

Article

Research on Aerodynamic Characteristics of Three Offshore Wind Turbines Based on Large Eddy Simulation and Actuator Line Model

Chen Fu ¹, Zhihao Zhang ¹, Meixin Yu ^{2,3}, Dai Zhou ¹, Hongbo Zhu ¹ , Lei Duan ¹, Jiahuang Tu ^{4,5} 
and Zhaolong Han ^{1,*} 

¹ State Key Laboratory of Ocean Engineering, School of Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China; fc2021@sjtu.edu.cn (C.F.); 13873225135@163.com (Z.Z.); zhoudai@sjtu.edu.cn (D.Z.); hongbozhu@sjtu.edu.cn (H.Z.); leidian@sjtu.edu.cn (L.D.)

² China Shipbuilding NDRI Engineering Co., Ltd., Shanghai 200090, China; zsyumeixin@163.com

³ Shanghai Engineering Research Center of Ocean & Shipbuilding Maritime Engineering, Shanghai 200090, China

⁴ Foshan Green Intelligent Manufacturing Institute, Xiangtan University, Foshan 528000, China; tujiahuang1982@163.com

⁵ College of Civil Engineering, Xiangtan University, Xiangtan 411105, China

* Correspondence: han.arkey@sjtu.edu.cn

Abstract: Investigating the aerodynamic performance and wake characteristics of wind farms under different levels of wake effects is crucial for optimizing wind farm layouts and improving power generation efficiency. The Large Eddy Simulation (LES)–actuator line model (ALM) method is widely used to predict the power generation efficiency of wind farms composed of multiple turbines. This study employs the LES–ALM method to numerically investigate the aerodynamic performance and wake characteristics of a single NREL 5 MW horizontal-axis wind turbine and three such turbines under different wake interaction conditions. For the single turbine case, the results obtained using the LES–ALM method were compared with the existing literature, showing good agreement and confirming its reliability for single turbine scenarios. For the three-turbine wake field problem, considering the aerodynamic performance differences under three cases, the results indicate that spacing has a minor impact on the power coefficient and thrust coefficient of the middle turbine but a significant impact on the downstream turbine. For staggered three-turbine arrangements, unilateral turbulent inflow to the downstream turbine causes significant fluctuations in thrust and torque, while bilateral turbulent inflow leads to more stable thrust and torque. The presence of two upstream turbines causes an acceleration effect at the inflow region of the downstream single turbine, significantly increasing its power coefficient. The findings of this study can provide methodological references for reducing wake effects and optimizing the layout of wind farms.

Keywords: method of large eddy simulation–actuator line model; OpenFOAM; offshore wind power; wake field; aerodynamic performance



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1. Introduction

Offshore wind energy, as a form of renewable and clean energy, has broad development prospects [1–3]. China boasts abundant offshore wind energy resources and significant development potential [4]. Developing offshore wind energy is of great importance for ensuring national energy security and achieving the goals of “peak carbon dioxide emissions” and “carbon neutrality” [5].

Offshore wind farms are the primary equipment for harnessing offshore wind energy. However, due to the wake effect of wind turbines, the airflow passing through upstream turbines slows down behind the turbines, reducing the power generation efficiency of the downstream turbines. The wake effect can lead to a total power generation loss of up to

20% in a typical wind farm [6]. Therefore, reducing the impact of the wake effect on the overall power generation of wind farms to increase total power output has become an important research topic.

The wake interaction mechanism in wind farms has been a research focus in recent years. Reddy [7] proposed a wind farm layout optimization framework, combining it with a single-objective hybrid optimization algorithm for wind farm layout optimization, effectively reducing the impact of the wake effect and improving wind farm power efficiency. Wu et al. [8] compared the effects of different inflow conditions and wind farm layouts on the degree of wake interaction and overall power efficiency of wind farms. Antonini et al. [9] proposed a method for optimizing wind farm layouts that allows CFD models to accurately simulate terrain-induced wake effects, achieving optimized wind farm layouts on complex terrains. Rezaeiha et al. [10] studied the power fluctuations and wake interaction of two tandem floating wind turbines under surge conditions using the actuator disk model. Wang et al. [11] conducted numerical simulations based on the actuator line model to study the wake field of three NREL 5 MW wind turbines arranged in tandem with varying distances, discovering the patterns of power and wake variations with changing distances between the three turbines.

Currently, actuator-based methods using computational fluid dynamics (CFD), such as the LES-ALM (Large Eddy Simulation–actuator line model) method, are widely used to predict wind farm power efficiency under various wake interaction conditions. Strijhak et al. [12] conducted numerical simulations on a wind farm consisting of 14 wind turbines using the ALM method. Zhang et al. [13] used the Unsteady Reynolds-averaged RANS turbulence model and a CFD grid with tens of millions of cells to simulate the power generation and wake characteristics of a dual-rotor floating wind turbine. Guggeri et al. [14] employed the LES-ALM method to simulate a real 7.7 MW onshore wind farm under different wind conditions. By comparing the simulation results with actual wind farm monitoring data, they confirmed that the LES-ALM method can accurately simulate the power efficiency of wind farms under multi-turbine wake interaction conditions with moderate computational costs. Tu et al. [15] used the LES-ALM method with a multi-million-cell grid to simulate the power loss due to wake effects for two tandem wind turbines under different yaw angles and spacings. Xu et al. [16] quantitatively studied the mechanical response of offshore wind turbines under complex atmospheric inflow conditions using the LES-ALM method. Bai et al. [17] simulated the wake field of three staggered wind turbines in an atmospheric boundary layer using the actuator line model and found that vertically staggered turbine arrangements can effectively enhance the power generation of downstream turbines.

In summary, the LES-ALM method has gained favor among researchers for its ability to accurately predict the power efficiency of multiple wind turbines under wake interaction conditions in large wind farms. However, there is limited research on the aerodynamic performance and wake characteristics of wind farms under different types of wake interaction. Further research in this area is important for predicting wind farm power efficiency and minimizing wake interaction, thus optimizing wind farm layout plans, and is worth deeper exploration.

This study considers a three-turbine array as the basic unit of an offshore wind farm, examining the wake conditions under full wake and staggered conditions. This approach helps to understand the relationship between key power generation parameters and wake inflow, aiding in the prediction of wake effects and power efficiency for the entire wind farm. However, there is still limited research on the aerodynamic loads and wake effects of three-turbine arrays, which this study aims to address.

Toosi et al. [18] also investigated the aerodynamic performance and wake characteristics of three wind turbines based on the LES-ALM method. But the differences between our work and their work in the above paper are as follows: 1. Research Focus: Our work aims to investigate the impact of wake interaction effects on three wind turbines under different layout cases, including three tandem turbines with varying spacing ratios, and three turbines in staggered configurations, whereas the referenced paper focused on the

wake effects of three tandem turbines caused by yaw and tilt control methods. 2. Research Content: Our research further analyzes the force characteristics of three turbines, while this part was not included in referenced paper. 3. Application: The referenced paper applies to the optimization of yaw and tilt control, while our work can provide references for layout optimization.

The framework of this paper is as follows: First, the aerodynamic characteristics of a single turbine are validated by comparing the LES-ALM method with literature results. Then, the power efficiency and flow field characteristics of three turbine arrays under three different cases (full wake and staggered conditions) are compared. Finally, the LES-ALM method is used to study the unsteady mechanical characteristics of each turbine in the three-turbine arrays under different cases. This research provides a methodological reference for predicting wind farm power efficiency and optimizing layout plans.

