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Experimental characterization of wind turbine wakes: Wind tunnel tests and wind LiDAR measurements

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ABSTRACT

The characterization of wind turbine wakes produced for different loading conditions of the turbine and incoming wind is a crucial task for design of wind farm layout. Indeed, the optimization of the power harvested from a wind farm can only be achieved if detrimental wake interactions are carefully inhibited or mitigated. In this paper the importance of performing wind turbine wake measurements is emphasized through two experiments, which are complementary for the experimental measurement techniques used and scientific results achieved. First, wind tunnel tests of a down-scaled wind turbine are presented, for which fixed-point turbulence measurements are leveraged to predict the hub vortex instability encountered in the near wake. The second experiment consists in wind LiDAR measurements of the wake produced by a utility-scale wind turbine under different regimes of the atmospheric thermal stability. It is shown that wind turbine wakes recover faster under convective conditions than for neutral ones.

1. Introduction

Wind energy is growing in popularity and becoming one of the most profitable renewable energy source. Consequently, optimized and improved wind turbines and wind farms are needed, which require a better characterization of their interaction with the atmospheric boundary layer (ABL) flow. Of particular interest it is also the mutual interaction of wind turbine wakes within wind farms, which is responsible for reduction in power harvesting and increase in fatigue loads for waked wind turbines (see e.g. Barthelmie et al., 2010). Moreover, downstream evolution and recovery of wind turbine wakes are strongly affected by atmospheric conditions, and in particular by the ABL thermal stability (Baker and Walker, 1984; Zhang et al., 2013; Iungo and Porté-Agel, 2014).

Wind turbine wake flows have been investigated via computational fluid dynamics (CFD) techniques, with different degrees of complexity and accuracy. Early CFD tools have adopted the Reynolds-averaged Navier Stokes (RANS) approach, in which the mean flow is computed and effects of the turbulence are parameterized using closure models (Sørensen et al., 2002; Gomez-Elvira et al., 2005; Iungo et al., 2015). More recently, large eddy simulation (LES) frameworks have also been developed for wind energy applications (Jimenez et al., 2008; Calaf et al., 2010; Lu and Porté-Agel, 2010; Porté-Agel et al., 2011; Wu and Porté-Agel, 2011; Martinez-Tossas et al., 2015).

The above-mentioned numerical models need a significant amount of experimental data for their validation and optimization. Experimental fluid dynamics in wind energy mainly consists in wind tunnel tests and field measurements. Wind tunnel investigations present the advantage of reproducing a broad range of well characterized wind conditions. However, the natural variability of the ABL flow, such as for wind velocity and direction, turbulence intensity, spatial heterogeneity and thermal stability, is difficult to be entirely reproduced through wind tunnel experiments. Moreover, the used down-scaled models represent a limitation consequent to the smaller Reynolds number reproduced through wind tunnel experiments than the one for utility-scale wind turbines. The mentioned motivations largely justify the use of different remote sensing techniques to measure wakes produced by full scale wind turbines in order to characterize the real temporal and spatial evolution of wind turbine wakes. However, the large measurement volumes connected with a wind turbine wake, and the varying wind conditions still represent a big challenge for the different remote sensing techniques, such as wind Doppler Light Detection And Ranging (LiDAR). Therefore, a synergistic approach consisting in wind tunnel and field tests may allow achieving a deeper understanding on wind turbine wakes.

In this paper, wind tunnel velocity measurements of wakes produced by down-scaled wind turbine models are presented in Section 2. The turbulence data acquired for a uniform incoming flow are then leveraged to predict the hub vortex instability

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List of symbols and abbreviations

ABL	Atmospheric boundary layer
CFD	Computational fluid dynamics
d	Rotor diameter
L	Obukhov length
LiDAR	Light detection and ranging
LES	Large eddy simulations
LOS	Line-of-sight (velocity)
RANS	Reynolds-averaged Navier Stokes (equations)
TSR	Tip speed ratio
U	Axial velocity
U_{hub}	Axial velocity at hub height
U_{min}	Minimum wake velocity deficit
V_θ	Azimuthal velocity

observed in the near wake of a wind turbine. In order to extend the results obtained through the wind tunnel experiment to the wake flow produced by utility-scale wind turbines, wake velocity measurements for a 2-MW Enercon E-70 wind turbine were performed with Scanning Doppler wind LiDARs (Section 3). Specifically, those measurements allow investigating on the wake variability consequent to a different thermal atmospheric stability. Finally, discussion and concluding remarks are reported in Section 4 and Section 5, respectively.

