $U_{in}$  is the inflow velocity,  $\Omega$  is the angular velocity of rotation,  $r$  is the distance from the blade element to the rotation center,  $U_{rot}$  is the velocity component in the rotor plane and  $U_M$  is the platform motion velocity. To project the driving force onto the computational domain, the Gaussian weighting function is defined as follows:

$$\eta_\varepsilon(d) = \frac{1}{\varepsilon^3 \pi^{3/2}} \exp \left[ -\left( \frac{d}{\varepsilon} \right)^2 \right] \quad (8)$$

The volumetric force at  $(x, y, z)$  in the flow field can be calculated as

$$f_\varepsilon(x, y, z, t) = f \otimes \eta_\varepsilon = \sum_{j=1}^N f(x_i, y_i, z_i, t) \frac{1}{\varepsilon^3 \pi^{3/2}} \exp \left[ -\left( \frac{d_i}{\varepsilon} \right)^2 \right] \quad (9)$$

where  $(x_i, y_i, z_i)$  is the actuator point,  $d_i$  is the distance between  $(x, y, z)$  and  $(x_i, y_i, z_i)$ ,  $\varepsilon$  is the Gaussian smoothing parameter.



**Figure 1.** Velocity components on the blade section.

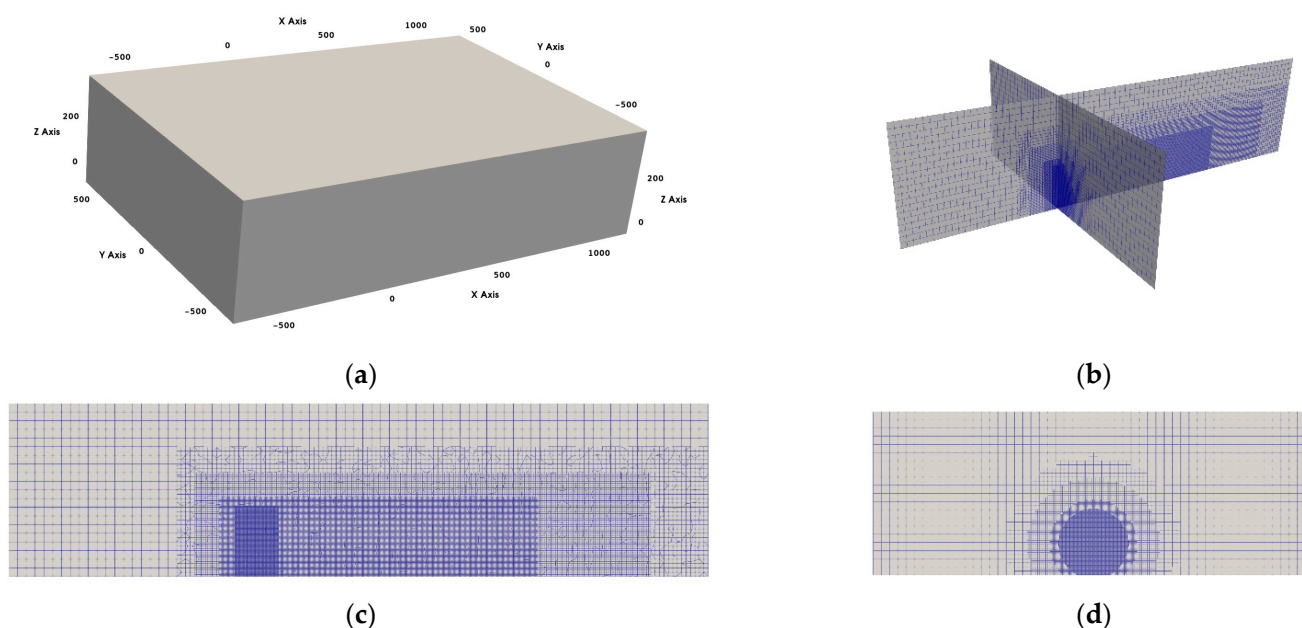
### 3. Model Description and Validation

This study employs the NREL 5 MW reference wind turbine developed by the National Renewable Energy Laboratory (NREL), with its key parameters listed in Table 1. In the present CFD modeling, the rotor setup was simplified by omitting the overhang, shaft tilt, and precone angles. The computational grid is shown in Figure 2. The computational domain has dimensions of  $15 D \times 10 D \times 5.7 D$ , where  $D$  denotes the rotor diameter. The rotor is positioned  $5 D$  from the inlet boundary and  $10 D$  from the outlet boundary, with the rotor hub located  $5 D$  from the top boundary. Local grid refinement was applied in the rotor and wake regions, with a maximum grid size of  $24 \text{ m}$ . The finest grid resolution in the rotor area is  $1.5 \text{ m}$ , yielding a total of approximately 1.26 million cells. A uniform inflow velocity of  $11.4 \text{ m/s}$  was prescribed at the inlet. The top, bottom, and lateral boundaries

were set as symmetry planes, while the outlet was specified as a pressure outlet. For the unsteady simulations, the time step is set to correspond to a blade rotation of  $1^\circ$  in azimuth, i.e.,  $\Delta t = 0.0137$  s. Each operating condition is simulated for a sufficiently long duration (typically 20 complete rotor revolutions) to ensure that the flow reaches a fully developed, periodically stable state. In the actuator line model, the Gaussian force projection smoothing width  $\varepsilon$  is scaled with the local grid size  $\Delta x$  and set to  $\varepsilon = 2\Delta x$ , following the widely adopted empirical guideline in the field to ensure a reasonable distribution of body forces on the grid and to avoid numerical singularities.

