Qualitative Investigation of Wake Composition in Offshore Wind Turbines: A Combined Computational and Statistical Analysis of Inner and Outer Blade Sections

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Abstract. High-fidelity numerical simulations are used to thoroughly analyze the evolution of the wake behind a megawatt-scale offshore wind turbine. The wake features are classified in terms of wake dynamics composition and the associated turbulence characteristics originating from the inner and outer sections of the blades. Understanding the wake is essential for developing compact layouts for future wind farms. We employed a transient Sliding Mesh Interface (SMI) technique to analyze the fully dynamic wake evolution of the offshore NREL 5MW full turbine. Our high-fidelity results have been validated against previously published results in the literature. We thoroughly investigated the dominant structures of the wake using Proper Orthogonal Decomposition (POD) techniques, which we applied to transient simulations of fully developed flows after five wind turbine revolutions over the snapshot data. Our findings show that the inner section of the blades, which is composed of airfoils with larger cross-sections, is responsible for the dominant components of the wake, while the contribution of the wake from the outer section of the blade is significantly lower. Therefore, designing more aerodynamic sections for the blade's inner section can help reduce the dominant wake components and thus decrease the inter-turbine distance in future wind farms.

1 Introduction

Over the past decade, wind energy has experienced rapid growth due to the global demand for renewable energy resources [1].To maximize yields, wind turbines are typically placed

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in limited areas and clustered together to maximize gains [2,3]. While clustering improves and lowers the cost of energy, it also negatively impacts the aerodynamic efficiency of turbines. The wake generated by upstream turbines affects the performance of downstream turbines[4–6]. This exhibits significant challenges for designers to develop efficient layouts for wind farms that minimize the reduction in park performance due to wake effects [7]. Understanding and addressing the impact of wake effects is crucial for achieving high levels of efficiency and performance in wind parks [8].

Due to the large size of modern megawatt wind turbines, it is not viable to conduct full-scale experimental investigations to study the impact of the wake due to the limited sizes of wind tunnel facilities. On the other hand, analytical methods based on Blade Element Momentum (BEM) are still not suitable due to the high degree of approximation and simplification used in their development [9]. Therefore, numerical modelling approaches are considered more efficient due to the increasing computational capacity of modern supercomputers [10]. Recent investigations of wind turbines involve integrating simple wake models into numerical setups. One approach is to model the turbine blade with body forces represented by an actuator line or actuator disc model within the numerical setup [11]. However, such investigations may not accurately resolve turbulence characteristics and wake dynamics, leading to unreliable conclusions.

Fully resolved, high-fidelity numerical solutions of complete wind machines are essential for a state-of-the-art understanding of wake characteristics. Although this approach requires significantly higher computational effort, the results provide accurate information about wake characteristics. One approach to achieving this is through Reynolds-Average Navier-Stokes solutions (RANS) that resolve all scales in the flow field. This method reasonably estimates the scales in the flow field's operational conditions. While RANS provides an excellent overall estimation of flow characteristics, the simulation can be post-processed through statistical methods such as Proper Orthogonal Decomposition (POD), as depicted in [12]. This approach helps to investigate the dominant modes present in the flow that contain the maximum energy and can be used to analyze the flow field under different operating conditions quickly and ease the development of future wind turbines.

In the present work, we employ RANS to simulate the whole turbine geometry integrated inside the computational setup. A boundary layer mesh near the turbine is generated with highly dense prism extrusion around the structure, which resolves the boundary layer up to the *yplus* value of around 30. High-fidelity three-dimensional numerical simulations are performed with the SMI technique, and the wake is resolved with the dominant contribution of the tip and central vortex in the downstream direction. The turbulence that affects the downstream turbine is investigated in detail through quantitative and qualitative comparisons. The wake immediately behind the wind turbine comprises a regular tip vortex corresponding to each turbine blade. After a certain distance away, the vortices start to break and develop into small-scale turbulence. The POD technique checks the wake strength, and the dominant modes are analyzed with their corresponding eigenvalues. The combination of RANS and POD techniques provides a detailed analysis of the wake contribution (as presented in the article [12] from the inner and outer sections of the blades through qualitative and quantitative plots and helps identify the significant components of the wake from the blades of an offshore wind turbine. The present work is an extension of the work conducted by the authors in the study [12].

