Low Dimensional Representations and Anisotropy of a Model Wind Turbine Array Versus an Array of Porous Disks

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Abstract
An array of model turbines having rotors is compared to an equivalent array of porous disks experimentally. Proper Orthogonal Decomposition as well as a characterization of the invariants of the Reynolds stress anisotropy tensor is employed to examine the structure of the flow and the attributes of the turbulence originating from the rotors and disks. The two cases differ in that the rotor displays a greater degree of large-scale spatial organization in both the near and far wake and more homogeneous values of the invariants of the anisotropy tensor than the disk case.

Keywords: *Anisotropy, Proper Orthogonal Decomposition, Actuator disk, Wind farm model*

Introduction

In many operational wind farms, turbines are spaced such that downstream turbines are influenced by the wakes of turbines further upstream. As a result, the wakes of upstream turbines influence farm characteristics and it becomes crucial to predict as well as be cognizant of the properties of these wind turbine wakes. Both experimental and computational approaches have yielded important insight into wind turbine wakes. Challenges inherent in creating equivalent computational simulations and experiments have prompted experimental work comparing rotor wakes with those arising from turbine parametrizations. In such work, porous disks have been employed as a physical analog of an actuator disk [1, 2]. In the present research, an experimental approach is used to compare and contrast the turbulence in the wakes arising from a porous disk versus a rotor when these models are embedded deep in a farm.

Methods

Experiments are conducted in the closed-loop wind tunnel facility at Portland State University. A 4x3 model turbine array having four rows of turbines in the streamwise direction is employed. Each model turbine has a 0.12 m hub height and both the model rotors as well as the porous disks have a diameter (D) of 0.12 m. A set of equivalent porous disks and rotors were created by matching the induction factor of these two devices. Stereo particle image velocimetry measurements are done 0.6D to 5.5D downstream of the center turbine in the fourth row. Further experimental details in Camp *et al.* [1].

Results

Three-component vectorial Proper Orthogonal Decomposition (POD) is performed in both the near and far wake of both the rotor and the disk. The POD reflects the organization of turbulent kinetic energy of the flow within these wakes in both a spatial and temporal sense. The three components of first POD mode are shown in Figure 1 for both the near and far wake of the rotor and the disk. Each subfigure in Figure 1 is composed of four panels with the top two panels illustrating the rotor and the bottom two panels representing the disk. The streamwise (ϕ_u) and wall normal (ϕ_v) components of the spatial components of the first POD mode are comparable. In contrast, the cross-stream component (ϕ_w) illustrates significant coherence in the rotor case, particularly in the near wake that persists into the far wake while the disk wake lacks such clear structure.

The anisotropy of the Reynolds stress tensor has played a role in both modelling and also provides a means to probe the characteristics of turbulent flows. One common approach is to describe the invariants of the normalized Reynolds stress anisotropy tensor, denoted η and ξ [3]. The invariant η represents the degree of anisotropy while ξ describes the shape of the characteristic spheroid. Figure 2 showes these two invariants as a function of wall-normal height. Notably, the invariants for the rotor case are much more tightly clustered while those for the disk have a larger range of anisotropy as well as characteristic spheroidal shapes.

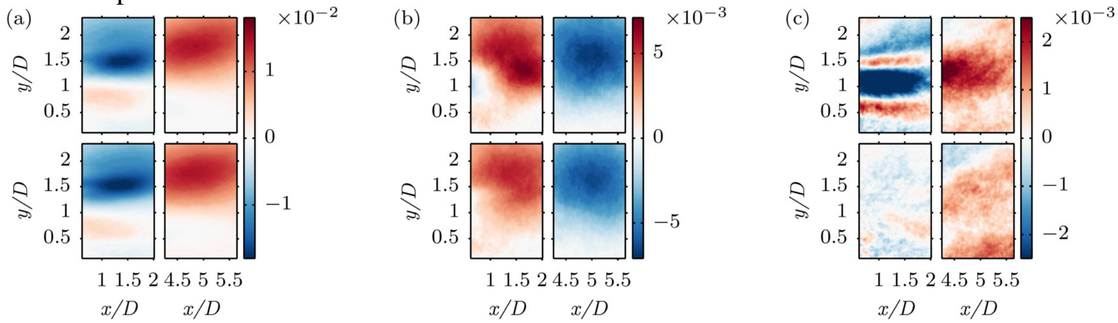

Figure 1. Components of the first spatial POD mode. (a) streamwise component ϕ_u, (b) wall normal component ϕ_v, and (c) cross-stream component ϕ_w.

The anisotropy of the POD modes themselves has been determined in order to probe the anisotropy of the structures that dominate the turbulent kinetic energy of the flow. At streamwise locations in the near and far wake, the low rank modes that contain the largest amount of energy are the most anisotropic in both the rotor and disk case while the high rank modes are the most isotropic. In both the near and far wake, the disk modes are consistently more anisotropic than the rotor. Intermediate modes tend to become more isotropic at a lower rank in the far wake than in the near wake for both cases.

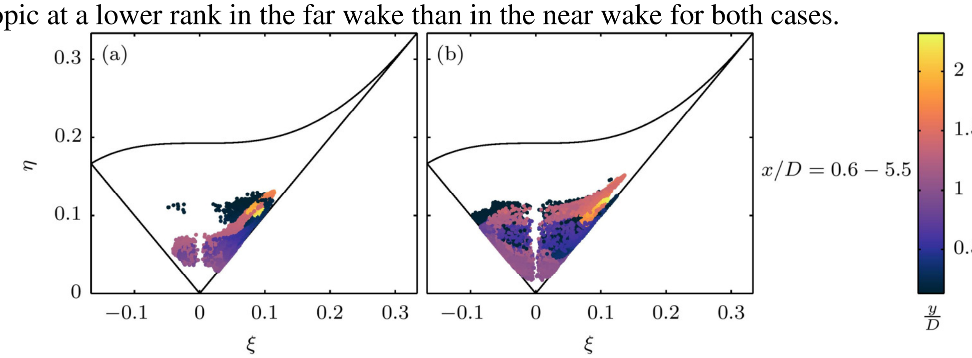

Figure 2. Invariants of the normalized Reynolds stress anisotropy tensor for (a) the rotor wake and (b) the disk wake.

Conclusions

The structure of the wakes originating from turbines having rotors and those modelled with stationary porous disks are contrasted in terms of the organization of turbulent kinetic energy via Proper Orthogonal Decomposition and in terms of their anisotropy. The first POD mode is similar spatially for the rotor and the disk in both the near and far wake in the streamwise as well as vertical components. However, the cross-stream component for the rotor exhibits marked coherence while the rotor lacks such large-scale organization. The invariants of the Reynolds stress anisotropy tensor have a larger range of values in the disk case. Furthermore, the flow is significantly more anisotropic at the top tip in the disk case which is important since this wall-normal height is key to the vertical exchange of kinetic energy. Differences between the two cases present in the far wake in both the coherence as well as the anisotropy of the turbulence are relevant to the use of the actuator disk model in computational modelling work and are expected to influence predictions on quantities such as fatigue loads.

References

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