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Wind shear estimation and wake detection by rotor loads — First wind tunnel verification

J Schreiber¹, S Cacciola¹, F Campagnolo¹, V Petrović¹,
D Mourembles¹, C L Bottasso^{1,2}

¹ Wind Energy Institute, Technische Universität München, Boltzmannstraße 15, D-85748 Garching bei München, Germany

² Dipartimento di Scienze e Tecnologie Aerospaziali, Politecnico di Milano, Via La Masa 34, I-20156 Milano, Italy

E-mail: {johannes.schreiber, stefano.cacciola, filippo.campagnolo, vlaho.petrovic, carlo.bottasso}@tum.de

Abstract. The paper describes a simple method for detecting presence and location of a wake affecting a downstream wind turbine operating in a wind power plant. First, the local wind speed and shear experienced by the wind turbine are estimated by the use of rotor loads and other standard wind turbine response data. Then, a simple wake deficit model is used to determine the lateral position of the wake with respect to the affected rotor. The method is verified in a boundary layer wind tunnel using two instrumented scaled wind turbine models, demonstrating its effectiveness.

1. Introduction

The wake shed by a wind turbine is mainly characterized by a lower wind speed and higher turbulence intensity than the free stream. In a wind farm environment, a wake can adversely affect other downwind turbines, leading to reduced power output and increased fatigue loads. It has been suggested that there is a large potential in wind farm control (WFC) by means of active wake deflection or wake management [1]. For example, using a WFC algorithm for wake deflection by yawing, a CFD simulation study showed a possible increase of power production for a specific favourable configuration of more than 10% [2]. Wind tunnel experiments confirm that a power increase of the same magnitude can indeed be achieved [3]. If brought to maturity and eventually deployed in the field, such technology has the potential of leading to significant increases in energy capture and reduced loading, and might also impact the way wind power plants are designed.

Knowing the wind conditions within a wind farm is of major importance for any WFC algorithm. In fact, wake management may lead to a positive outcome if one knows the correct location of the affecting wake. On the contrary, an erroneous knowledge of the conditions may lead to a detrimental effect on power, loads, or both.

The wake position in a wind farm depends on the ambient wind direction, the conditions of the atmosphere and the neighboring orography of the terrain, and the possible misalignment of the turbine with the wind. There are several methods to measure wind characteristics. However, nacelle sensors or met-masts provide only point-wise measurements, which might not be sufficient for enabling sophisticated wind farm control. Scanning LiDAR systems on the other hand might



very effectively map the flow field, but they are not available in most wind farms yet. Another approach uses the rotor response to estimate wind properties. Based on the turbine power or torque, the rotor effective wind speed can be estimated, which gives an indication of the mean wind speed at each turbine [4]. In addition, it was shown that shear can be also detected by a linearized wind turbine model [5] or by a data driven approach based on blade load harmonics, a method that can also estimate wind direction [6, 7].

In this paper a method is proposed for estimating the position of a wake relative to an affected wind turbine rotor. The method first estimates the local wind speed and horizontal shear using measured blade root bending moments, as more fully described in Ref. [8]. Then, by using a model of the wake deficit, the wake position is determined. The paper first formulates the proposed approach and then experimentally demonstrates it by using scaled wind turbines operated in a large boundary layer wind tunnel. Experiments included several different operating conditions, characterized by different degrees of wake interference between an upstream and a downstream wind turbine. Results give evidence of the fact that the horizontal shear and relative wake position experienced by a waked turbine can be estimated in operation.

2. Formulation

The method relies on measurements of the blade root bending moments, which are typically available on modern MW-turbines. By the definition of a cone coefficient, these loads are correlated with the local effective (LE) wind speed at the rotor blade. This is a similar approach to the well-known method based on the power coefficient, where torque is correlated with the rotor effective wind speed.