2. Numerical Method

LES-ALM Method

This study utilizes the LES-ALM (Large Eddy Simulation–actuator line model) method [19] in the open-source software OpenFOAM-4.0.x [20] to analyze the aerodynamic performance and flow field characteristics of a three-turbine array. The model employs Large Eddy Simulation to solve the flow field problems around the wind turbines. The filtered incompressible Navier–Stokes equations are as follows:

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

$$\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j \frac{\partial \tilde{u}_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \tilde{p}}{\partial x_i} + \nu \frac{\partial}{\partial x_j} \frac{\partial \tilde{u}_i}{\partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} + f_i \quad (2)$$

In Equations (1) and (2), u_i and p represent the velocity and pressure, respectively, while $\tilde{\cdot}$ denotes the resolved flow quantities. ρ and ν represent the air density and kinematic viscosity, respectively. τ_{ij} represents the subgrid-scale (SGS) stress tensor. The f_i term denotes the body force applied to the flow field by the wind turbine. Equations (1) and (2) are solved using the PimpleFoam incompressible transient flow solver in OpenFOAM, which has been applied in numerous fluid flow studies [21–23].

The actuator line model is used to calculate the body force f_i at each actuator point of the wind turbine. The ALM discretizes the blade along the radial direction into a series of two-dimensional airfoil sections, with each section's quarter-chord point referred to as an actuator point. The body force at each actuator point can be expressed as:

$$\vec{f} = (L, D) = \frac{1}{2} \rho c U_{rel}^2 dr \left(C_l \vec{e}_L + C_d \vec{e}_D \right) \quad (3)$$

where c is the chord length of the local airfoil section, and $U_{rel} = \sqrt{U_\Omega^2 + U_{wind}^2}$ is the relative wind speed with respect to the blade. C_l is the lift coefficient of the local airfoil, and C_d is the drag coefficient of the local airfoil, both of which can be pre-calculated based on the angle of attack of the relative wind speed. To avoid numerical singularities, a Gaussian weighting function is embedded in the ALM, as shown in Equation (4), to apply the actuator force back into the flow field:

$$\eta_\epsilon(d) = \frac{1}{\epsilon^3 \pi^{3/2}} \exp \left[-\left(\frac{d}{\epsilon} \right)^2 \right] \quad (4)$$

Thus, the body force at the flow field point (x, y, z) is:

$$f_{\epsilon,i}(x, y, z, t) = f \otimes \eta_\epsilon = \sum_{i=1}^N f(x_i, y_i, z_i, t_i) \frac{1}{\epsilon^3 \pi^{3/2}} \exp \left[-\left(\frac{d_i}{\epsilon} \right)^2 \right] \quad (5)$$

In Equation (5), d is the distance between the measurement point and the actuator point on the blade. ϵ is a parameter that adjusts the concentration of the distributed load, and it is set to twice the local grid size [24].

3. Verification and Validation

3.1. Single Turbine Parameter Settings

This study investigates the aerodynamic characteristics of a single wind turbine using the LES-ALM method. A time step of $\Delta t = 0.024$ s is set to ensure $Co \leq 0.2$ (where Co , the Courant number, is the ratio of the fluid displacement within the time step to the mesh unit length in a rectangular mesh), ensuring computational convergence [25]. The simulation is carried out for at least 100 rotor revolutions, with a total duration of 500 s. The stable simulation results from the 50th to 100th rotor revolutions are used to analyze the aerodynamic performance and flow field characteristics. All the results were obtained when C_p reached the stabilization stage, indicating the wake and vortices were fully developed in the calculation.

The inlet boundary condition is defined with a uniform velocity at the rated wind speed $U_\infty = 11.4$ m/s and a zero-gradient inlet velocity. The pressure of the outlet boundary is set to $p = 0$ Pa. All other boundaries are specified as slip boundaries. The air density ρ is set to 1.224 kg/m³. Furthermore, both the wind shear and turbulence intensity are assumed to be zero.

This study employs the actuator line model (ALM) to conduct Large Eddy Simulations (LESs) of the flow over three wind turbines, aiming to understand the impact of wake effects on wind farms under different layout cases from the perspectives of aerodynamic performance and wake dynamics. We focus on an idealized setup, ignoring the influence of the atmospheric boundary layer. This simplification allows us to clearly evaluate the sole impact of the layout.

This study utilizes the NREL 5 MW wind turbine [26] (see Figure 1), with the main technical parameters of the turbine listed in Table 1. The blade of the NREL 5 MW wind turbine is discretized along the radius into 19 elements using the actuator line model. The LES-ALM method used in this study does not consider the wind turbine hub and tower [15]. The power coefficient C_p of the NREL 5 MW wind turbine is defined by the formula $C_p = P/(\rho U_\infty^3 A/2)$, where P is the generated power of the turbine, and the thrust coefficient C_T is defined by the formula $C_T = T/(\rho U_\infty^2 A/2)$, where T is the thrust force experienced by the turbine, and $A = \pi R^2$ represents the circular area swept by the turbine blade.

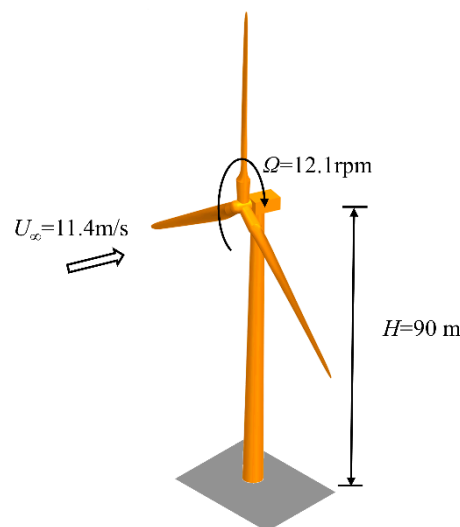


Figure 1. Key parameter schematic of a single NREL 5 MW WT.

Table 1. Key parameters of the NREL 5 MW wind turbine (WT) model used in this study.

	NREL 5 MW	Units
Rated power	5.0	MW
Rotor diameter	126.0	m
Number of blades	3	
Hub diameter	3.0	m
Hub height	90	m
Rated wind speed U_∞	11.4	m/s
Rated rotor speed	12.1	rpm

3.2. Results of the Mesh Independence Test

The quality of the mesh in the LES-ALM method significantly affects the accuracy of the simulation results. Therefore, a mesh independence test is necessary to verify the computational accuracy and precision [27]. By only changing the mesh density of the computational domain, the following three mesh density schemes were set: “coarse mesh”, “medium mesh”, and “fine mesh”.

The comparison of the power coefficient C_p calculated for different grid schemes with a tip speed ratio $\lambda = 7$ for a single turbine is shown in Table 2. In the table, Δ_g represents the mesh size around the turbine blades. It can be seen that as the mesh density increases, the obtained C_p gradually approaches the result of the fine mesh scheme. When the number of meshes is 6.52×10^6 , the predicted C_p has a relative difference of 0.64% compared to the “fine mesh” result, which is almost negligible. Therefore, considering the requirements for both the number of meshes and the computational accuracy, the mesh density for all LES-ALM method cases in this study is based on the “medium mesh” scheme.

Table 2. LES-ALM simulation mesh independence test for a single wind turbine.

	Total Mesh	R/Δ_g	C_p	Relative Difference (%)
Coarse mesh	3.62×10^6	28	0.5502	4.30
Medium mesh	6.52×10^6	36	0.5275	0.64
Fine mesh	8.86×10^6	40	0.5241	/

3.3. Comparison and Validation with Existing Literature Results

To validate the computational effectiveness of the LES-ALM method, OpenFOAM-4.0.x opensource software platform was used with uniform inflow conditions and other environmental parameters controlled to match those in the related literature [15,28,29]. The resulting velocity profiles of the wake from a single turbine at (a) $x/D = 3$, (b) $x/D = 5$, (c) $x/D = 4$ are shown in Figure 2. The LES-ALM method simulation results, RANS results [29], results obtained by LES-ALM in other studies [15], and results obtained by LES-ADM in other studies [30] were compared. It can be observed that the streamwise velocity profiles for the LES-ALM method exhibit a “W” shape. Due to the absence of modeling the turbine hub and tower in our LES-ALM method, a significant discontinuity in the streamwise velocity occurs at $y = 0$ [14]. Furthermore, there is not a significant change in the streamwise velocity in the LES-ALM method results. The LES-ALM method results from our work align closely with those obtained using LES-ALM in other studies.