2 CFD model, mesh and solver settings

2.1 CAD model

The 5MW NREL turbine was developed using the available data provided by NREL. The model is based on three blades constructed by the Delft University and National Advisory Committee for Astronautics Airfoil series, including the DU21, DU25, DU30, DU35, DU40, and NACA64. According to NREL's report [13], the turbine nacelle is placed 87.5 meters from the ground. The tower is cylindrical in shape, with its diameter varying from the base to the point where it meets the nacelle. The CAD description can be seen in Figure 1.

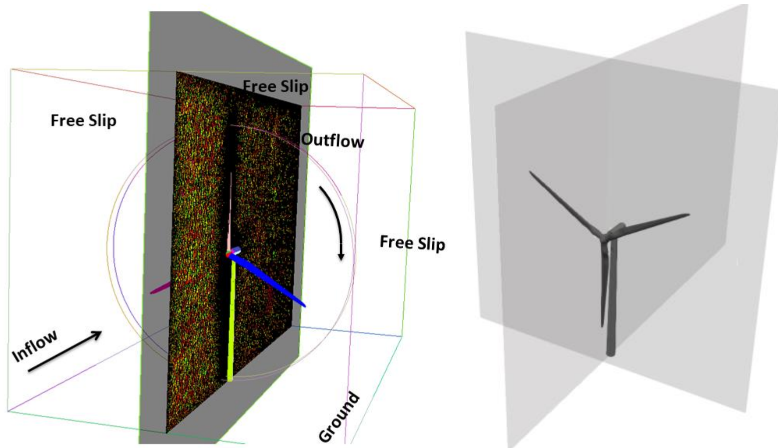

Fig 1. NREL 5MW: (left) Schematic of computational setup employed with information about boundary conditions. The extent of the domain is 5R × 1.5R × 3R. (right) Illustrates the planes for POD analysis.

2.2 Mesh boundary condition and solver details

The mesh used in this study employed a combination of tetrahedral and hexahedral cells to cover the entire domain. High-quality prisms were generated near the turbine blade to capture sharp gradients in that region accurately, and a wake block with hexahedral cells was created to analyze wake dynamics behind the turbine. The resulting mesh consisted of a total of 10^6 elements as depicted in Figure 2. *Inflow* and *outflow* boundary conditions were applied to the inlet and exit faces of the domain, respectively, to ensure accurate simulations. *No-slip* boundary conditions were applied on the turbine and ground surfaces, while a wall function was applied for the velocity components. The *k-ω SST* model was employed to compute the boundary condition for *k* and *ω* near-wall nodes. A *slip* boundary condition was applied to the lateral and top surfaces of the domain, as illustrated in Figure 1. The domain was developed using a two-zone approach, where the stationary and rotating zones were connected via an interface. The free stream velocity at the reference height was set to 9 m/s, while the turbine's rotational speed was fixed at Ω of 1.08 rad/sec to achieve a tip speed ratio (TSR) of 7.55. A reference fluid density of 1.225 kg/m^3 and dynamic viscosity of 1.82 x 10^{-5} kg/m.s were used for all calculations. The solver used in this study was OpenFOAM-2.3.0 (OF), which employs an elliptic equation for the modified pressure to ensure continuity. This equation combines the continuity equation with the divergence of the momentum equation. The elliptic, momentum, and turbulence equations were solved using the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) algorithm in a segregated manner.

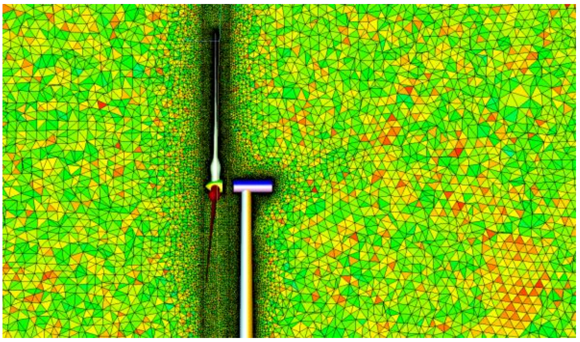

Fig 2. NREL 5MW: The computational mesh comprises tetrahedral and hexahedral elements with high-quality prisms with fifteen successive layers of refinement near the turbine geometry. A zonal approach with an interface boundary is coupling the rotating (rotor) and stationary (rest of the domain) regions. The computational grid consists of 10×10^{6} elements.