The cone coefficient is defined as

$$C_{m_0}(\lambda_{LE}, \beta, q) = \frac{m(\psi)}{\frac{1}{2}\rho AR V_{LE}^2}, \quad (1)$$

where λ_{LE} is the local effective tip speed ratio, β the pitch angle, q the dynamic pressure, m the out-of-plane root bending moment of the blade occupying the azimuthal position ψ , V_{LE} the local effective wind speed, ρ the density of air, A the rotor disc area and R the rotor radius. Based on the knowledge of the measured loads and other operational parameters, Eq. (1) can be solved at every time instant for the V_{LE} wind speed.

Next, the LE wind speed of each blade can be used to calculate average velocities in predefined non-rotating sectors on the rotor disc. By choosing four equally sized quadrants, four sector effective (SE) wind speed estimates on the rotor disc (left, right, top and bottom quadrant) can be inferred.

The observed SE wind speed can be further processed to estimate a horizontal shear coefficient κ_{lin} , defined by

$$V(y) = V_h \left(1 + \kappa_{lin} \frac{y}{R} \right), \quad (2)$$

where $V(y)$ is the longitudinal wind speed at the lateral position y , and V_h the wind speed at the hub. For linear shear profiles, it was shown that the SE speed represents the wind speed sampled at about $2/3R$ [8]. Assuming that the hub wind speed is known through a rotor effective (RE) wind speed estimate ($V_h \approx V_{RE}$), one can then infer the linear horizontal shear coefficient $\kappa_{lin,obs}$ as

$$\kappa_{lin,obs}(t) = \frac{V_{SE,left}(t) - V_{SE,right}(t)}{4/3V_{RE}(t)}. \quad (3)$$

Based on the knowledge of wind conditions as the ambient turbulence intensity (TI) and wind speed, engineering wake models [9] can be used to estimate the wake shape and its speed deficit. In turn, one can calculate the expected shear $\kappa_{lin,exp}(d)$ and expected rotor effective wind speed

$V_{\text{RE,exp}}(d)$ that a turbine operating within the wake at a given lateral distance d to the wake center should be exposed to. The idea is then to match expected and observed shear and rotor effective wind speed, in order to estimate the lateral distance d of the wake. This is obtained by solving the following optimization problem

$$\min_d \left(\begin{bmatrix} V_{\text{RE,obs}} - V_{\text{RE,exp}}(d) \\ \kappa_{\text{lin,obs}} - \kappa_{\text{lin,exp}}(d) \end{bmatrix}^T \begin{bmatrix} \frac{c}{V_\infty^2} & 0 \\ 0 & \frac{1-c}{\kappa_{\text{ref}}^2} \end{bmatrix} \begin{bmatrix} V_{\text{RE,obs}} - V_{\text{RE,exp}}(d) \\ \kappa_{\text{lin,obs}} - \kappa_{\text{lin,exp}}(d) \end{bmatrix} \right), \quad (4)$$

where scaling is performed by weights based on the mean ambient wind speed V_∞ and a reference shear κ_{ref} , while $c \in [0, 1]$ allows one to give more emphasis to one term or the other. For example, the actual value of V_∞ can be set to the low pass filtered RE wind speed estimation of the first row of wind turbines, while κ_{ref} can be set to the maximum expected shear.

3. Results

The present method was verified with two scaled wind turbines (termed **G2s**, for **G**eneric wind turbine, **2** m diameter) operated in one-to-one interference conditions within in the boundary layer wind tunnel of the Politecnico di Milano [10].

Each **G2** is managed by a torque-pitch controller and a supervisory system, similarly to a full scale machine. The **G2** wind turbine has a hub height of 1.7 m, and a rated rotor speed of 380 rpm (clockwise rotation). The machine is equipped with three blades each housing, in the hollow root, its own pitch actuator commanded by an electronic control board mounted on the shaft. The shaft rotates on two bearings, held by a rectangular carrying box and it is instrumented with strain gages to measure torsional and bending loads. Similarly, each blade root is equipped with strain gages that measure bending moments. The transmission of all electrical signals from the rotating system to the fixed one and vice versa is provided by a slip ring. At the tower base a balance provides measurements of the three force and three moment components. The general arrangement of a one-to-one interference condition realized with two **G2s** is shown in Fig. 1.