Figure 3a,b show the data results for the power coefficient C_p and thrust coefficient C_T of a single NREL 5 MW turbine at varying tip speed ratios (TSR), obtained by the LES-ALM method from our work and other methods, such as LES-ALM [15], blade element momentum (BEM) theory [30], fully resolved mesh (FRM) [31], and LES-actuator disk model (LES-ADM) [32]. It can be observed that the C_p predicted by the LES-ALM method is consistent with the FRM method results, with better agreement at TSR values higher than 6. Due to the absence of modeling the turbine hub and tower in our LES-ALM method, there are some differences between the C_p obtained by the LES-ADM and LES-ALM method at high TSR values. At lower TSR values, the C_p obtained by the LES-ALM method tends to

be underestimated compared to the FRM and BEM method results. The C_T predicted by the LES-ALM method is consistent with the BEM method and LES-ADM method, with better agreement at TSR values higher than 6. Therefore, in the subsequent study, the TSR of the NREL 5 MW turbine is controlled at 8 to ensure the accuracy of the simulation data. In summary, a comparison of results calculated using the LES-ALM method with those obtained from various other methods shows good agreement, demonstrating the accuracy of the LES-ALM method in predicting C_P and C_T for a single turbine.

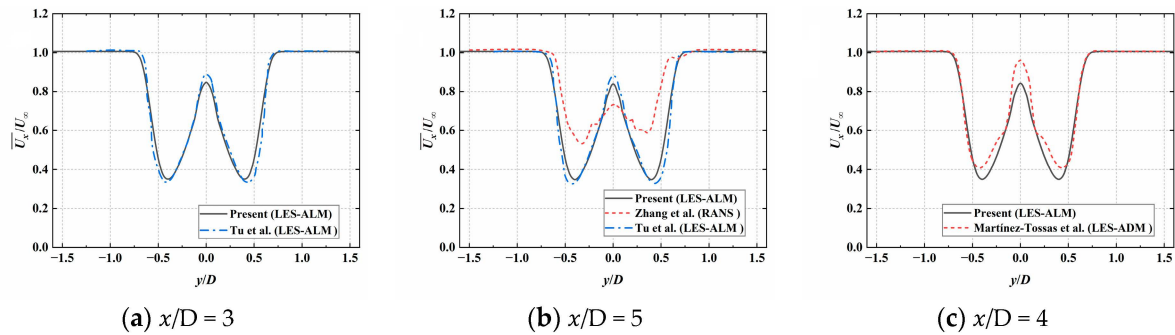


Figure 2. The cross-stream velocity profile of the mean wake at the hub height with the results from this study and relevant studies [15,28,29].

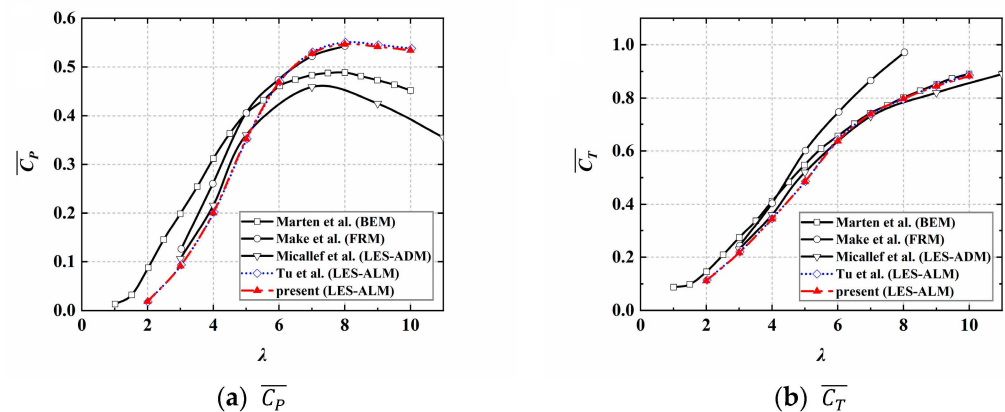


Figure 3. The comparison of (a) $\overline{C_P}$ and (b) $\overline{C_T}$ of the NREL 5 MW turbine under different TSR conditions with the results from this study and relevant studies [15,30–32].

4. Three-Turbine Array Configuration

4.1. Three-Turbine Configuration and Computational Domain Grid Division under Full Wake Cases

A tandem layout of three turbines is used to study the wind farm power efficiency under the full wake case. The corresponding mesh generated by OpenFOAM's blockMesh and refineMesh tools is shown in Figure 4. The three NREL 5 MW turbines are arranged in series within a rectangular computational domain, with a length of 38D (D being the rotor diameter) along the X direction and a width of 10D. The length of the refined area around the cylindrical region surrounding the turbines is 20D along the X direction, and the diameter of the cylinder's base is 5D, corresponding to a blockage ratio of 0.78%.

The hub center of the first turbine (WT1) is located at $(X, Y, Z) = (0, 0, 0)$, while the hub center of the second turbine (WT2) is located at $(L_1, 0, 0)$, where L_1 is the distance between the hub centers of WT1 and WT2 along the X direction. The hub center of the third turbine (WT3) is located at $(L_1 + L_2, 0, 0)$, where L_2 is the distance between the hub centers of WT2 and WT3 along the X direction. The sum of L_1 and L_2 is maintained at 12D, with only the value of L_1 being varied. The tip speed ratio for all three turbines is set to 8. A zero-gradient condition is applied to the velocity at the outlet, where a reference pressure

$p_\infty = 0$ is applied. The rest of the boundaries are set as slip. The turbine hub, tower, and ground effects are not considered in our work.

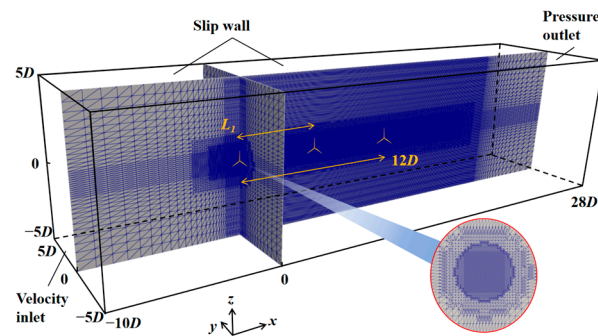


Figure 4. The grid distribution of the flow field of three turbines using LES-ALM method.

4.2. Cases of Three Turbines under Staggered Arrangement

Figure 5 shows the two staggered cases of the three turbines used in this study. In Case 2, WT1 is placed upstream, with the turbine hub center located at $(X, Y) = (0, 0)$ on the 2D projection plane. The hub centers of WT2 and WT3 are located at $(L_1, 126)$ and $(L_1, -126)$, respectively. In Case 3, WT1 and WT2 are placed upstream, with their hub centers at $(0, -126)$ and $(L_1, 126)$, respectively. The hub center of WT3 is located at $(L_1, 0)$. In both cases, the inflow wind is set to uniform inflow along the X direction, $U_\infty = 11.4$ m/s. The setting of the inflow condition for this case is the same as that for the full wake case. And L_1 is the distance in the X direction between the upstream and downstream turbines.

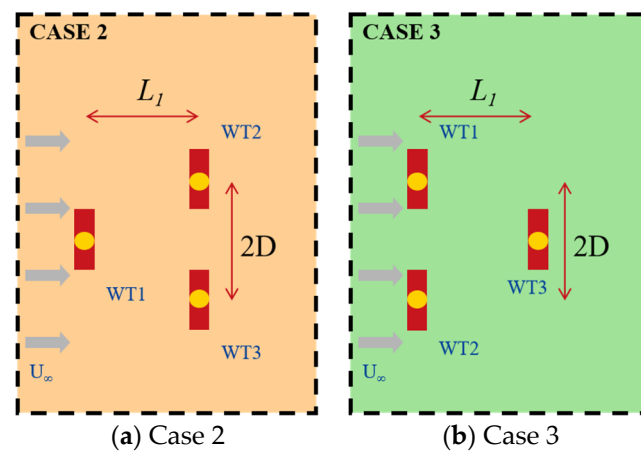


Figure 5. Two cases of three turbines under staggered arrangement.

