Wind turbine wake tracking and its correlations with wind turbine monitoring sensors. Preliminary results

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Abstract. Within the frame of the French project ANR SMARTOELE, a 6-month measurement campaign has been set-up in the north of France to study the wake behaviour of two wind turbines, with an original set-up using: one ground based scanning LiLight Detection And Ranging system (LIDAR), 2 nacelle-mounted LIDARs and a nacelle-embedded 2-axis inclinometer. The present paper will give first insight into the results and describe the different post-processing strategies used to prepare the data to be cross-correlated; within the project the final objective is to characterise the influence of the large-scale atmospheric turbulent eddies on the overall wind turbine nacelle displacement and wind turbine wake behaviour.

1. Introduction and work objectives

Past research on rotor and wake aerodynamics has contributed to improve the wind energy efficiency. The aerodynamics has replaced engineering rules by a physical understanding and flow modelling. However, the understanding on the flow field in a wind farm is still on development. Many wind tunnel tests [1-4] have shown that downstream of a Wind Turbine (WT), there is a velocity deficit and a substantial increase in the turbulence intensity that moves downwards along the wind direction; such effects are globalized in the term wake. The wake affects WTs located along its way, reducing WTs efficiency, life-time and the overall wind farm efficiency; numerical simulations have been able to reproduce the wake behaviour [5, 6], until certain point, but there is still a big gap between simulations and field measurements. This discrepancy is assumed to be due to the difference between changing real flow conditions and simulated ideal uniform conditions; hence, it has become extremely important to be able to response to such changing real flow. Following this path, some field measurements have been done [7-11], where the use of wake measurements of LIDAR are used as an input for an efficient management of the WT and wind farms.

In the framework of the French national project SMARTOELE (2015-2018), control strategies are being tested, from the lab to the full scale, in order to alleviate load fluctuations that are responsible for the structural fatigue of wind turbines. The load fluctuations are, partly, due to the turbulent properties of the incoming flow and can be even more severe if a wind turbine is located within the wake of an upstream wind turbine [10]. Within the project, it is being evaluated control strategies at blade, rotor and farm scales. Different strategies are considered depending on the time scale, at shorter time scale (seconds) load fluctuations can be alleviated by active flow control on the blades; whereas at moderate time scale (tens of seconds) load fluctuations can be alleviated by pitch control [8]. A more global strategy considered in wind farm control strategies is to alleviate the wake interactions by operating...
wind turbine at non-optimum configurations and/or deviating the wind turbine wake by forcing yawed configurations. All these strategies require collecting real-time information about incoming flow fluctuations, global and local load fluctuations, unsteady wake behavior, and determine the correlations between this flow field information.

The present paper will illustrate the field measurement campaign that has been performed within the project SMARTEOLE and will give first results about the strategy used to track wind turbine wakes and about the post-processing strategies applied to the wind turbine monitoring sensors in order to look for the correlation between both data sets. The final and future objective is to evaluate if the wind turbine wake position can be assessed by only measuring the incoming flow fluctuations and/or the mechanical response of the wind turbine, as it has been shown in experimental tests[13], or if additional instruments like LIDARs would bring the necessary information with a more accurate determination of the wake position. It is expected that the data collection could contribute to the improvement of wake meandering models and wind turbine control strategies for farm management.

2. Approach and methods

The field measurement campaign started in November, 2015 and is still running. The field site is owned by Maia Eolis and is located in the Picardie Region, at Ablaincourt-Pressoir, in France (Fig. 1). The measurement campaign focuses on wind turbines SMV5 and SMV6. Wind turbines are Senvion MM82 with a hub height of 80m and a rotor diameter of $D = 82m$. According to the wind rose, the most frequent wind direction comes from the south-west and the SMV5 will frequently experience interaction with the SMV6 (207°) wake. A nacelle-mounted 5-beam LIDAR and a Wind Iris LIDAR from Leosphere/Avent are installed on SMV6 and SMV5, respectively, providing wind data up to 300m ahead each wind turbine.