The rotor blades were designed using special low-Reynolds airfoils. The aerodynamic performance of the rotors was measured, for different values of the airfoil Reynolds numbers, by operating the models at several combinations of tip speed ratio (TSR) λ and collective pitch settings β . Measurements were then corrected for wall blockage [10]. Non-negligible differences were observed between the experimentally measured and theoretical Blade Element Momentum (BEM)-based rotor aerodynamic performance computed using nominal polars. To correct for this problem, an identification procedure [11] was used to calibrate the nominal airfoil polars obtained by other authors from wind tunnel measurements or numerical simulations. Based on this calibrated polars, the cone coefficient of the turbines was computed with an aeroelastic turbine model implemented in the simulation environment **Cp-Lambda** [12].

The ambient wind tunnel mean wind speed was measured with a pitot tube and set to $\bar{V} = 4.8$ m/s, which represents an operating condition below rated wind speed. By placing spires at the wind tunnel inlet, a turbulent flow characterized by a TI of 8% and a vertical shear with power law exponent $\kappa = 0.26$ could be modeled. The second turbine was placed four diameters (4D) downwind of the first turbine at different lateral displacements.

To establish the reference against which to compare observations, this study directly utilizes wake measurements instead of an engineering wake model. In order to define the expected shear $\kappa_{\text{lin,exp}}(d)$ and wind speed $V_{\text{RE,exp}}(d)$, the mean wake wind speed was measured 4D downstream of an isolated turbine along a horizontal line at hub height, by using triple hot wire probes. Figure 2a shows the nondimensional longitudinal wind speed measurements, together with a symmetric Gaussian fit. Therein, each measurement point represents a 60-second recording at a sampling frequency of 100 Hz. The wake center is located at a small lateral distance

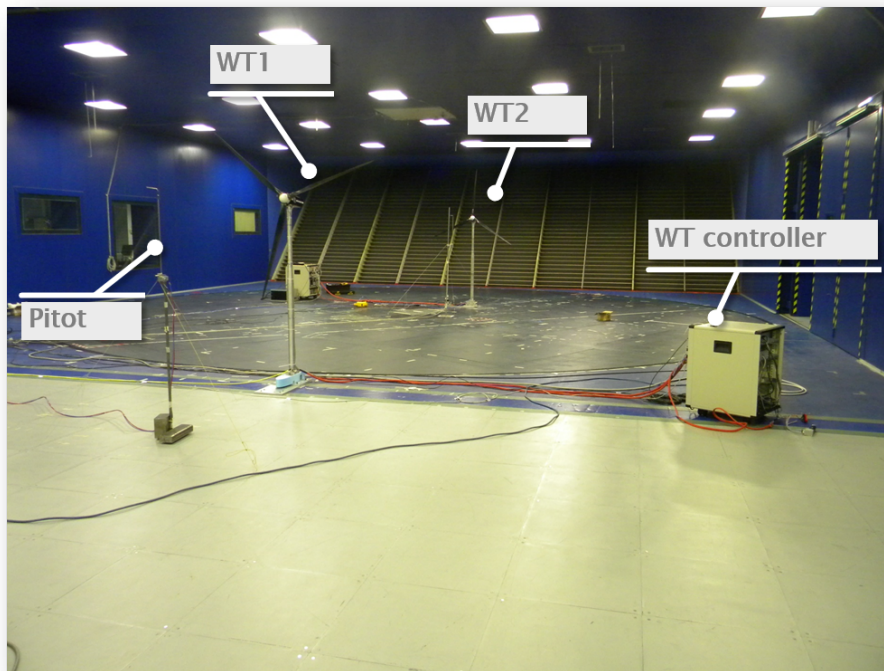


Figure 1: G2 models for one-to-one interference conditions.