Table 3 summarizes the three-turbine cases using the LES-ALM method. Case 1 features a tandem layout with L_1 varying from $4D$ to $7D$ in intervals of $0.5D$. Cases 2 and 3 feature staggered layouts with a lateral offset of $2D$, and L_1 varies from $4D$ to $6D$ in intervals of $0.5D$.

Table 3. Distribution table of the three-WT simulation cases using LES-ALM method in this article.

Case		L_1/D	S/D	
1	Full wake cases	4~7, interval = 0.5	0	

Table 3. Cont.

Case		L_1/D	S/D	
2	Staggered cases	4~6, interval = 0.5	2	
3	Staggered cases	4~6, interval = 0.5	2	

5. Comparative Analysis of Three-Turbine Simulation Results

5.1. Three Turbines under Full Wake Conditions

5.1.1. Comparison of Aerodynamic Performance Results

Using the LES-ALM method, the variations in C_P and C_T of three tandem turbines under full wake conditions with respect to the distance L_1 between the turbines are shown in Figure 6a,b. It can be seen that the value of L_1 has a negligible impact on the C_P and C_T of the middle turbine WT2, as WT2 experiences a significant reduction in C_P and C_T due to the wake effect from the upstream turbine. The C_P and C_T of WT3 gradually decrease as L_1 increases. The reasons for these trends will be explained later. Variation in the power ratio with the spacing ratio of three tandem turbines under full wake conditions based on real offshore wind farm data and data from other studies are shown in Figure 6c. The results are consistent with findings in the related literature using the LES-ALM method [15,18,33]. Additionally, the results we obtained are consistent with the actual measurements in terms of trends, further validating the reliability of the simulations in this study.

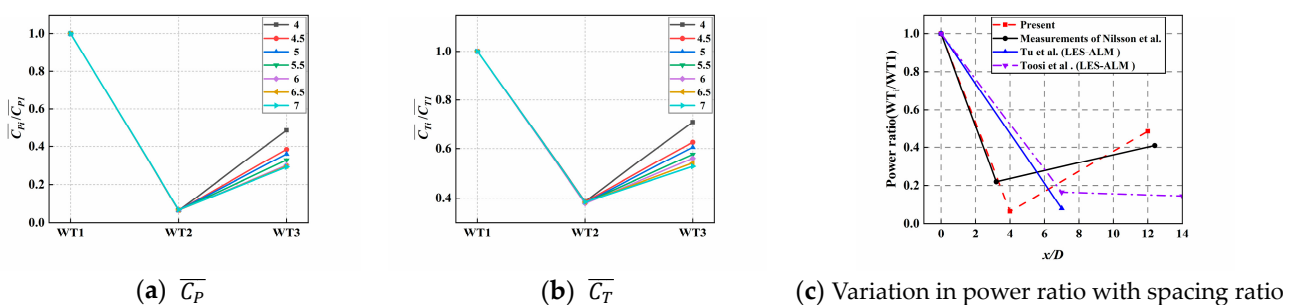


Figure 6. The ratio of $\overline{C_P}$ and $\overline{C_T}$ of the tandem three turbines at different L_1 values to those of WT1.

5.1.2. Comparison of Wake Characteristics Results

Next, we analyze the wake profiles of the three turbines to explain the aerodynamic calculation results. Simulations are conducted with $L_1 = 4D$. Figure 7a shows the mean flow field distribution of the tandem three turbines, Figure 7b shows the flow field distribution at 400 s, and Figure 7c shows the corresponding turbulence kinetic energy. It can be observed that the wake width at the inflow of WT3 is significantly reduced, with notable wake recovery, while WT2 is completely under the wake of WT1. The turbulence kinetic energy at the inflow of WT2 is relatively low, and as the distance in the X direction increases, the turbulence kinetic energy of WT1's wake does not change significantly, while the turbulence

kinetic energy at the inflow of WT3 is relatively high. This explains why the mean C_p and C_T of WT3 are greater than those of WT2 and why the corresponding data for WT2 change little with distance D . Figure 8 shows a 3D vortex structure of the tandem three turbines at 400 s based on the Q-criterion. It can be seen that the near wake of the upstream turbine is mainly composed of helical vortices shed from the blade tips. When the upstream wake reaches the plane of the middle turbine, a ring vortex forms around the rotor and then breaks down in the far wake, explaining why WT3 is significantly affected by the distance change. A large amount of scattered vortex structures from the upstream and middle turbine wakes impact the downstream turbine. The inflow wind to the midstream turbine has fewer vortex structures and is more stable, while the inflow wind to the downstream turbine has more vortex structures and is less stable.

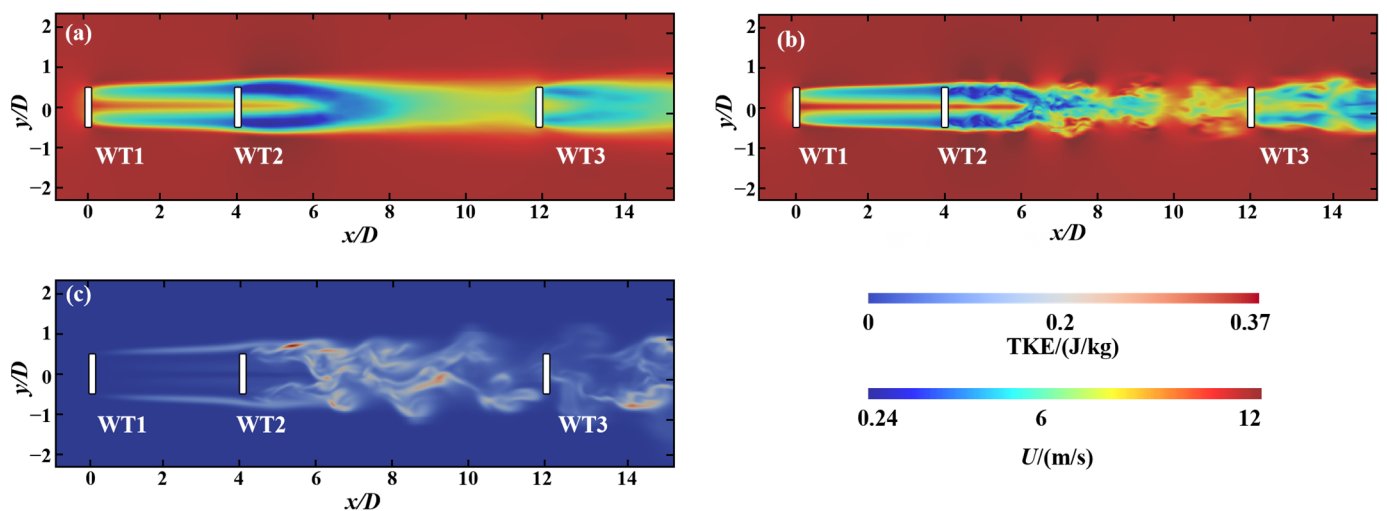


Figure 7. Diagram of time-averaged flow field distribution and turbulent kinetic energy at $z = 0$ of tandem three turbines ($L_1/D = 4$): (a) Time-averaged flow field; (b) Flow field at $t = 400$ s; (c) Turbulent kinetic energy (TKE) at $t = 400$ s.

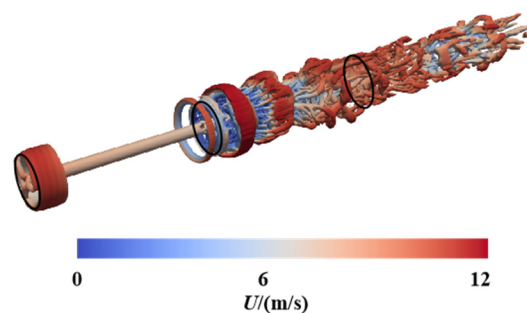


Figure 8. Three-dimensional vortical structure of tandem three wind turbines at $t = 400$ s based on the Q-criteria. The black circles denote the position of turbines.