![Figure 1: Field site. Measurement campaign focuses on area surrounding WTs SMV5 and SMV6.](Image)
A scanning LIDAR Windcube 200S from Leosphere is located at 1.5km on the east side of the wind turbines of interest (SMV5 and SMV6), therefore the wake of both wind turbines can be captured. Three Plan Position Indicators (PPI) have been programed. Each PPI is composed of 30 Lines of Sight (LOS) displaced 1° in azimuthal direction, at $2\,\text{s}^{-1}$ acquisition rate, each LOS is composed of 1000 pulses, the resolution along the LOS is 25m and 0.1m $\text{s}^{-1}$ velocity accuracy. Geometrical scanning parameters are summarized in Table 1. PPI azimuth angle range is chosen to capture wind turbine wakes from SMV5 and SMV6 for the most frequent wind directions. PPI elevation angles are chosen in order to cross the SMV6 hub height at a downstream distance of $2.5\,D$, $5\,D$ and $10\,D$, respectively, for southwestern wind directions (Fig. 2).

![3D representation of the PPIs](image)  

**Figure 2**: 3D representation of the PPIs. The UTM coordinates has been translated to local coordinates taken as origin of the reference system the location of the LIDAR. The yellow PPI correspond to elevation of 5.2°, while the cyan colour to the elevation of 2.5°.

SMV6 is also equipped with a Murata Electronics SCA121T dual axis inclinometer located within the nacelle, giving the unsteady inclination angles with a dynamic response of 18Hz.

1-hour averaged meteorological conditions are supplied by local Modern-Era Retrospective analysis for Research and Applications (MERRA) data, giving access to the hourly wind speed, wind direction and the Monin-Obukhov (MO) length $L$. Data are then classified according to the wind direction ($10^\circ$ sectors) and the thermal stability (neutral conditions are assessed with $|L|>1000$).

| Elevation angle | Azimuth angle | Accumulation time | Acquisition rate | Acquisition time |
|-----------------|---------------|-------------------|------------------|------------------|
| PPI #1          | 2.5°          | 248° – 278°       | 0.5s             | 2° $\text{s}^{-1}$ | 15s             |
| PPI #2          | 3.8°          | 248° – 278°       | 0.5s             | 2° $\text{s}^{-1}$ | 15s             |
| PPI #3          | 5.2°          | 248° – 278°       | 0.5s             | 2° $\text{s}^{-1}$ | 15s             |
| RHI #1          | 0° - 10°      | 255°              | 0.5s             | 1° $\text{s}^{-1}$ | 15s             |

**Table1**: Description of the LIDAR measurement protocols

At each elevation was calculated the horizontal velocity temporal mean, and the turbulence intensity is the ratio of the wind speed standard deviation in a particular location to the temporal mean wind speed in the same spatial position and calculated over each PPI.

3. **LIDAR- ground based results**

From the whole campaign the 22th December, 2015 was selected for further analysis because presented wind direction remaining almost constant with $213^\circ \pm 2^\circ$ (South-West wind) from 4:00am to 12:00am UTC. Also from 9:00am to 2:00pm UTC, the meteorological conditions reported by MERRA were particularly constant: the thermal stability conditions were neutral, with a MO length $L$ higher than...
1,000, the temperature at 10m high was $11.8 \pm 1^\circ\text{C}$, the wind speed at 50m high was $13.4 \pm 0.1 \text{ m s}^{-1}$ and the wind direction was $213 \pm 2^\circ$. During the period from 7:00am to 5:00pm UTC, the wind turbine power was curtailed to 1,600kW instead of its nominal value of 2,050kW.

Fig. 3 shows the velocity field measured during one PPI#3 set-up, and retrieved through a specific algorithm developed by Leosphere. The algorithm first retrieves the averaged wind direction and then converts the raw radial wind speed measurements into estimated horizontal wind speeds by applying a correction from the cosine of the averaged wind direction. On this PPI is noticeable the far-wake of SMV6 impacting on SMV5 and then merging into one wake, near wake of SMV6 is not captured due to the chosen elevation angle).