**Table 1.** Parameters of the NREL 5 MW wind turbine.

| Turbine Parameter                 | Value                        |
|-----------------------------------|------------------------------|
| Rated power                       | 5 MW                         |
| Rotor orientation, configuration  | Upwind, 3 blades             |
| Rotor diameter                    | 126 m                        |
| Hub diameter                      | 3 m                          |
| Hub height                        | 90 m                         |
| Cut-in, rated, cut-out wind speed | 3 m/s, 11.4 m/s, 25 m/s      |
| Cut-in, rated rotor speed         | 6.9 rpm, 12.1 rpm            |
| Rated tip speed                   | 80 m/s                       |
| Overhang, shaft tilt, precone     | 5 m, $5^\circ$ , $2.5^\circ$ |



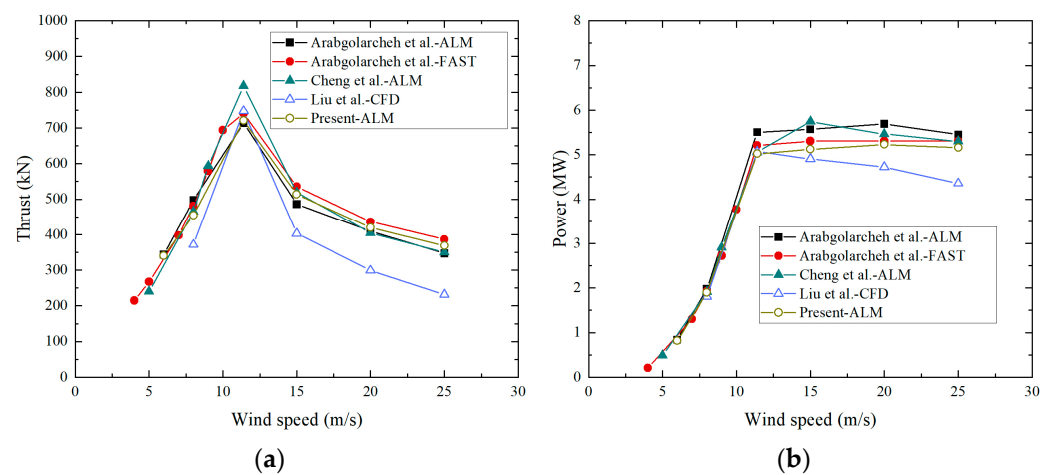
**Figure 2.** Mesh for the simulation: (a) Overall geometric model; (b) Close-up view of internal mesh details; (c) Side view; (d) Front view.

Prior to analyzing the aerodynamic performance of the wind turbine, a verification of the numerical model is first conducted. Three distinct grid resolutions are employed, consisting of approximately 0.91 million, 1.26 million, and 1.74 million cells, respectively. The verification results are presented in Table 2. The results indicate that the differences in thrust and power between the medium and fine grids are negligible, suggesting that the medium grid yields sufficient accuracy for the present analysis. Therefore, the medium grid is adopted in the subsequent simulations as it offers a favorable balance between computational efficiency and numerical accuracy. Furthermore, the thrust and power predicted by the present model under various wind speeds are compared with reference

data from previous studies [28,29,38]. As shown in Figure 3, good agreement is achieved, thereby validating the accuracy of the present numerical model.

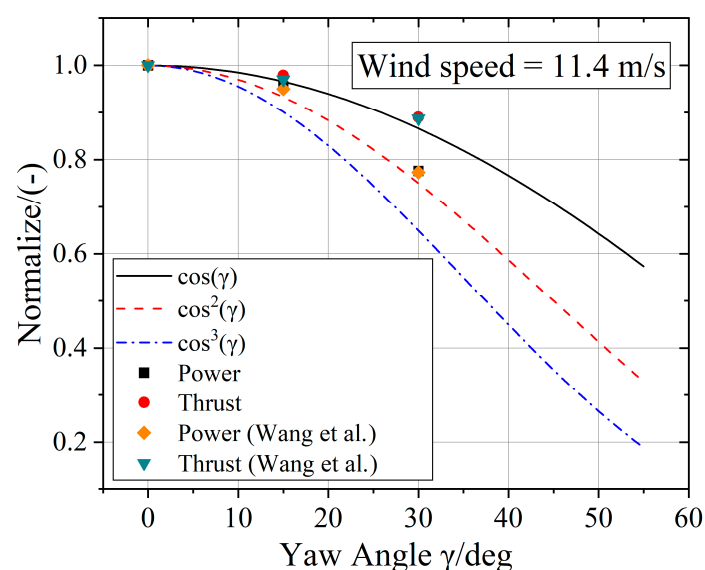
**Table 2.** Grid convergence analysis of thrust.

| Mesh   | Cell Number (in Million) | Thrust (kN)    | Power (MW)   |
|--------|--------------------------|----------------|--------------|
| Coarse | 91                       | 721.67 (0.25%) | 5.04 (0.25%) |
| Medium | 126                      | 720.58 (0.09%) | 5.02 (0.09%) |
| Refine | 174                      | 719.89 (0%)    | 5.01 (0%)    |



**Figure 3.** Comparison of ALM results with other literature for the NREL 5-MW wind turbine: (a) Thrust, (b) power [28,29,38].

Additionally, Figure 4 presents the simulation results after normalizing thrust and power according to the  $0^\circ$  yaw angle value across various wind speed conditions. As the yaw angle increases, both power and thrust exhibit a gradual decline. The decreasing trends of power and thrust correspond to the  $\cos(\gamma)$  and  $\cos^2(\gamma)$  curves, respectively, aligning with the findings of Wang et al. [33], thereby confirming the efficacy of the blade CFD model in analyzing aerodynamic characteristics at different yaw angles.