Further examination of the wake characteristics of the tandem three turbines is shown in Figure 9, which presents the along-wind turbine wake velocity profiles at the hub height of the tandem three turbines. It can be observed that at the wake of WT1, the wake velocity profile is approximately symmetrical, with an average wind speed showing a symmetric concave shape near the centerline. At the wake of WT2, there is a certain offset in the concave areas on both sides, and the streamwise mean wind speed profile is significantly deformed with noticeable velocity losses. As $x/D > 12$, the streamwise mean wind speed gradually recovers.

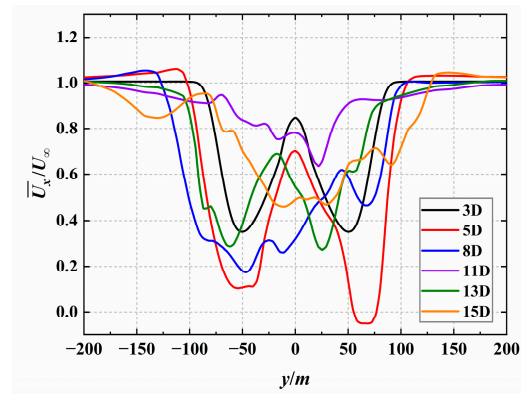


Figure 9. Downwind wake velocity profile at hub height of tandem three turbines in series.

5.1.3. Unsteady Aerodynamic Characteristics of Three Turbines under Full Wake Conditions

The time travel curves of thrust T and torque Q experienced by the tandem three turbines within the 110th rotation cycle, as computed using the LES-ALM method, are shown in Figure 10a,b. It can be observed that the thrust and torque experienced by WT1 are relatively stable, attributed to a stable inflow wind for WT1. WT2 experiences a weak periodic variation in thrust and torque due to certain disturbances from the upstream wake of WT1, with a thrust variation amplitude of approximately 2.70 kN and a torque variation amplitude of approximately 9.67 kN·m. Compared to WT1, the thrust and torque experienced by WT2 decrease by approximately 60.0% and 93.3%, respectively. WT3 exhibits a noticeable periodic fluctuation in thrust and torque, primarily due to more significant disturbances from the upstream wake; the peak frequency of this fluctuation is $f = 0.69$ HZ, which corresponds to three-times the rotational frequency f_0 of the wind turbine at $TSR = 8$, where $f_0 = \lambda U_\infty / (2\pi R) = 0.23$ HZ, due to the fact that the wind turbine used in our work consists of three blades. The physical disturbances referred to here can be referred to as the fluctuations generated by the unsteady wake flow formed by the upstream and midstream wind turbines as it flows through the plane of the downstream wind turbine, see Figure 8. The thrust variation amplitude for WT3 is approximately 68.6 kN, and the torque variation amplitude is approximately 668.4 kN·m. Compared to WT1, the thrust and torque experienced by WT3 decrease by approximately 24.3% and 44.6%, respectively.

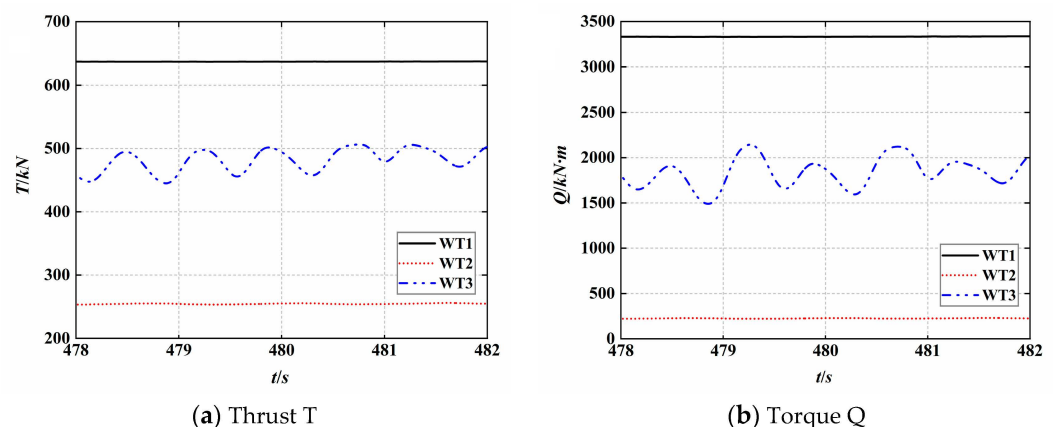


Figure 10. Time travel curves of thrust and torque for tandem three turbines ($L_1/D = 4$).

5.2. Three Turbines under Staggered Cases

5.2.1. Comparison of Aerodynamic Performance Results

Using the LES-ALM method to calculate the variations in C_P and C_T of the misaligned three turbines in Cases 2 and 3 with the spacing L_1 between the turbines, the relevant parameters, mesh density, and the full wake conditions for the three turbines in Case 1 are consistent.

The variations in aerodynamic performance of the three turbines in Case 2 with the spacing L_1 are shown in Figure 11. Figure 11a shows C_P , and Figure 11b shows C_T . It can be observed that the impact of spacing L_1 on C_P and C_T is relatively weak. Specifically, as the spacing L_1 increases, there is a stable upward trend in C_P and C_T for WT2 and WT3, but the variation remains within 1%. In the proposed Case 2, WT2 shows about a 0.2% increase compared to WT1 in C_P and C_T , and both values are higher than the corresponding parameters for WT3. The variations in aerodynamic performance of the three turbines in Case 3 with the spacing L_1 are shown in Figure 12. It can be seen that the impact of spacing L_1 on C_P and C_T of the three turbines in Case 3 is relatively small. C_P and C_T for WT1 and WT2 gradually increase with increasing L_1 , with a variation rate within 1%. In Case 3, the C_P and C_T obtained by the LES-ALM method for WT3 are higher than those for WT1 and WT2, with WT2 showing higher values than WT3. The total power of the three wind turbines in Case 3 is higher than the total power of the three wind turbines in Case 2.

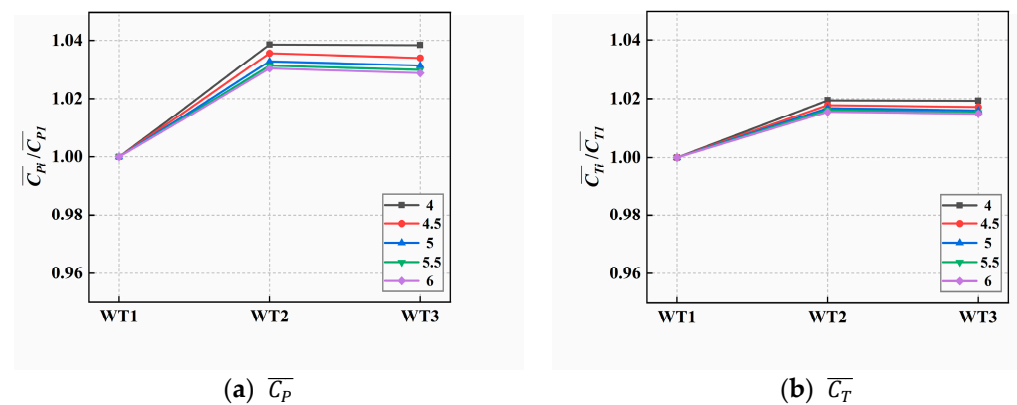


Figure 11. The ratio of $\bar{C}_P$ and $\bar{C}_T$ of three turbines at different L_1 values to those of WT1 in Case 2.