![Figure 3](image.png)

**Figure 3**: One PPI of velocity magnitude field measured with a scanning LIDAR, for a period with a wind direction of $213^\circ$.

Fig. 3 shows that some measures do not pass the validation process included into the Leosphere algorithm and are represented as non a number (NaN), leading to holes in the velocity flow field. In the following, the missing values were interpolated according to the neighboring velocities. In the PPI, if the flow field measured contains more than 1/5 of invalid measures, it is rejected and will not be used to compute the statistics.

As it was already said, between 9:00am and 02:00pm UTC, MERRA reported almost constant meteorological conditions (wind direction, wind velocity and temperature), hence its use for the statistical analysis. Fig. 4 shows the 5-hour mean velocity field measured at the PPI#2 (corresponding to the average of 192 consecutive PPIs with the same elevation angle). It is noticeable that the all wakes are aligned with the wind direction. The cumulative effect of the SMV6 wake impacting SMV5 to merge into a more intense wake is visible through the strong velocity deficit downstream of SMV5 (circa 40% of the velocity at hub height). The residual wake of SMV7 is still distinguishable.

Fig. 5 shows the associated turbulence intensity field. The turbulence intensity is the ratio between the standard deviation and the average of the estimated horizontal velocity from the 192 snapshots measured with the PPI#2 set-up. The turbulence production within the wakes can lead to a local turbulence intensity of 55%. One part of the SMARTEOLE project is to determine the contribution of the meandering process to these global velocity fluctuations.
Figure 4: 5-hour time-averaged velocity field measured with a scanning LIDAR during a period with a wind direction of 213° and under neutral conditions (2015, December 22, 9:00am – 02:00pm UTC). Elevation angle 3.8°.

Figure 5: 5-hour turbulence intensity field calculated from scanning LIDAR measurements during a period with a wind direction of 213° and under neutral conditions (2015, December 22, 9:00am – 02:00pm UTC). Elevation angle 3.8°.

A wake tracking analysis is applied to each PPI in order to capture the instantaneous wake location. The PPI is first rotated in order to align the streamwise direction with the axis north-south, and so the
wake trajectory, with a new coordinate system \((X_{WD}, Y_{WD})\). The procedure to calculate the horizontal wake position is the one proposed in [13] applied in wind tunnel measurements. It is based on the calculation of a weighted average of the location of the measurement locations distributed in the crosswise direction \(\pm 0.8D\) from the wind turbine position, where the weighting is chosen as the exponential of the instantaneous local velocity deficit, for the \(N\) profile points:

\[
Y_{wake}(X_{WD}, t) = \left( \sum_{i=1}^{N} \exp(Du_i(X_{WD}, Y_{WD}, t) \times Y_{WD}) \right) / \sum_{i=1}^{N} \exp(Du_i(X_{WD}, Y_{WD}, t))
\]  

(1)

The local velocity deficit, \(Du_i\), for each data point is defined as the difference between the local velocity and the maximum velocity in the selected profile. This weighting has no physical meaning. It gives more importance to locations with strong velocity deficit, which are associated to the wake itself. Additionally, it was reported in [13] that this weighting is the less dependent on the space resolution of the velocity profile. Other methods to detect the wake position are available in the literature and are often based on the fit of a Gaussian-type distribution function to the instantaneous wake deficit profile [8][14] or on the instantaneous wake boundary detection [2]. It is not discussed here whether the present method enables one to get a more precise wake position but it is not dependent of a fitting procedure that needs to determine precisely the external velocity, that might be dramatically deteriorated by the high level of local turbulence and of wind shear.