**Figure 4.** Verification for thrust and power in yawed inflow [33].

#### 4. Results and Discussion

This study primarily investigates the variations in aerodynamic characteristics induced by changes in wind direction, as well as the effects of platform surge motion under varying wave directions, as illustrated in Figure 5. A total of 15 distinct operating conditions are examined, encompassing surge motion amplitudes of 2 m, 4 m, and 8 m, yaw angles of  $0^\circ$ ,  $15^\circ$ , and  $30^\circ$ , and surge motion directions of  $0^\circ$ ,  $15^\circ$ , and  $30^\circ$ . The detailed configurations of these operating conditions are summarized in Table 3.

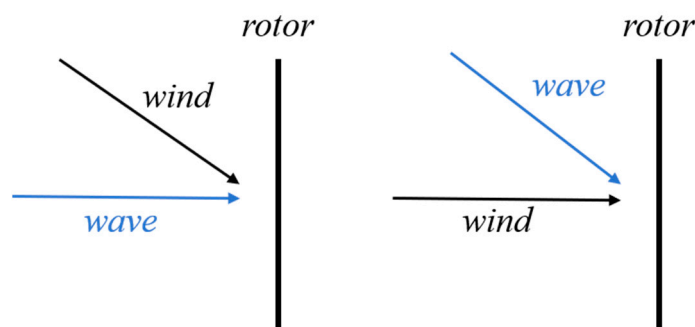


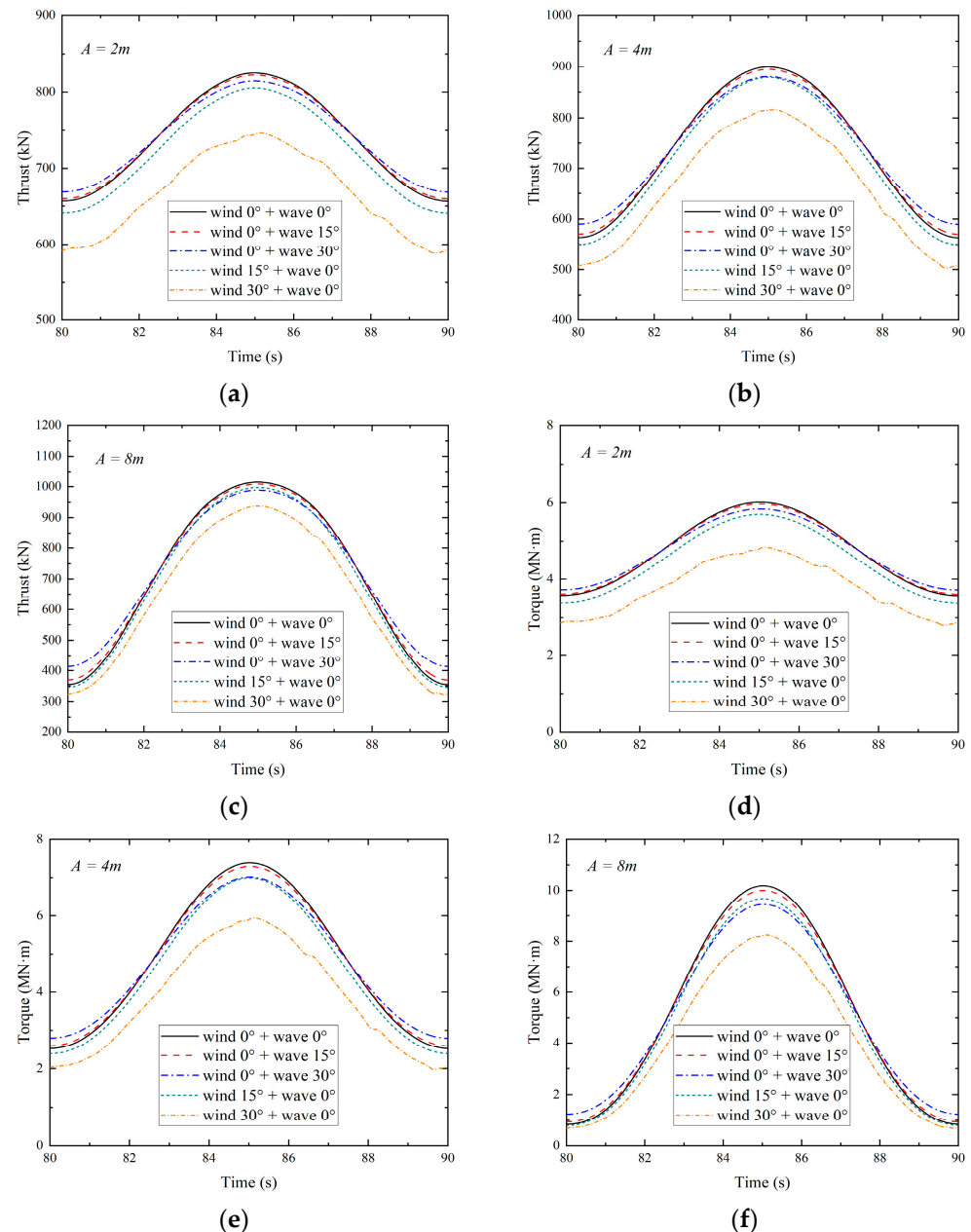
Figure 5. Sketch of wind and platform surge motion directions.

