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Statistical characteristics of interacting wind turbine wakes from a 7-month LiDAR measurement campaign

E. Torres Garcia [a], S. Aubrun [a, *], O. Coupiac [b], N. Girard [b], M. Boquet [c]

[a] Univ. Orléans, INSA-CVL, PRISME, EA4229, 8, Rue Léonard de Vinci, 45072, Orléans, France
[b] Engie Green, Tour de Lille, Bvd de Turin, 59777, Lille, France
[c] Leosphere, 14-16 rue Jean Rostand, 91400, Orsay, France

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ABSTRACT

The present study focuses on the wakes of two wind turbines that, depending on the wind direction, experienced different degrees of interactions, by processing field wake observations made from a 7-month ground based scanning LiDAR measurement campaign. This duration ensures an acceptable statistical convergence of the ensemble-averaged flow fields obtained after a classification according to the wind speed at hub height and the wind direction, and limited to neutral atmospheric stability. The mean flow fields showed a well-defined wake evolution for all configurations. As expected, the wake centerlines are aligned with the wind direction, however when wakes are in intermediate interaction, wakes centerlines are skewed. This has been imputed to the wake center determination method, which is not appropriate to dissociate multiple wakes. For the lower degree of interactions, the mean wakes are aligned. However the standard deviation of the instantaneous wake centerlines shows the mutual influence that one wake has on the other. Obtained results showed an increase in the turbulence intensity within the wake, but an asymmetric distribution was observed. Listing the possible reasons, no plausible explanation has been found. The wake meandering had been quantified by the standard deviation of the instantaneous wake centerlines, showing that this phenomenon is amplified by the level of interactions. The velocity deficit recovery showed a good agreement with proposed models, as soon as there is no neighboring wakes. If that is the case, the velocity deficit is increased in function of the position of the neighboring rotor.

1. Introduction

One of the ongoing challenges in the field of wind energy is the correct characterization of wakes. When a wind turbine (WT) is inside the wake of another WT, the reduced incoming wind velocity produces power output losses that can reach up to 20% of the total environmental potential [1,2]. Moreover, the increase in turbulence intensity induces additional dynamic loads on blades and mast, reducing the turbine lifetime. The study of wakes has therefore generated extensive research [3] and interest, not only for the scientific community but also for wind energy developers.

Many efforts to describe wakes have been based on wind tunnel studies [4–8] and numerical simulations ([9,10]). However, these results are not compared with field measurements due to the lack of statistically converged field data. This is a major drawback since the constantly changing atmospheric conditions and features of the terrain make a huge contribution to the wake properties; hence, for an appropriate description of the wake development, structure and dynamics, long term field observations are essential [11].

Punctual sensors, mounted either on meteorological masts or on the turbines themselves, have been used to measure wakes in the field [1,2,11–13]. Li et al. [13] were able to quantify, through field experiments conducted with a rake of sonic anemometers located at 2 diameters downstream of a 10 m-diameter wind turbine, the velocity deficit in the near wake and the influence of the incoming turbulence intensity on the wake recovery. The observations showed that as the wake is a transient phenomenon evolving in space and time, a full description requires simultaneous measurements in many positions. But even respecting this requirement, this kind of set-ups is difficult to apply to utility-scale wind turbines, which are significantly larger, has a poor space resolution and is

* Corresponding author. Present address: Ecole Centrale Nantes, LHEEA, 1Rue de la Noë, F-44321 Nantes, France.
E-mail address: sandrine.aubrun@ec-nantes.fr (S. Aubrun).

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limited in wind direction that can be studied. It therefore excludes a long-term study of the far-wake evolution, taken into account the influence on the wind direction.

One of the most promising measuring techniques, that can overcome the problem of the wake's volume, is Light Detection And Ranging (LiDAR) wind profilers. LiDARs remotely sense the Doppler shift of laser light backscattered from particles carried by the wind in order to measure a line-of-sight (LOS) radial wind velocity. LiDARs measure LOS velocity in multiple radial positions in order to estimate wind characteristics [14] up to some km away from the position of the optical system. They have already been used to estimate the wind characteristics of boundary layer dynamics [15,16] and also for wake dynamics [17–20] and their usefulness has been proved. Trujillo et al. [17] were able to capture the-wake dynamics at 4 rotor diameters downstream by installing a scanning LiDAR on a WT nacelle. The wake center fluctuations were then used to validate the Dynamic Wake Meandering model developed by DTU, corroborating the conjecture that the wake behaves as a passive tracer. Rhodes et al. [18] performed field experiments with two ground-based scanning LiDARs, one capturing the inflow and the other one the wake flow at 3 rotor diameters downstream of the wind turbine. They observed strong variability of the wake flow with atmospheric stability Aitken et al. [19] performed 100-h field experiments with a ground-based scanning LiDAR, capturing LOS velocity fields through PPI scans downstream of a utility-scale WT. They elaborated quantitative procedures for determining the velocity deficit, the wake size and the location of the wake centerline and categorized the results by ambient wind speed, turbulence, and atmospheric stability. Additionally, they established an empirical law for the velocity deficit attenuation based on previous literature that will be compared to the present results. Heisel et al. [20] performed wind tunnel and field experiments with ground-based scanning LiDAR in order to study the spectral signature of the wake meandering process. They developed a specific data processing to overcome the low time resolution of the LiDAR measurement, using colocated lidar and sonic anemometer, and observed a frequency peak that scales with a Strouhal number based on the turbine rotor diameter, and that is the signature of a meandering due to shear instabilities. The second mechanism of meandering based on the large-scale turbulent eddies of the incoming flow is also studied.