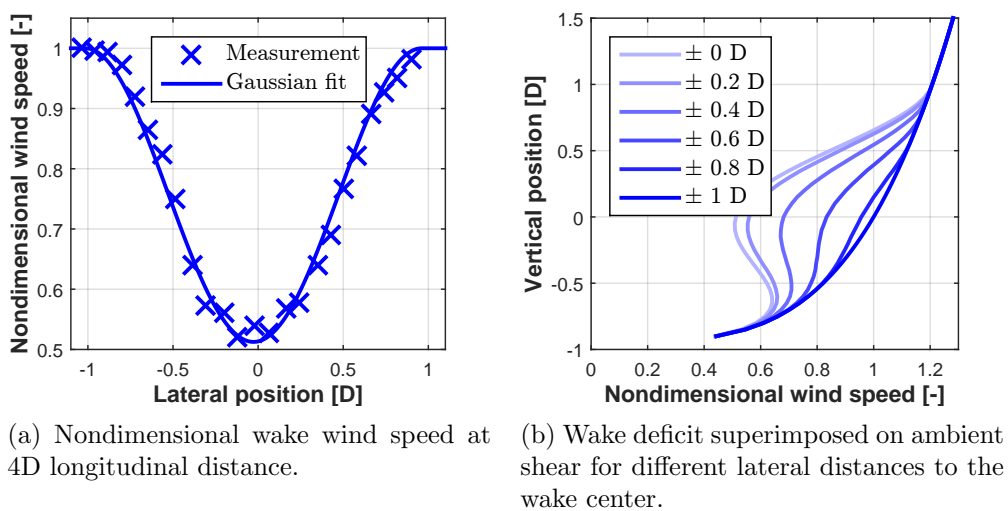


Figure 2: Wake measurements and symmetric wake modeling.

$d_0 = -0.03 D$ with respect to the upwind turbine. This translation is believed to be caused by several effects, including the complex aerodynamic interaction between wake rotation and vertical shear as well as the up-tilt of the turbine. Assuming a rotationally symmetric wake, the Gaussian fit is superimposed to the ambient shear as shown in Fig. 2b. Based on this wake shape, a least squares algorithm is used to calculate the expected shear $\kappa_{lin,exp}(d)$ and wind speed $V_{RE,exp}(d)$ that should be experienced by a turbine operating in that wake at a given

lateral displacement to the wake center d .

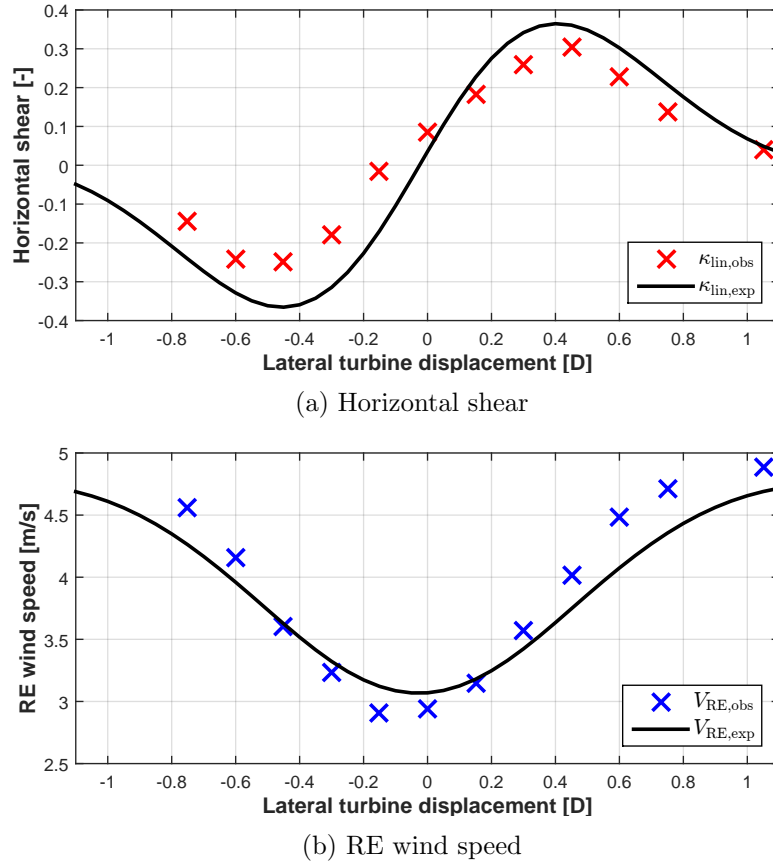
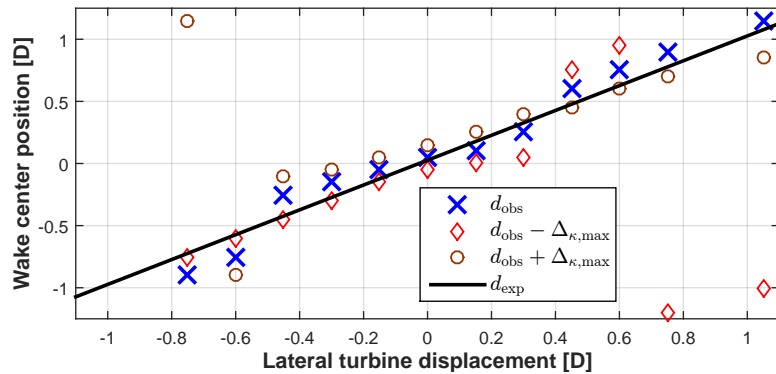


