Abstract

The low-frequency oscillatory motion of wind turbine wakes, also known as wake meandering, is crucial in wind farms as it causes the wake to "periodically" and partially impact downstream machines, thus leading to aggravated unsteady fatigue loads. The wake meandering is therefore a central and fundamental challenge for the development of reliable and affordable wind energy. This research aims at the investigation of the horizontal axis wind turbine wake meandering physics through the combination of numerical and experimental tools.

The first step to study this phenomenon is to track the wake centerline. Several methods are assessed on Large-Eddy Simulations (LES) results of the NREL 5-MW wind turbine subjected to a synthetic turbulent inflow. The most robust technique is then applied to LES performed for several inflow turbulence levels. These simulations reveal that the wake meandering amplitude increases with the downstream distance from the rotor and with the inflow turbulence level, and that the wake meandering starts closer to the rotor when the inflow turbulence level increases. Furthermore, the amplitude appears weaker in the vertical than in the horizontal plane due to the inflow anisotropy. From fairly constant wavelengths ranging between $2.75D$ and $4.0D$, Strouhal numbers between 0.2 and 0.3 are obtained using Taylor's frozen turbulence hypothesis. The strong correlations between the inflow centroid, the machine loads and the wake centroids in the near wake, and the fact that the wake meandering amplitude decreases when the inflow integral length scales are smaller, highlight the significant influence of the inflow turbulent scales on the wake meandering. In addition, it is shown that a modeling approach affordable at wind farm scale, i.e. a fourth-order finite difference code combined with a rotating actuator disk, provides equivalent results in terms of wake meandering compared to a method with a higher fidelity level, i.e. a Vortex Particle-Mesh method combined with immersed lifting lines, especially in the near wake or for the lowest inflow turbulence intensities.

Within the framework of this thesis, a complete experimental setup, including a control/acquisition board and a torque sensor system, is developed for a three-row three-column wind farm. This setup enables among others to measure the electrical and aerodynamic power produced by each machine. Time-resolved Particle Image Velocimetry (TR-PIV) measurements are performed in the horizontal plane at hub height for several configurations including an isolated wind turbine, a row of three wind turbines, a three-row three-column wind farm, and porous disks with various solidities. Each configuration is subjected to two atmospheric boundary layers (ABLs). The incoming ABLs appear to largely influence the wake meandering characteristics obtained from the wake centerlines tracked in the horizontal plane. Investigating the various configurations shows that the wake meandering increases within the row of wind turbines and that the lateral rows of the wind farm have no influence on the wake meandering characteristics of the central row. For the porous disks, the wake meandering amplitude and wavelength decrease when the solidity decreases for only one of the two ABLs, which highlights the significant influence of the inflow. From the TR-PIV measurements, wavelengths ranging between $2.75D$ and $3.75D$ were obtained, what results in Strouhal numbers ranging between 0.19 and 0.29 using Taylor's frozen turbulence hypothesis.

A modal analysis, referred to as multi-scale Proper Orthogonal Decomposition (mPOD), applied to the TR-PIV data enables to investigate the wake meandering dynamics and its dependency from the inflow.

Finally, numerical results obtained at wind tunnel scale show a good agreement with the experimental results in terms of wake meandering characteristics.