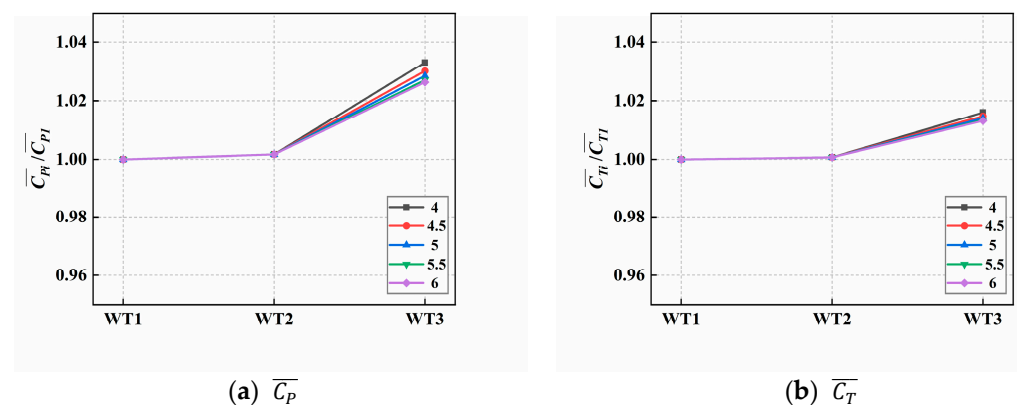


Figure 12. The ratio of $\bar{C}_P$ and $\bar{C}_T$ of three turbines at different L_1 values to those of WT1 in Case 3.

In conclusion, for the cases of three wind turbines in tandem, the optimal distance between the upstream and midstream turbines is 4D. For the staggered cases of three wind turbines, the optimal distance between the upstream and downstream turbines is also 4D.

5.2.2. Comparison of Wake Characteristics Results

Next, we analyze the wake characteristics of the staggered three turbines to explain the aerodynamic performance calculation results obtained above. Figures 13 and 14 show the average flow field distribution of the three turbines in two layout schemes (L_1 is $4D$). The left image represents the average flow field velocity contour, while the right image shows the turbulence kinetic energy results. The rectangles in the figures indicate the positions of each turbine.

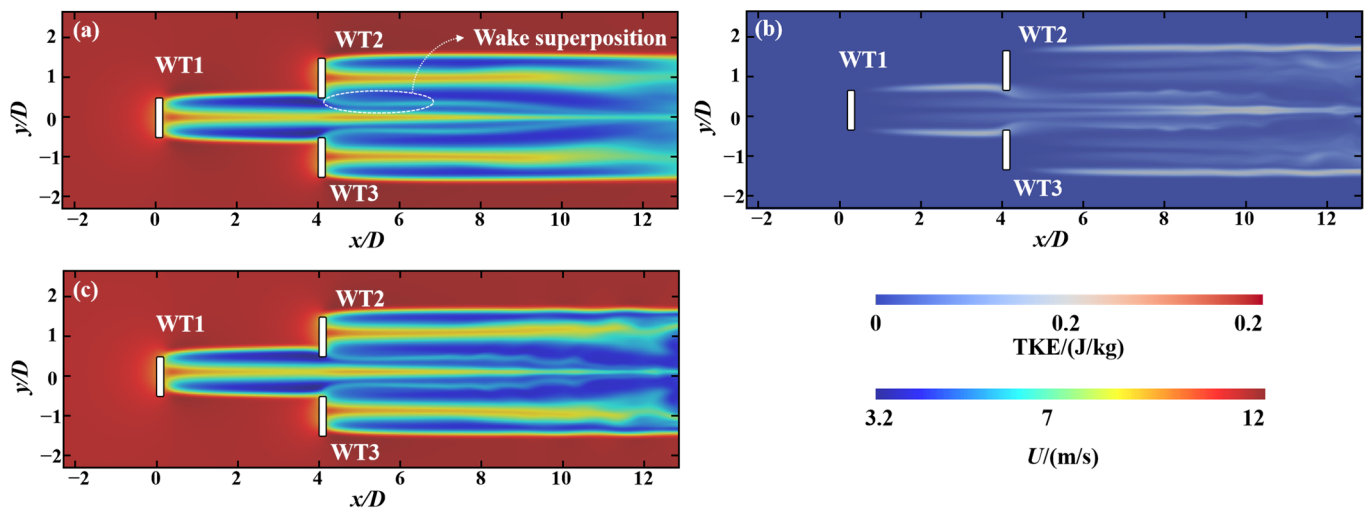


Figure 13. Diagram of time-averaged flow field distribution and turbulent kinetic energy at $z = 0$ in Case 2 of three turbines: (a) Time-averaged flow field; (b) Turbulent kinetic energy (TKE) at $t = 400$ s; (c) Flow field at $t = 400$ s.

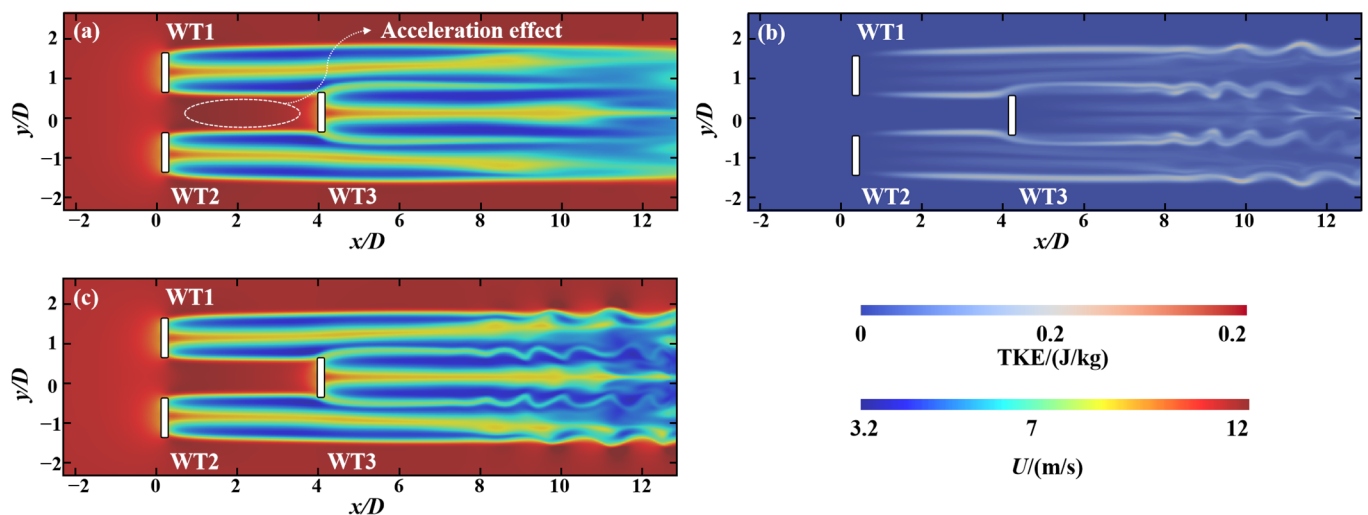


Figure 14. Diagram of time-averaged flow field distribution and turbulent kinetic energy at $z = 0$ in Case 3 of three turbines: (a) Time-averaged flow field; (b) Turbulent kinetic energy (TKE) at $t = 400$ s; (c) Flow field at $t = 400$ s.

As shown in Figure 13, the velocity contour and turbulence kinetic energy plot at $z = 0$ for Case 2 are displayed. It can be observed that in Figure 13a,c, there is an acceleration effect of the wake between WT2 and WT3 along the centerline of the two turbines, resulting in mutual interaction and a certain increase in C_P and C_T for downstream WT2 and WT3. In Figure 13b, the turbulence kinetic energy is higher on the side of WT2 and WT3 closer to the centerline of WT1, leading to significant fluctuations in the aerodynamic performance results of WT2 and WT3 due to this one-sided turbulent inflow.

Figure 14 shows the velocity contour and turbulence kinetic energy plot at $z = 0$ for Case 3. It can be seen that in Figure 14a,c, the interaction between WT1 and WT2 leads to an increase in the inflow velocity at the entrance of WT3, consistent with the relevant literature [9], resulting in increased inflow velocity for WT3. In Figure 14b, the turbulence kinetic energy is higher on both sides of WT3 at the inflow, leading to more stable aerodynamic performance results for downstream WT3. Additionally, it can be observed in Figure 14a that there is a difference in the wake velocity near WT1 and WT2 between the sides close to and away from downstream WT3, indicating the existence of interaction between WT1 and WT2.

