Characterizing long-time variations in fully developed wind-turbine array boundary layers using Proper Orthogonal Decomposition

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ABSTRACT

Temporal variation of wind-farm power production is caused, in part, by the presence of large-scale flow structures in the turbulent atmospheric boundary layer. Such structures can span several thousand meters, and they interact with the wind turbines in a non-trivial fashion. The purpose of this study is to identify the flow features and characterize their evolution in time. To unambiguously identify structures in the complex atmospheric flow around a wind farm, snapshot proper orthogonal decomposition (POD) has previously been applied to thousands of three-dimensional turbulent velocity fields around an infinitely large array of wind turbines [1]. The POD analysis determined the flow structures, spanning the entire domain, that contributed the greatest time-averaged fraction of turbulent kinetic energy in the domain. The most prominent spatial features identified in the atmospheric flow using POD are classified into one of three types: roller modes, oblique modes, and shear modes. The previous study focused on entrainment of mean kinetic energy, which replenishes the flow in the fully developed region. The current study examines the time evolution of the atmospheric large-scale structures (i.e. POD modes) and their impact on power production in a fully developed wind farm.

For this analysis, large eddy simulations (LES) with periodic boundary conditions in the horizontal directions are used to simulate an infinite array of wind turbines. In cases where the streamwise extent of the wind farm exceeds the height of the atmospheric boundary layer by an order of magnitude, the wakes merge such that the flow becomes fully developed and is well represented by an infinite wind farm. In this state, there is a balance between the roughness of the wind farm and the forcing of the atmospheric boundary layer. This fully developed region, the focus of the present study, is especially relevant to future wind farms that would be necessary to reach the goal of 35% of North American electricity from wind by 2035.

The 24 wind turbines that are explicitly included in the domain, arranged in an aligned configuration, are modeled using an actuator disk method [2] with low resolution requirements that permit the simulation of large domains over very long time periods. In this analysis, the neutral atmospheric flow is simulated using the Lagrangian scale-dependent dynamic model [3] in a 3 km x 3 km domain. The simulation is driven by a constant, imposed pressure gradient and run for an equivalent of 72 hours under stationary conditions. At each time, the complex three-dimensional velocity field is projected onto a Proper Orthogonal Decomposition (POD) basis, determined from the previous analysis, to identify time-scales associated with high-energy large-scale features in the outlying boundary layer flow. The variation in time of each POD mode is represented by a single scalar coefficient, $a^k(t)$, where k is the mode number. Sample time-series for the three types of POD modes are shown in Figure 1 with each coefficient normalized by its standard deviation.

Each of the three types of POD modes is found to have a unique imprint on the time-scales of the flow. The roller modes, which contribute the most to the kinetic energy entrainment [1], have very long time vari- ations which correspond to meandering of high- and low-speed streaks in the domain. The oblique modes, which are characterized primarily by streamwise variation, capture advection of velocity perturbations, and they therefore have a dominant frequency of variation which corresponds to the mean transport time between wind turbine rows. The shear modes vary in time over long time-scales and this variation strongly correlates with power production in the wind farm. The implications of these results are addressed by considering the relationship of the POD modes to unsteadiness in wind farm power generation and fatigue loading, as well as entrainment of kinetic energy which replenishes the flow in the very large wind farms considered in this analysis.

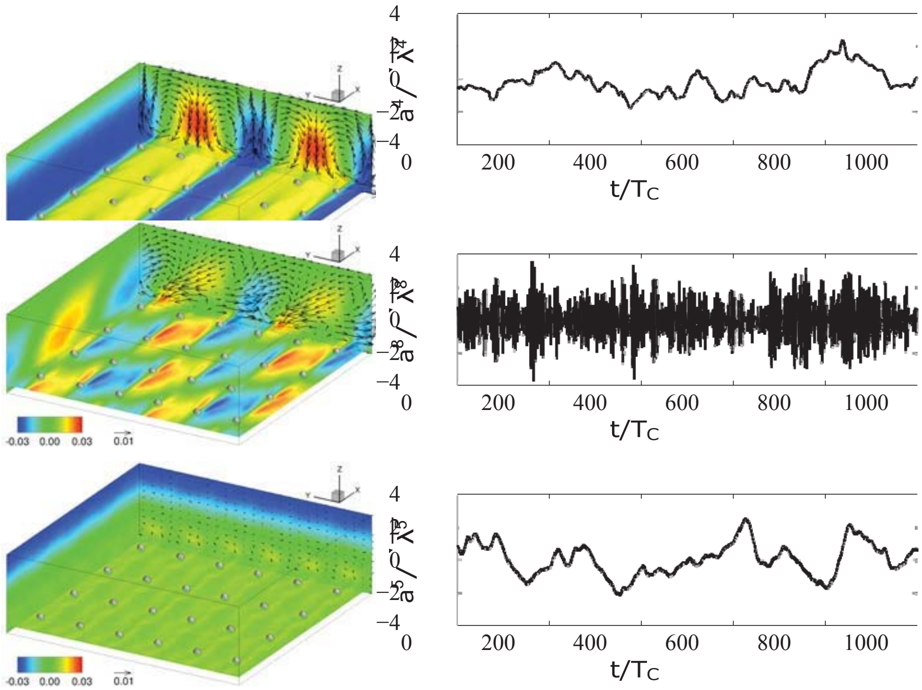

Figure 1: Temporal variation of sample roller, oblique, and shear modes is shown relative to T_C, the mean advection time between turbine rows. The standard deviation of the k^{th} POD time coefficient, $a^k(t)$, is given by the square-root of the POD mode energy, λ^k.

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