Table 3. Operating condition settings.

| Wind Direction (°) | Surge Direction (°) | Surge Amplitude (m) | Surge Frequency (Hz) |
|--------------------|---------------------|---------------------|----------------------|
| 0                  | 0                   | 2                   | 0.1                  |
|                    | 15                  |                     |                      |
|                    | 30                  |                     |                      |
|                    | 0                   |                     |                      |
|                    | 15                  |                     |                      |
| 15                 | 0                   | 4                   |                      |
|                    | 15                  |                     |                      |
|                    | 30                  |                     |                      |
|                    | 0                   |                     |                      |
|                    | 15                  |                     |                      |
| 30                 | 0                   | 8                   |                      |
|                    | 15                  |                     |                      |
|                    | 30                  |                     |                      |
|                    | 0                   |                     |                      |
|                    | 15                  |                     |                      |

##### 4.1. Variation in Total Thrust and Torque

To investigate the combined influence of platform motion and yawed inflow on the aerodynamic characteristics of the wind turbine, platform surge motion is selected as the representative DoF. By varying the motion amplitude  $A$  and the incident directions of wind and waves, the temporal evolution of the rotor-integrated thrust and torque is analyzed. Figure 6 presents the results for surge motion amplitudes of  $A = 2$  m, 4 m and 8 m. Under all considered conditions, both thrust and torque exhibit a smooth, nearly single-peaked variation over time, and the phases of the curves are largely consistent. This indicates that the variation in aerodynamic loads is primarily governed by the platform's reciprocating motion along the wind direction: when the platform moves upwind, the relative wind speed increases and the loads reach their maximum; when it moves downwind, the relative wind speed decreases and the loads correspondingly drop. Figure 6 primarily illustrates the effects of different surge amplitudes and yaw angles on rotor thrust and torque.



**Figure 6.** Variation in rotor thrust and torque under different conditions: (a–c) Thrust variation at motion amplitude of 2 m, 4 m and 8 m; (d–f) Torque variation at motion amplitude of 2 m, 4 m and 8 m.

Under various combinations of platform motion and yawed inflow, the rotor thrust ranges from 324.38 kN to 1014.65 kN, and the torque ranges from 0.69 MN·m to 10.19 MN·m. For a fixed wind direction of  $0^\circ$  and a given surge amplitude, varying the surge motion direction among  $0^\circ$ ,  $15^\circ$ , and  $30^\circ$  results in only minor changes in the thrust and torque time histories, with observable differences largely limited to the vicinity of the peak values. As illustrated in Figure 6b for the case of  $A = 4$  m, the variation in peak thrust across the three surge directions is less than 5%, and the differences in peak torque remain within approximately 5–7%. Similar trends are observed for both the smaller amplitude of 2 m and the larger amplitude of 8 m. These results indicate that, under the conditions considered, the direction of platform surge motion has a limited impact on the effective inflow upstream of the rotor and thus plays only a secondary role in modulating the aerodynamic loads.

In contrast, when the wind direction is yawed by  $15^\circ$  and  $30^\circ$  while the platform surge motion direction is maintained at  $0^\circ$ , a pronounced reduction in aerodynamic loads is observed. For the case with  $A = 2$  m, the peak thrust decreases by approximately 5% and 10% at yaw angles of  $15^\circ$  and  $30^\circ$ , respectively, while the corresponding peak torque is reduced by about 7% and 20%. For  $A = 4$  m, the reductions in peak thrust are on the order of 6% and 12%, and the peak torque decreases by roughly 10% and 23% at yaw angles of  $15^\circ$  and  $30^\circ$ , respectively. In the case with the largest motion amplitude of  $A = 8$  m, as shown in Figure 6f, the peak values at a yaw angle of  $30^\circ$  are reduced by approximately one quarter relative to the reference condition. Overall, the aerodynamic loads are highly sensitive to inflow yaw, whereas their sensitivity to the direction of platform surge motion is comparatively weak. This is consistent with the understanding that the loads are primarily governed by the velocity component of the incoming wind normal to the rotor plane.

An increase in platform motion amplitude primarily amplifies the temporal fluctuations of thrust and torque, without altering the relative ordering among different wind direction cases. Taking the reference condition (wind  $0^\circ$  + wave  $0^\circ$ ) as an example, the peak-to-trough difference in thrust increases from approximately 180 kN at  $A = 2$  m to about 320 kN at  $A = 4$  m, while the corresponding difference in torque rises from roughly  $2.5 \text{ MN}\cdot\text{m}$  to approximately  $9.6 \text{ MN}\cdot\text{m}$ . The absolute differences in peak loads among the various yawed inflow cases are correspondingly enlarged, indicating that larger platform excursions substantially enhance the cyclic variations in both thrust and torque.

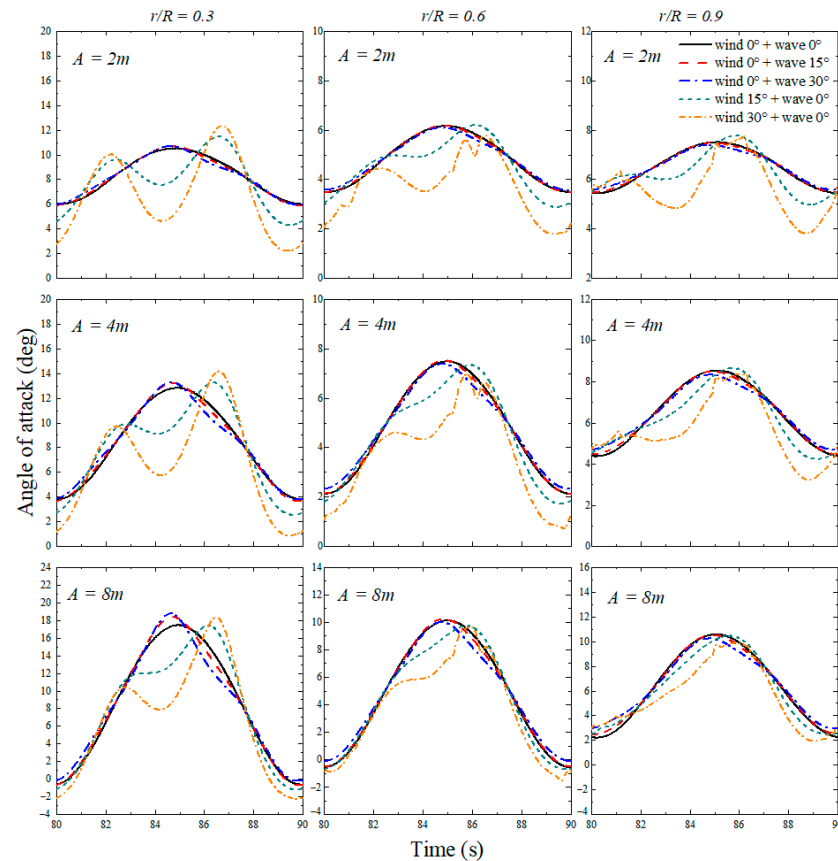
#### 4.2. Variation in Local AOA, Lift Coefficient and Drag Coefficient