As shown in Figure 15, the three-dimensional vortex structure of the side wake inflow layout scheme based on the Q-criteria is depicted at 400 s. For Case 2, it can be observed that the near wake of the upstream turbine is mainly composed of helical vortex structures shed from the blade tips. When the upstream turbine wake enters the inflow plane of the downstream turbine, it interacts with the vortex structures at the blade tips of the downstream turbine, resulting in the formation of ring-shaped vortices. For Case 3, the wakes of the two upstream turbines generate a pair of ring-shaped vortices on both sides of the inflow plane of the downstream turbine. These vortices interact with the vortex structures generated at the blade tips of the downstream turbine and gradually dissipate in the far wake.

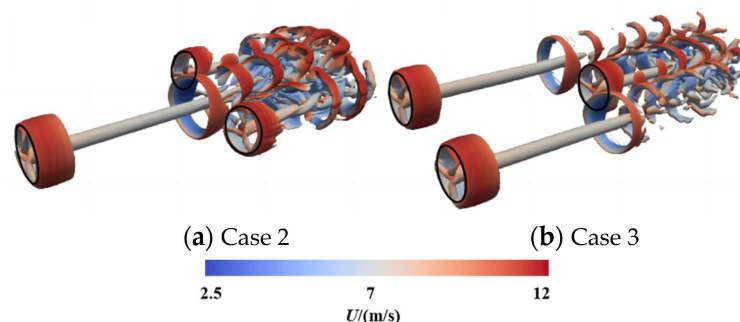


Figure 15. Three-dimensional vortical structure with three wind turbines in 400 s based on the Q-criteria. The black circles denote the position of turbines.

To gain further insights into the three-dimensional characteristics of the wake from the side-wake inflow layout with three turbines, the average velocity distribution of the wake slice in the Y-Z plane of the three turbines at different axial positions ($x/D = 1-11$) was obtained, as shown in Figure 16. It can be observed that in the near-wake region of the upstream turbine ($x/D \leq 3$), the wake velocity profile exhibits a thin-disk shape, and the magnitude of velocity deficit remains relatively constant with increasing axial distance. This explains the phenomenon where the C_P and C_T of the downstream turbine show only minor changes with the increase in spacing L_1 . In the wake region of the third turbines ($5 \leq x/D$), the interaction among the wakes of the three turbines intensifies, causing the shape of the wake velocity region to transition into a bird-head shape and a helical shape.

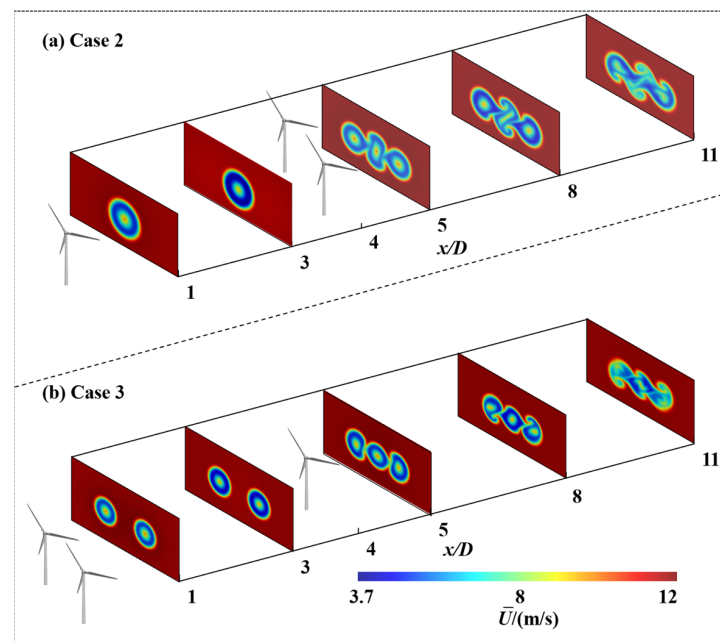


Figure 16. Average wake velocity profile of Y-Z plane wake slice at different axial positions.

5.2.3. Unsteady Aerodynamic Characteristics of Three Turbines under Staggered Conditions

Using the LES-ALM method to compute the unsteady dynamic characteristics of the three turbines under the staggered configuration with $L_1 = 4D$, Figure 17 shows the thrust and torque experienced by the three turbines in Case 2 during approximately one rotation in the 110th revolution cycle. It can be observed that WT1 experiences lower thrust and torque compared to WT2 and WT3, remaining stable. The thrust and torque experienced by WT2 and WT3 exhibit a cyclic variation with a period of one-third of a turbine rotation cycle, with significant amplitude changes. The thrust variation is approximately 27.0 kN, and the torque variation is about 248.0 kN·m, with an average value approximately 5.14% higher than WT1 for thrust and 2.46% higher for torque. The thrust and torque curves of WT2 and WT3 alternate between peaks and valleys at the same time points. The average values of WT2's $\overline{C_p}$ and $\overline{C_T}$ are greater than for WT3, confirming the conclusion that WT2's $\overline{C_p}$ and $\overline{C_T}$ are greater than WT3's corresponding data.

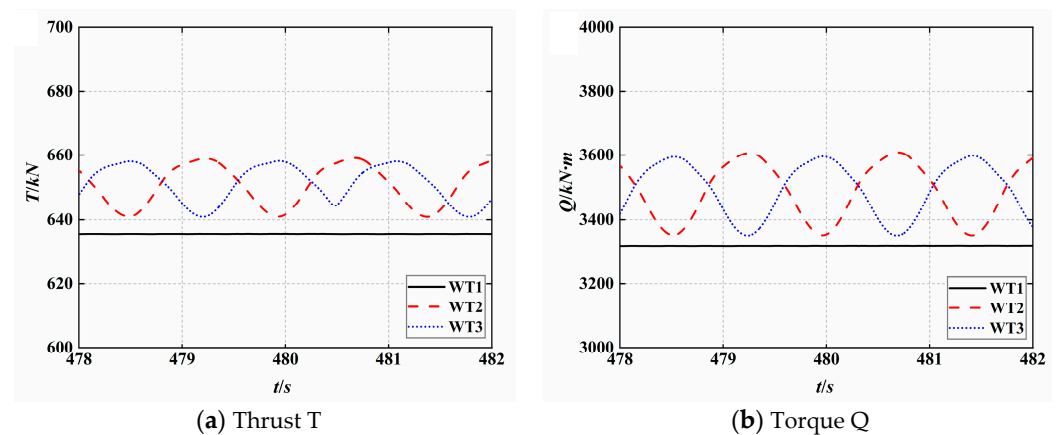


Figure 17. Time travel curves of thrust and torque for the three turbines in Case 2.

Figure 18 shows the thrust and torque experienced by the three turbines in Case 3 during approximately one rotation in the 110th revolution cycle. It can be seen that the thrust and torque experienced by WT1 are closer to those of WT2 and WT3, all exhibiting periodic

variations. The frequency of variation for WT3 is twice that of WT1 and WT2, with a thrust variation of about 5.2 kN and a torque variation of approximately 58.2 kN·m. The thrust and torque curves of WT1 and WT2 alternate between peaks and valleys at the same time points, with a thrust variation of about 5.7 kN and a torque variation of approximately 66.6 kN·m. The average values of WT2's corresponding data are greater than WT1's, confirming the conclusion that WT2's $\overline{C_P}$ and $\overline{C_T}$ are greater than WT1's corresponding data.