3 Result and discussion

3.1 High-fidelity solution NREL 5MW

This study analyzes the NREL 5MW wind turbine, which has a standard three-blade configuration, operating at its designed tip speed of 7.55 m/s. The turbine's rated speed is 2.8MW, and the wind speed at the hub height is estimated to be 9m/s. The simulation comprises 10 million elements and is conducted over five revolutions of turbine rotation to obtain an average solution value. To validate and verify the results, we compare our simulation results with those of [14], who conducted a Large Eddy Simulation (LES) at the same operating condition, and the results predicted by the designers of the NREL 5MW blade using FAST software. Figure 3 compares the aerodynamic torque value closely with the published results, which further confirms the accuracy of our simulation setup. For the POD analysis, we calculated 200 snapshots during the analysis, and the velocity was chosen as the field variable to generate the modes. Although the high-fidelity simulations were calculated for the mesh of 10^6 elements, the results were projected onto a uniform mesh for the statistical analysis, making the results similar for all the snapshots in the present work.

3.2 Wake characterization using POD analysis

The Proper Orthogonal Decomposition (POD) using eigenvalue decomposition is a dimensionality reduction technique that truncates the number of modes used for reconstruction in the original data field. It is considered a statistical method that provides an optimal linear subspace to determine the turbulent kinetic energy levels with optimal variance. As a result, the generated POD modes constitute a linear subspace that contains the modes with the significant energy level of the whole spectrum. One advantage of POD is that it significantly reduces the complexity of the problem and provides the basis of modes that can be used to calculate solutions at a reduced computational cost. It also helps us understand the dominant components in the flow, making it helpful in analyzing the evolution of the wake in the downstream direction, as was done in the present work using high-fidelity simulation data from the previous section to study the spatial development of the wake. For details of POD techniques and mathematical formulation, the reader is referred to the previous work by authors [12].

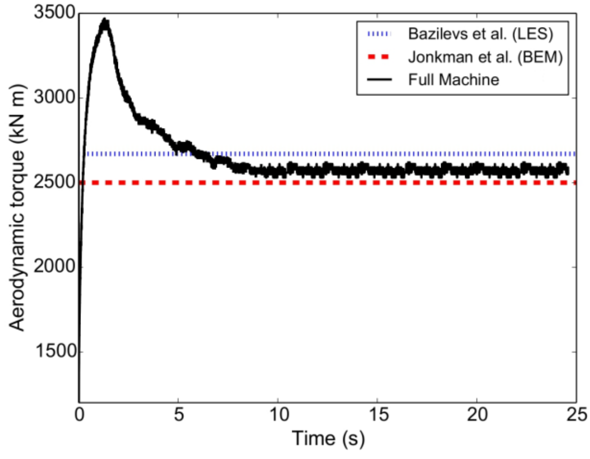

Fig 3. NREL 5MW: Validation and verification study conducted to assess the accuracy of the present numerical simulation setup against the available data in the literature [14].

Table 1. Mode eigenvalues for velocity obtained after POD

Mode #	1	2	3	4	5	6	7	8
Velocity	0.204	0.153	0.112	0.054	0.045	0.033	0.025	0.012

The POD technique was used to analyze data obtained from 200 snapshots. The first eight modes were found to have a significant contribution. Table 1 provides quantitative results for velocity, while Figure 4 presents qualitative behavior and exhibits certain essential characteristics. The figure illustrates two portions of the wake evolution, with the significant portion being located at the center of the turbine blade section. Tip vortices were identified near the tip, but their contribution was significantly lower than those generated near the center around the hub region. The large vorticity from these two distinct places starts to become less pronounced at a certain distance downstream from the turbine due to turbulent diffusion. The root structure is destroyed and begins to disappear a certain distance from the turbine.

Due to the orthogonality property of the POD modes, the second mode has a phase shift of 90º. The first four modes constitute a significant part of the energy of the wake, containing the most kinetic energy distribution and describing the optimal system. The third mode shows certain distinct regions in the vicinity of the radial directions of the turbine. The energy generated near the monopole is high, corresponding to the most significant spatial redistribution of turbulent kinetic energy between different scales. A similar investigation was performed by [15], demonstrating comparable wake characteristics in the downstream direction.