In this section, three representative radial positions along the blade—the inner, mid, and outer sections ( $r/R = 0.3, 0.6$ , and  $0.9$ )—are selected to examine the temporal evolution of the local AOA, as well as the lift and drag coefficients. Figures 7–9 present the time histories of these quantities at the three radial locations under various motion amplitudes and wind–wave incidence directions, respectively. Overall, when the inflow wind direction is  $0^\circ$ , varying only the platform surge motion direction does not significantly alter the shape of the local time histories. In contrast, at yaw angles of  $15^\circ$  and  $30^\circ$ , particularly at the inner blade section, the time histories of AOA, lift coefficient, and drag coefficient exhibit pronounced double peaks or irregular waveforms.

As shown in Figure 7, for a wind direction of  $0^\circ$  with varying platform surge motion directions, the AOA at all three radial positions exhibits a primarily smooth, nearly single-peaked temporal variation, with only minor differences in peak values and timing. As the platform motion amplitude increases, the amplitude of fluctuations is notably amplified: the local peak AOA rises, the trough deepens, and the AOA range at the inner section ( $r/R = 0.3$ ) expands from approximately  $6\text{--}11^\circ$  to about  $4\text{--}18^\circ$ . The changes at the mid and outer sections are relatively minor, with the curve shapes remaining closer to a single-peaked profile. When the yaw angle is  $15^\circ$  or  $30^\circ$ , the local AOA shows a marked change and exhibits distinct double peaks or pronounced peak undulations, with two comparable maxima appearing within one platform motion cycle. As the motion amplitude increases, these double-peaked or irregular features gradually diminish, and the curves tend to revert toward a single-peaked shape.

As illustrated in Figure 8, the evolution of the lift coefficient generally follows the same trend as the AOA. Under conditions where only the platform surge motion direction is varied, with a motion amplitude  $A = 2$  m, the lift coefficient  $Cl$  at  $r/R = 0.3$  ranges from 0.8 to 1.4, at  $r/R = 0.6$  from approximately 0.8 to 1.6, and at  $r/R = 0.9$  within a narrow interval of about 0.85–0.95. When the motion amplitude increases to  $A = 8$  m,  $Cl$  at the inner section fluctuates between about 0.5 and 1.7, at the mid-section between about 0.7 and 1.7, while the outer section still remains in the range of roughly 0.85–0.95. This demonstrates

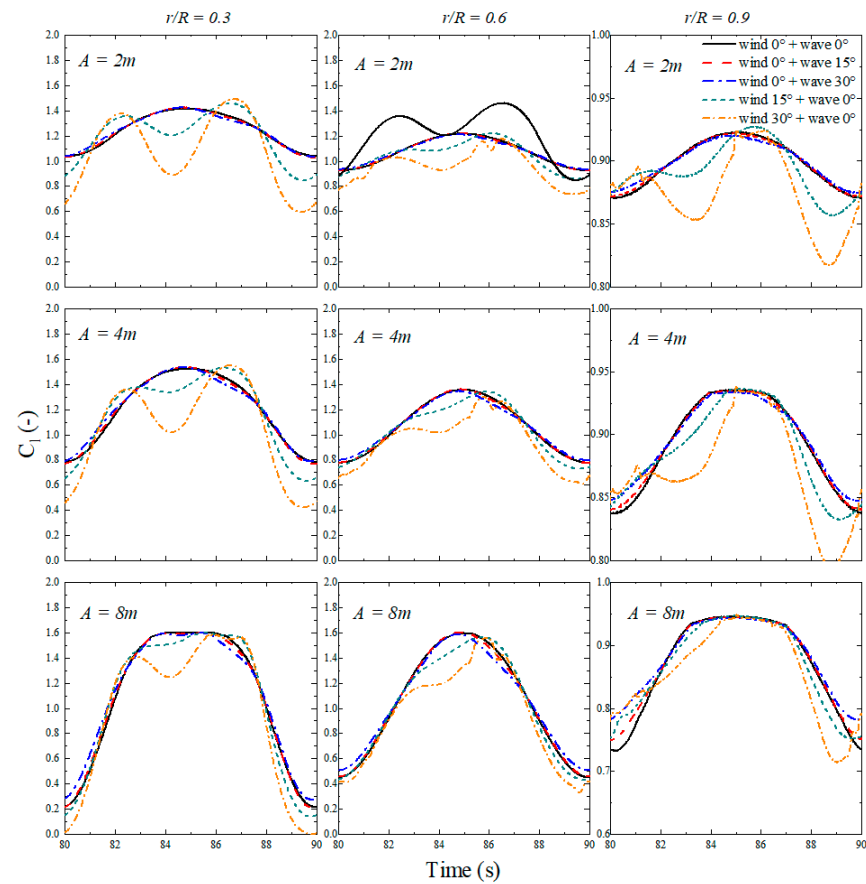
that increasing platform motion amplitude predominantly affects the lift coefficient at the inner and mid-sections, with only a minor influence on the outer section. Under yawed inflow conditions, a clear double-peaked pattern appears at  $r/R = 0.3$  when  $A = 2$  m, and the corresponding time history gradually evolves into a single-peaked waveform as the motion amplitude increases.