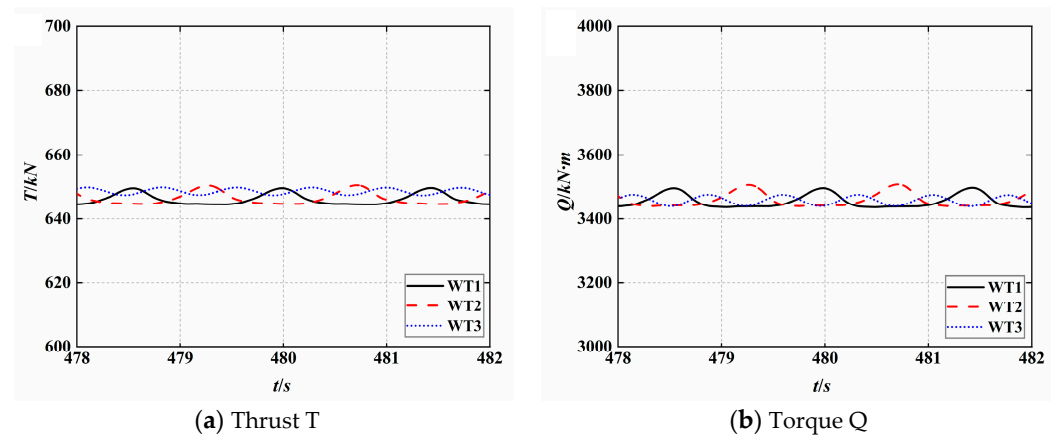


Figure 18. Time travel curves of thrust and torque for the three turbines in Case 3.

The observed fluctuations in thrust and torque are attributed to the instability of the incoming wind caused by the wake of the upstream turbine. As shown in Figure 15, the wake generated by the upstream turbine creates a substantial vortex structure at the inflow plane of the downstream turbine. In Case 3, the downstream turbine, WT3, is influenced by the wakes of both upstream turbines, which leads to fluctuations in thrust and torque at a frequency that is twice that of the corresponding data from the upstream turbines. Thus, it is anticipated that as the number of rows and columns of turbines in extensive wind farms increases, the phenomenon of wake interaction may become more pronounced. Consequently, the instability within the wakes of upstream turbines may also intensify, giving rise to these fluctuations.

To further illustrate the unsteady aerodynamic response results of blade 1 of the downstream wind turbine WT3, the time histories of the tangential and normal loads (per unit span) for WT3 in Cases 2 and 3 were obtained, as shown in Figure 19. It can be observed that the tangential and normal loads of WT3 exhibit significant fluctuations at the blade tip, while the loads at the blade root and mid-section are relatively stable. Additionally, the fluctuations in the tangential and normal loads for WT3 in Case 2 are greater than those in Case 3. These results further validate the results presented in Figures 17 and 18.

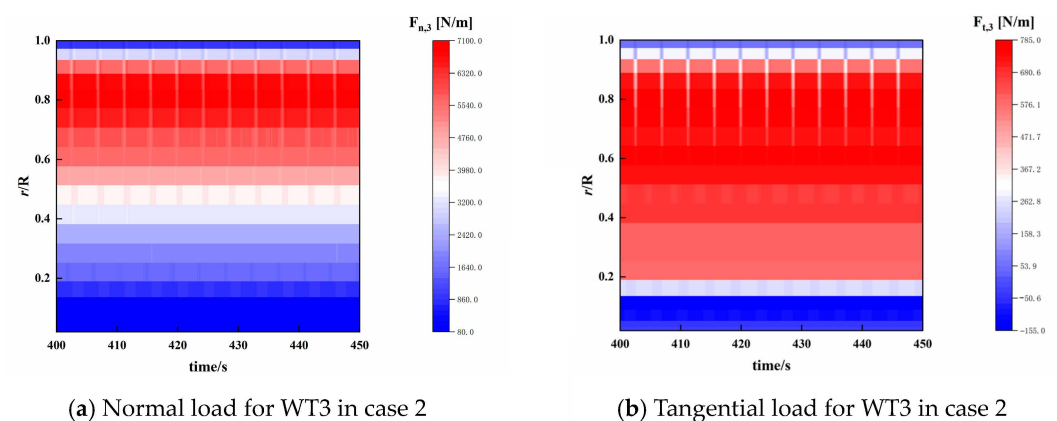


Figure 19. Cont.

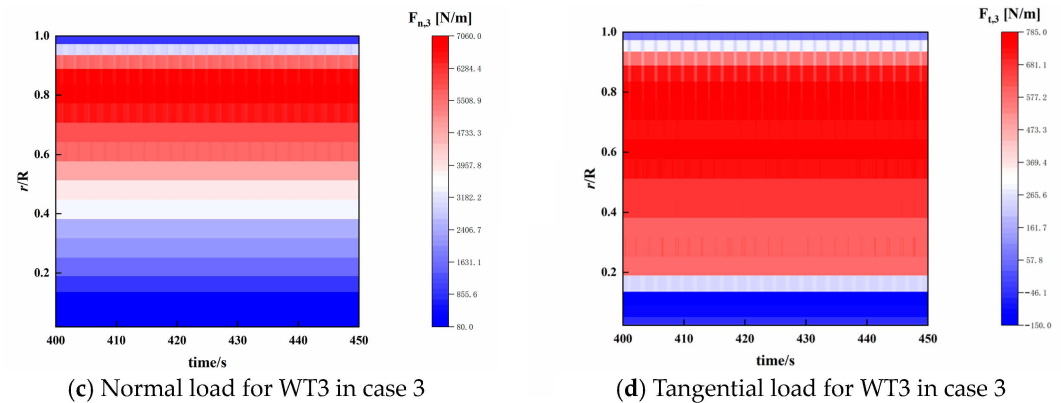


Figure 19. Spatiotemporal contour plots of tangential and normal loads (per unit span) for the WT3.

6. Conclusions

This study employs the LES-ALM method to study the power generation efficiency and wake characteristics of three turbines under different wake interaction conditions. It explores the differences and patterns of related unsteady dynamic characteristics and explains the causes of these differences through the flow field distribution and turbulence kinetic energy characteristics. By comparing and analyzing the aerodynamic performance and flow field distribution of three NREL 5 MW horizontal-axis turbines under different cases, the following main conclusions are drawn:

1. Under the full wake condition of three turbines, it is found that the spacing has a relatively small impact on the power coefficient and thrust coefficient of the middle turbine but has a significant impact on the power coefficient and thrust coefficient of the downstream turbine. Additionally, when the spacing between the upstream and middle turbines decreases, the total power of the three-turbine system tends to increase.
2. For the staggered arrangement of three turbines, the unilateral turbulent inflow to the downstream turbine causes significant fluctuations in thrust and torque, while bilateral turbulent inflow to the downstream turbine results in more stable thrust and torque. The presence of two upstream turbines causes an acceleration effect at the inflow region of the downstream single turbine, leading to a significant increase in the power coefficient of the downstream turbine.
3. Regarding wake field characteristics, the wake velocity of a single upstream turbine does not change significantly in the downwind direction. However, when the wake velocities of two upstream turbines overlap, the recovery of the wake velocity deficit in the X direction is notable.

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Abbreviations

Nomenclature

C_t	Thrust coefficient [-]
C_p	Power coefficient [-]
$\overline{C_T}$	Mean thrust coefficient [-]
$\overline{C_P}$	Mean power coefficient [-]
L_1	Distance between the upstream and downstream turbines [m]
D	Rotor diameter [m]
k^*	Turbulent kinetic energy [J/kg]
P	Power output [MW]
Q	Torque of the rotor [N·m]
T	Thrust of the rotor [kN]
S	Distance in the Y direction between the turbines [m]
U_∞	Wind speed [m/s]
$\bar{U}$	Mean wake velocity [m/s]

Greek letters

ρ	Fluid density [kg/m ³]
λ	Tip speed ratio
Ω	The rotation speed of the rotor [r/s]

Abbreviations

3D	Three dimensional
SGS	Subgrid-scale
FRM	Fully resolved mesh
BEM	Blade element momentum theory
CFD	Computational fluid dynamics
LES	Large Eddy Simulation
ALM	Offshore floating wind turbine
TSR	Tip speed ratio
TI	Turbulence intensity
RANS	Reynolds Averaged Navier–Stokes
WT1	Wind turbine 1
WT2	Wind turbine 2
WT3	Wind turbine 3

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