2. Wind tunnel experiment and hub vortex instability

Velocity measurements of the wake produced by down-scaled wind turbine models were performed in the boundary layer wind tunnel of the École Polytechnique Fédérale de Lausanne (EPFL), Switzerland. The facility is an open loop wind tunnel with an inlet providing a contraction with 4:1 area ratio. Several turbulence devices consisting of coarse meshes and honeycomb flow straighteners are used to increase flow quality. The test section has a length of 28 m, a width of 2.5 m and a height of 2 m. This testing chamber provides an adjustable ceiling in order to set a negligible pressure gradient. The flow is produced by a single fan with a power of 90 kW, producing a maximum velocity of 7 ms^{-1} with a minimum turbulence level of 2%. A three-degrees-of-freedom traversing system allows probes to be positioned with an accuracy higher than 0.1 mm.

The used wind turbine model is a three-bladed GWS/EP-6030x3 anticlockwise. The rotor, with a diameter, d, of 152 mm, is connected to a DC motor with a diameter of 10 mm. The wind turbine model is mounted with a stem of height 127 mm, which is in turn placed on a vertical support with a NACA 0018 cross-section and height of 500 mm. This set-up enables the turbine to be placed outside the boundary layer, thus allowing it to have a uniform incoming flow. Typically for the tests considered here, the tip speed ratio of the turbine (TSR), which is the ratio between the speed of the blade tip and the incoming velocity at hub height, U_{hub}, is 4.7. The turbine's rotational velocity was monitored through a laser tachometer manufactured by Monarch with an accuracy of 10 r.p.m. For these tests the mean rotational frequency, f_{hub}, was 57 Hz, with average fluctuations of 2.7% of the mean value. The velocity at hub height is 5.8 ms^{-1} and the turbulence level is equal to 7%, which was obtained by removing one of the three turbulence screens located in the wind tunnel relaxation chamber. A Reynolds number of 60,800 is obtained by considering U_{hub} as reference velocity, and the rotor diameter, d, as reference length.

Measurements of three components of the velocity were performed with a customized Cobra probe produced by Turbulent Flow Instrumentation, which is a four-hole pressure probe. This probe, with an external diameter of 1.5 mm, can measure velocity fluctuations characterized by frequencies lower than 300 Hz. The maximum admissible angle between the probe stem and the wind direction is 45°. This miniaturized version of the Cobra probe allows us to obtain accuracy higher than 2% in the velocity module and 1° for pitch and yaw angles. Cobra measurements were typically carried out with a sampling frequency of 5 kHz and a number of samples equal to 2^{19}.

The reference frame used has its origin placed just behind the hub of the wind turbine, with the x-axis corresponding to the streamwise direction, positive pointing downstream. The z-axis is along the vertical direction, positive from the bottom towards the top, while the y-axis is along the spanwise direction oriented so as to produce a right-handed Cartesian coordinate system. Velocity measurements were performed from a downstream distance of 0.125d up to 20d. For each downstream location considered, two-dimensional maps were measured with an area of 1.5d × 1.5d with a spacing between adjacent points of 0.025d. Moreover, measurements over the horizontal and vertical planes passing through the hub location were performed with a higher resolution along the streamwise direction.

The velocity field of the wind turbine wake obtained via wind tunnel measurements is presented in Fig. 1. The axial velocity component is characterized by a significant velocity deficit at the wake location, which gradually recovers to the incoming wind velocity, U_{hub}, by moving downstream (Fig. 1a). The wake recovery, which is strongly affected by the performance of the turbine and turbulence characteristics of the incoming wind, is an essential feature for the estimation of the turbine separation distance within a wind farm. In Fig. 1b significant peaks of the azimuthal velocity are detected for radial positions $y/d \approx 0.15$, which are connected to the rotational velocity induced by a vorticity structure mainly oriented along the streamwise direction, referred to as hub vortex. The azimuthal velocity induced by the hub vortex rapidly reduces by moving downstream, and the hub vortex can be considered as completely diffused for downstream distances larger than 4d. Secondary peaks of the azimuthal velocity are also observed for radial positions $y/d \approx 0.5$, which are connected with the presence of the helicoidal tip vortices. The axial normal stress, which is plotted in Fig. 1c, has an enhanced intensity in the near-wake, which represents the mechanically produced turbulence due to the presence of the wake axial velocity deficit. This wake turbulent energy gradually dissipates by moving downstream, while the wake diffuses and increases its transversal width. Moreover, velocity fluctuations associated with the helicoidal tip vortices are also detected from the axial normal stress for the locations $y/d \approx 0.5$. Tip vortices diffuse by moving downstream, and for this particular experiment they start interacting with the wake core at a downstream distance of $x/d \approx 3$.

Differently, the normal stress connected with the azimuthal velocity component gradually increases by moving downstream up to $x/d \approx 1$, then it reduces further downstream. This feature indicates that the velocity fluctuations connected with the wake swirl induced by the hub vortex are not related to its turbulent diffusion. Moreover, spectral analysis of the velocity signals shows not only the presence of the spectral component connected to the helicoidal tip vortices, but also the presence of a low frequency