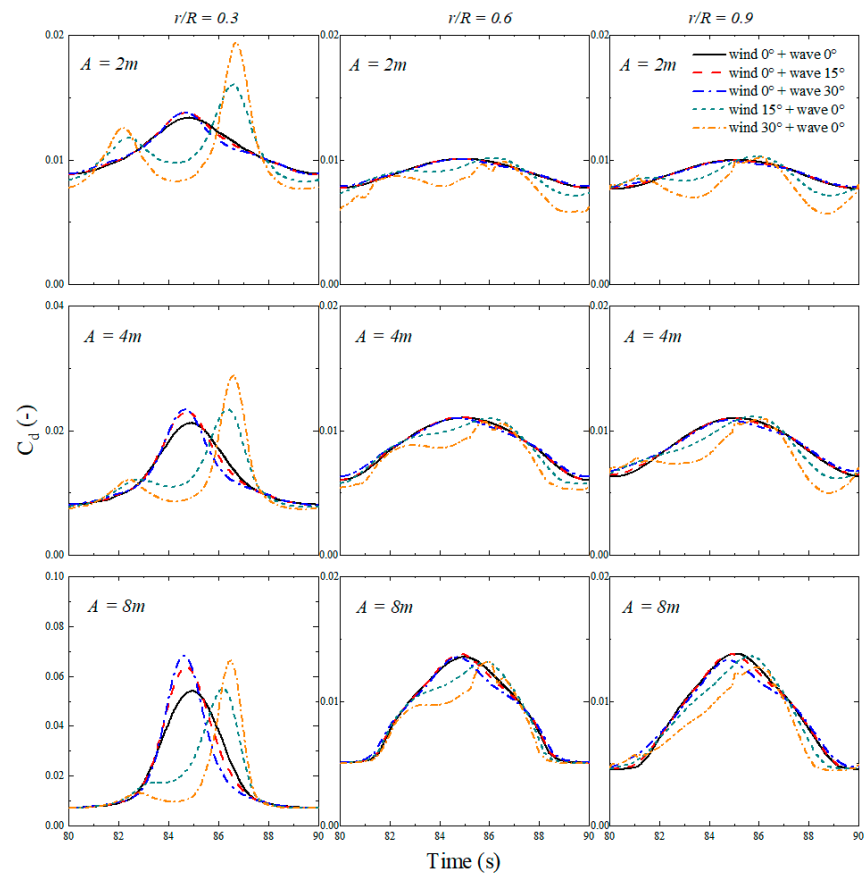
**Figure 7.** Variation in local AOA at different blade sections.

As shown in Figure 9, in contrast to the lift coefficient, the drag coefficient responds more sensitively to platform motion and yawed inflow. This is especially evident at the inner section ( $r/R = 0.3$ ) under yawed conditions. For  $A = 2$  m, the drag coefficient curve exhibits two connected peaks, with the second peak becoming sharper and higher for a yaw angle of  $30^\circ$ . When  $A = 8$  m, all cases exhibit relatively high and narrow peaks; however, the timing of the peak occurrence differs among inflow directions, and the yawed cases show the highest peak values. At the mid-section ( $r/R = 0.6$ ), a weaker double peak or peak-top undulation is also observed for  $A = 2$  m, which gradually transforms into a single peak as the motion amplitude increases. The drag coefficient curve at the outer section ( $r/R = 0.9$ ) is overall smoother and more rounded.

When the inflow wind is aligned with the rotor axis, the platform surge motion modifies the local AOA and thereby induces periodic temporal fluctuations in the lift and drag coefficients. In the presence of yaw, however, the superposition of axial and lateral wind speed components, blade tangential velocity, and platform surge velocity can produce two distinct combinations of relatively favorable or unfavorable inflow conditions within a single motion cycle. As a result, the AOA, lift coefficient, and drag coefficient at certain blade sections exhibit double peaks or pronounced peak-top undulations. The yaw-induced local fluctuations in AOA and sudden increases in drag coefficient near the blade root are particularly detrimental to the structural safety of the wind turbine.



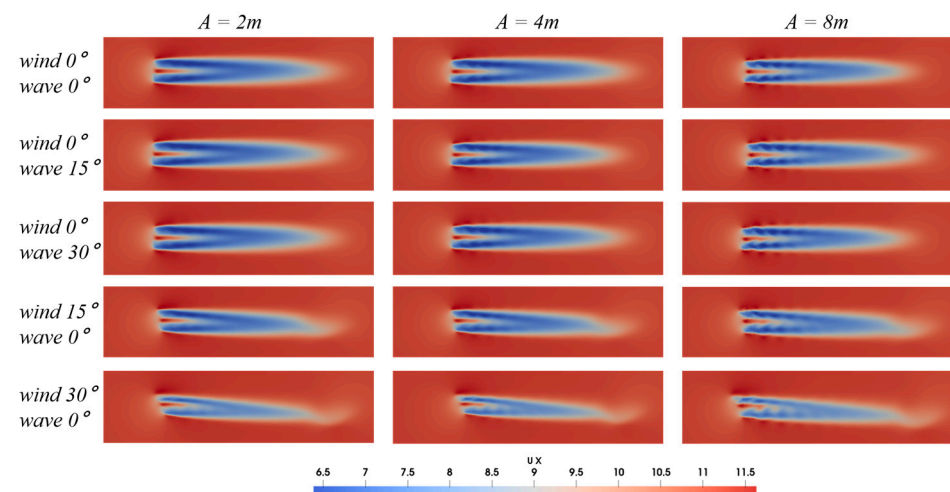
**Figure 8.** Variation in lift coefficient at different blade sections.