Even if these previous studies had provided highly valuable information on WT wake properties and dynamics, the rather short campaign durations (a few hours to 100 h) due to equipment and test site availabilities often limit the statistical convergence of the results obtained.

The present study attempted to tackle this limitation by processing field wake observations made during a 7-month ground-based scanning LiDAR measurement campaign, with a set-up that enables to capture two wind turbine wakes up to 10 diameters downstream and for a wind sector of 40°. Depending on the wind direction, WT wakes experienced different degrees of interaction. This long measurement campaign gave the possibility to go beyond the observations and to obtain statistically converged ensemble averaged results on wake properties.

In what follows, section 2 provides a detailed description of the equipment and experimental set-up. In section 3, the measurement processing, classification and analysis are described. In section 4, the main results and observations are presented, in which the wakes were categorized by the characteristics of the undisturbed incoming wind. Finally in section 5, a summary and recommendations for future research are provided.

2. Experimental set up

The measurement campaign took place on a Wind Farm (WF) located in the north of France (Fig. 1) with measurements done 24 h a day between November 15th, 2015 and May 31st, 2016. The WF (Engie Green owned) is located on the western limit of the Ablaincourt-Pressoir municipality (Fig. 1). Seven WTs, which compose the WF, are sited from north to south and spaced approximately 3.5 D apart. The turbines are named SMV1 to SMV7, SMV1 being the northernmost. According to the historical wind rose, the wind resource comes mainly from the south west; since SMV5 and SMV6 are aligned to a 207° reference line, their positions make it possible to observe wake interactions. The SENVION MM82 WTs have a diameter (D) and hub height (HH) of D = 82 m and HH = 80 m; the WT nominal power is 2050 kW for a nominal wind speed of 14.5 m s^{-1} and its cut-in wind speed is 3.5 m s^{-1}.

An 80-m high lattice met mast is located 1.6 km northeast of SMV6 (A in Fig. 1 right), where an anemometer (at 80 m high) and a wind vane (at 40 m high) were intermittently operational during the measurement campaign. On the SMV6 and SMV5 hubs, a wind vane and an anemometer registered the conditions at WT locations (within the SCADA system).

A pulsed scanning LiDAR, Windcube 200S by Leosphere, with a

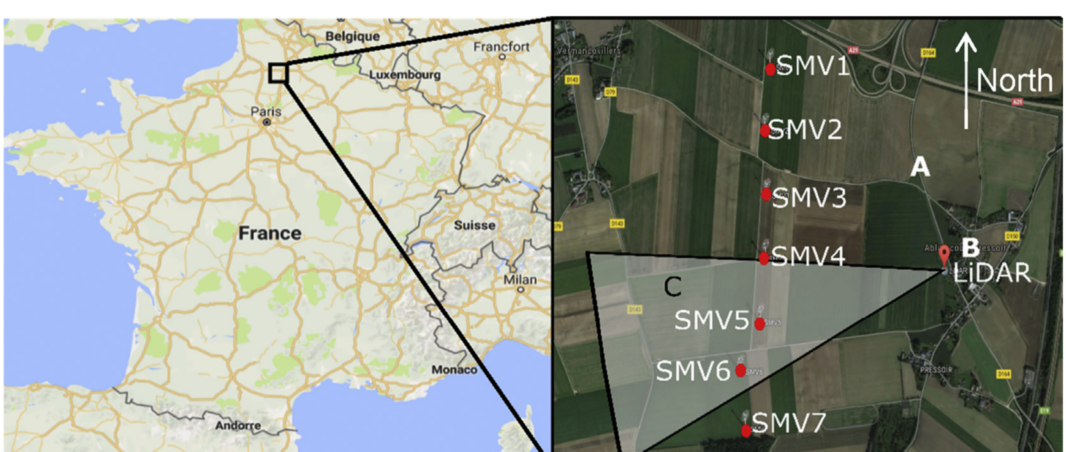

Fig. 1. Left, Map of France indicating the wind farm site. Right, the wind farm composed of seven WTs marked with red dots. A meteorological mast (A) is located in the surrounding area. The location of the LiDAR is marked with a B. The shadowed area, C, is the top view of the area scanned by the LiDAR. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)