Fig. 6a shows the Ensemble-averages of the instantaneous horizontal wake positions measured downstream of SMV6 and SMV5 on 22nd December, 2015, 9:00am – 02:00pm UTC. All three PPI’s are presented. It is therefore important to remind that the PPI’s do not cross the wakes at the same locations, and so this might affect the wake tracking procedure. In the presented frame of reference, it is expected that the ensemble-averaged horizontal wake position is centered on the wind turbine location. It is mainly the case, except in the vicinity of the wind turbines. Scanning LIDAR measurements closer to a distance equal to the probed volume, in that case 75m (circa the wind turbine diameter) from an obstacle can be biased [15].

Fig. 6b shows the associated standard deviations of the instantaneous horizontal wake locations. These values are expected to be the signature of the meandering process due to the large-scale atmospheric turbulent eddies. Dimensionless with the wind turbine diameter, they are comprised between 0.15 and 0.3, which is in good agreement with previous literature [2]. It is noticeable that the standard deviation is increasing with the downstream distance after the merging of the SMV6 wake with the SMV5 wake. This behavior was also detected in the case of the cumulative wakes of two models of wind turbines immersed in a modelled atmospheric boundary layer [13]Some biased results are again noticeable in the vicinity of the measurement obstacles that are the wind turbines themselves.

4. Inclinometer-based results

Streamwise and crosswise inclination fluctuations of the wind turbine nacelle are directly obtained through nacelle-mounted inclinometer measurements. They are the signature of nacelle displacements in the streamwise and crosswise directions. Fig. 7 shows the Power Spectral Densities for 10-min time series in both components \((x, y)\). The signatures of the rotor rotation velocity and its harmonics are visible from a reduced frequency range higher than 1. It is expected that the low-frequency inclination fluctuations are induced by the response of the wind turbine to the atmospheric turbulent eddies contained in the freestream flow and larger than the rotor diameter. The time-series are therefore low-pass filtered with a zero-phase delay filtering method and 3rd-order Butterworth filter at a cut-off frequency of \(f_c \approx 0.16\text{Hz}\), i.e. \(f_c D/H_{hub} = 1\) (Fig. 6). After this filtering, the residual inclination fluctuations are 10 to 20 lower than the non-filtered ones, and are extremal inclination fluctuations of \(\pm 1^\circ\) and standard deviations of \(0.11^\circ\). These filtered inclination time series will be correlated with the incoming flow velocity time series measured by the 5-beam nacelle-mounted LIDAR (the velocity time series reconstruction is under process) in order to characterize the transfer function between both signals.
Figure 6: Ensemble-average (top) and standard deviation (bottom) of the instantaneous horizontal wake positions measured downstream of SMV6 and SMV5 during a period with a wind direction of 213° and under neutral conditions (22nd December, 2015, 9:00am – 02:00pm UTC).

Figure 7: Power Spectral Density of streamwise and crosswise inclination fluctuations (non-filtered and low-pass filtered) of the wind turbine nacelle (SMV6) (left), non-filtered and low-pass filtered crosswise inclination time series (right). During a 10 min time series with a wind direction of 213° and under neutral conditions (22nd December, 2015, 00:47:21 pm UTC).

5. Conclusions
A 6-month measurement campaign has been set-up in the north of France to study the wake behavior of two wind turbines, the original set-up uses one ground based scanning LIDAR, 2 nacelle-mounted
LIDARs and a nacelle-embedded 2-axis inclinometer. The difficulty of the present study is to correlate several signals, having different dynamic responses and being polluted by variable meteorological conditions, by the broadband turbulent scales and by the wind turbine structural response. The first processing strategies are described regarding the scanning LIDAR and the nacelle inclination measurements. The wake tracking method applied to scanning LIDAR measurements is implemented. Data preprocessing are performed in order to filter out out-of-scope time scales from the inclination time series. Unfortunately, the reconstruction of the incoming velocity time series measured from the 5-beam nacelle-mounted LIDAR is still under development.

The future steps of the study will be to perform correlation analysis between the instantaneous nacelle inclination fluctuations, the instantaneous incoming flow properties and the instantaneous wake behavior.

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