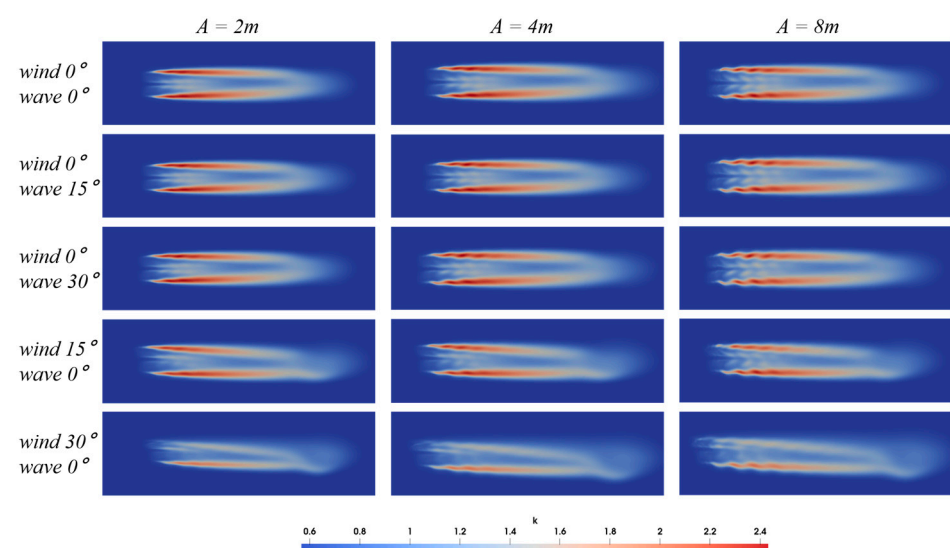
**Figure 9.** Variation in the drag coefficient at different blade sections.

### 4.3. Wake Analysis

The axial velocity and turbulent kinetic energy (TKE) contours obtained from the RANS–ALM simulations are presented in Figures 10 and 11. When the wind direction is aligned with the rotor axis, the wake develops essentially along the main flow direction, and the differences in velocity deficit and TKE distribution among the three platform surge motion directions are marginal. Increasing the platform motion amplitude primarily enhances shear-layer perturbations and wake meandering, resulting in a slightly deeper velocity deficit in the near wake and a longer downstream extension of the high-TKE streaks. Under yawed inflow conditions, the entire wake undergoes pronounced deflection, with the wake deflection angle increasing as the yaw angle increases. Additionally, the centerline velocity deficit is reduced, the high-TKE region becomes more concentrated on the windward side, and the shear layer exhibits a more distinct wavy structure. As the platform motion amplitude increases, the high-TKE streaks within the yawed wake are progressively elongated and exhibit more evident spatial undulations, indicating that platform motion and yawed inflow jointly enhance wake unsteadiness and downstream mixing.



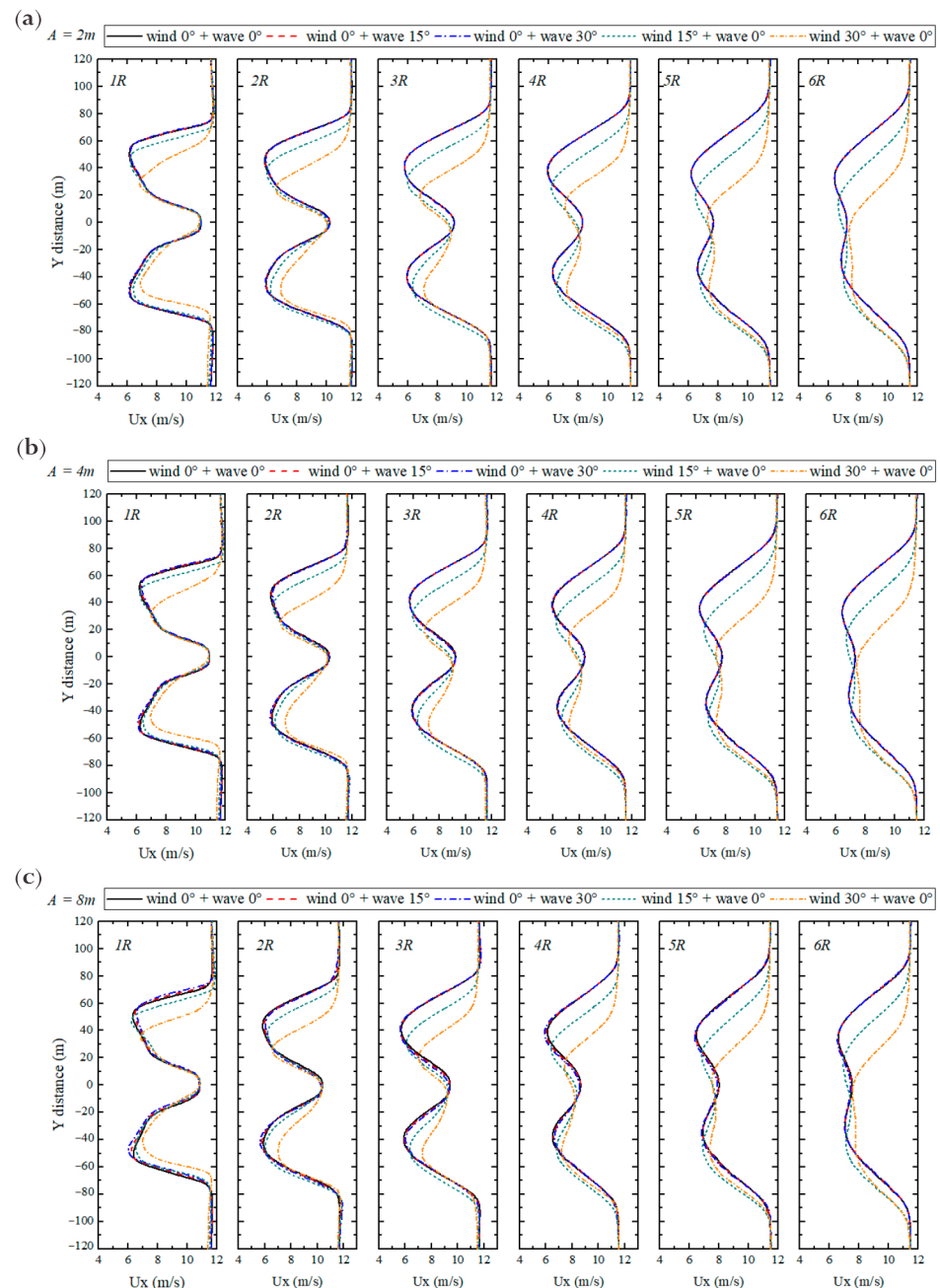
**Figure 10.** Contours of axial velocity in different cases.