The third mode shows a well-defined region near the wake, after which the wakes energy starts to decrease. Modes four and beyond demonstrate that the spatial significance of the modes is closer to the blades' tip than the central hub. The characteristics of the vortical structure corresponding to each of these higher modes show energy decay in the inner section followed by the outer sections. Thus, the tip vortices are significantly more dominant than the central vortex of the turbine. The energy content dramatically reduces after the first seven modes, while for mode eight, distinct modes start to appear in the far wake region, indicating the impact of the central vortex on wake development. It also shows that large scales break into more minor scales, and energy dissipation is visible for the central vortex core in the far region.Therefore, the current analysis of the POD modes has evidently confirmed that the wake's spatial development and dominant modes are characterized near the central region behind the center of the turbine, where sections are composed of airfoils with less aerodynamic performance, mainly used to provide blade strength. Conversely, the outer tip vortex has a significantly lower contribution. Hence, for the generation of future wind turbines, if these sections can be developed to be more aerodynamic while retaining the required strength at the blade's inner section, it would help lower the energy cost generated from these wind turbines.

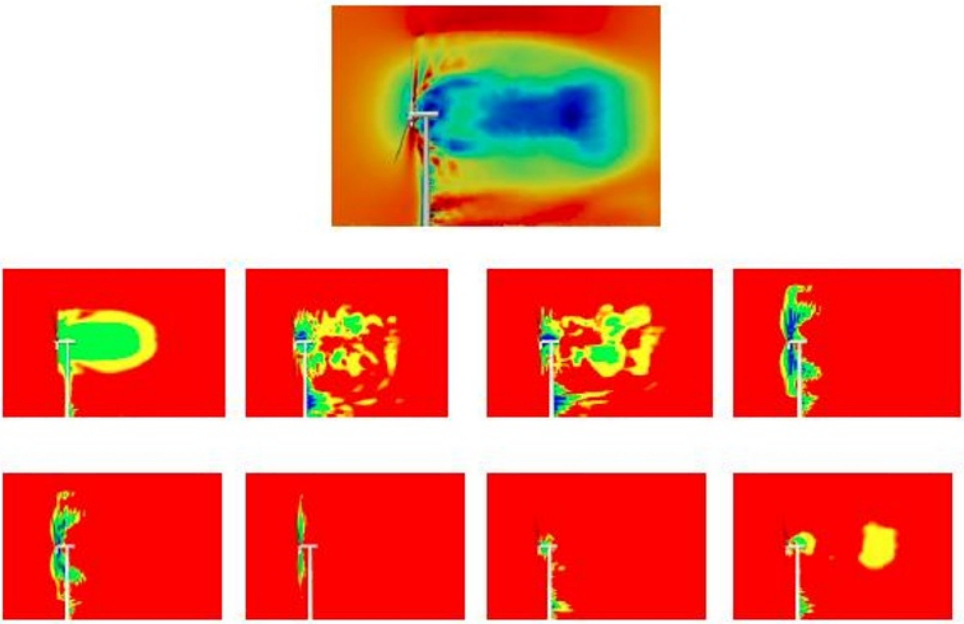

Fig 4. NREL 5MW: (top) High fidelity simulation results. The two rows show the POD modes obtained from a high-fidelity RANS analysis of the NREL 5MW wind turbine and depict the dominant modes and energy content in the flow, ranging from high to low energetic states (modes# 1-4 in row#1 from left to right, mode# 5-8 in row#2 from left to right). The spatial coherence analysis shows that the wake energy is more concentrated in the wake scales generated from the inner sections of the blades rather than in the blade tip vortices.

4 Conclusion

Reynolds Average Navier Stokes simulations were used to conduct high-fidelity simulations of the NREL 5MW wind turbine. The simulation data was then used to develop a database of snapshots, which was analyzed using the Proper Orthogonal Decomposition (POD) method to study the wake evolution in terms of its structure characterization and energy content of the tip and central vortices. The first few POD modes were determined, which capture a significant portion of the total energy inside the flow scales. The results showed that the inner section of the wake has a more outstanding contribution to the wake as compared to the outer section of the blades. The strength of the wake is more concentrated on the inner section, primarily developed to provide strength to the blade section than for aerodynamic characteristics. Therefore, for the generation of future wind turbines, significant research efforts should be put into designing the inner section carefully, which would help reduce the vortices shed in the wake from the inner section and help the wake to recover faster. Future research on the evaluation of the wake is anticipated to adopt a Large Eddy Simulation (LES) strategy to identify further even smaller scales present in the flow field to develop better estimates of how the flow field evolves over different sections of the offshore turbine blade.

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