**Figure 11.** Contours of turbulent kinetic energy in different cases.

To facilitate a more intuitive comparison of the wake distribution and its recovery in the vertical direction under different operating conditions, Figure 12 presents vertical

profiles of streamwise velocity along the turbine centerline at six downstream positions, from  $x = 1R \sim 6R$  (where  $R$  is the blade length) for platform motion amplitudes of  $A = 2\text{ m}$ ,  $4\text{ m}$  and  $8\text{ m}$ . The horizontal axis denotes the streamwise velocity  $U_x$ , and the vertical axis represents the horizontal lateral coordinate, with  $0\text{ m}$  corresponding to the rotor center and  $63\text{ m}$  approximately corresponding to the rotor tip positions on either side. Two distinct low-velocity regions are observed downstream of the blade tips, while outside the wake envelope, the velocity gradually approaches the incoming wind speed.



**Figure 12.** Velocity profile in different cases: (a) Motion amplitude of  $2\text{ m}$ ; (b) Motion amplitude of  $4\text{ m}$ ; (c) Motion amplitude of  $8\text{ m}$ .

The comparison of various wind–platform surge motion combinations reveals that, when the wind direction is fixed at  $0^\circ$ , and only the platform surge motion direction is varied, the velocity profiles across all downstream sections nearly converge. This convergence indicates that variations in platform surge motion direction have a minimal impact on the

mean wake distribution. Conversely, at yaw angles of  $15^\circ$  and  $30^\circ$ , the flow velocity near the wake boundary increases, and the low-speed region becomes significantly shallower, with this effect intensifying as the yaw angle increases. Analysis of the horizontal and vertical velocity profiles demonstrates that, within the near-wake region, the maximum velocity deficit at each section is predominantly located near the wake boundary, while the velocity at the rotor centerline experiences only a slight reduction, remaining close to the incoming wind speed. As the downstream distance increases from  $R$ , the low-speed region near the wake boundary is progressively eroded by the surrounding high-speed flow, leading to a rapid local velocity recovery. Comparing different platform motion amplitudes under the same wind direction and downstream position reveals that variations in surge amplitude have only a minor effect on the wake velocity distribution; the wake deficit and its recovery are governed predominantly by the inflow yaw angle. This finding is consistent with the previous analysis based on velocity and turbulent kinetic energy contours and further confirms that, under combined wind–wave loading, the yaw angle is the key parameter controlling the wake structure and downstream wind speed.

## 5. Conclusions

Based on the ALM, this study investigates the influence of different platform surge motion direction and yawed inflow conditions on the aerodynamic and wake characteristics of a floating wind turbine. The main conclusions are as follows:

- (1) For the range of yawed inflow and platform surge motion conditions examined, the differences in rotor thrust and torque from peak to trough increase significantly with the amplitude of platform motion. This suggests that platform surge primarily serves to amplify the cyclic fluctuations in thrust and torque. Under yawed inflow conditions, both the mean and peak values of thrust and torque experience a reduction. The aerodynamic loading is predominantly influenced by the downwind component of the inflow velocity and exhibits a high sensitivity to inflow yaw. In contrast, variations in platform surge motion direction and motion amplitude have a relatively minor impact on the overall load levels.
- (2) The sensitivity of blade aerodynamic parameters to platform surge motion and yawed inflow exhibits significant variations along the blade spanwise. Altering only the platform surge motion direction has a minimal impact on the temporal evolution of the local AOA, lift coefficient, and drag coefficient. In the inner and mid-sections, small amplitude platform motion combined with yawed inflow results in two distinct maxima in the local AOA and lift coefficient within a single platform motion cycle. Conversely, the drag coefficient demonstrates brief, sharp spikes, suggesting that the blade-root region is particularly susceptible to a reduction in the local aerodynamic safety margin due to the combined effects of yaw and platform motion. As the amplitude of platform motion increases, the fluctuations in the local AOA, lift coefficient, and drag coefficient become increasingly influenced by platform motion, while the outer blade section remains only weakly affected.
- (3) When the inflow wind direction is aligned with the rotor axis, the velocity deficit and regions of high turbulent kinetic energy are mainly concentrated in the shear layers above and below the blade tips. Changes in platform surge motion direction and platform motion amplitude only slightly strengthen shear-layer perturbations in the near wake and modestly extend the continuous high-TKE region in the downstream direction, with limited impact on the mean wake velocity distribution. Under yawed inflow, by contrast, the high-TKE region becomes clearly concentrated on the windward side, and the shear layer exhibits stronger spatial fluctuations, exerting

a substantial influence on wake depth, deflection direction, recovery process, and downstream wind conditions.

This study also has certain limitations that should be addressed in future work. The current research primarily focuses on the coupled effect of platform surge motion and turbine yaw misalignment. However, floating platforms in real marine environments may undergo more complex and coupled multi-DoF motions (e.g., heave, pitch, and their combinations). Future studies could further incorporate the coupled effects of these multi-physics and multi-DoF factors to provide a more comprehensive understanding of the true dynamic behavior and environmental adaptability of FOWTs.

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