Figure 3: Estimated and expected wind properties for a turbine operating in the wake of an upstream turbine at different lateral turbine displacements.

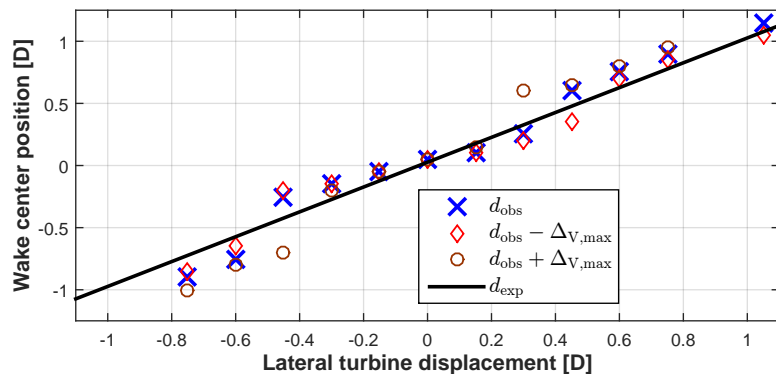
Figure 3a shows the expected shear $\kappa_{lin,exp}$ as a function of the lateral turbine displacement. For a turbine displacement of 0D the expected shear is slightly positive due to the small lateral displacement of the wake center described above. For 12 different lateral downwind turbine displacements, the average observed horizontal shear $\kappa_{lin,obs}$ (see Eq. (3)) is also displayed. The expected and observed shear correlate well, even though the observed absolute values tend to be smaller than the expected ones (maximum absolute error $\Delta_{\kappa,max} = 0.15$). This might be caused by estimation errors as well as by the simple approach used here for modeling the wake. Most importantly, the downwind turbine itself certainly affects the wake development, so that the expected wind properties used by the algorithm might differ from the real ones.

Figure 3b shows the expected and observed RE wind speed using the torque balance estimation. Both show a good correlation, but small errors are present also in this case ($\Delta_{V,max} = 0.40\text{m/s}$), due to the same reasons noted above.

By solving Eq. (4) (with $V_{\infty} = 4.8 \text{ m/s}$, $\kappa_{ref} = 0.3$ and $c = 0.5$) the wake center position d_{obs} can be estimated. Results are reported in Fig. 4a using blue cross symbols. In addition, the same plot reports results obtained by polluting the shear estimates with errors of $\pm\Delta_{\kappa,max}$. As a reference, the figure plots also the expected wake center position d_{exp} , which is the sum of the lateral turbine displacement and d_0 . As expected, a significant error in shear estimation can lead to a wake center position estimate on the wrong side of the wind turbine, especially for a



(a) Wake center position with pollution in observed shear.



(b) Wake center position with pollution in observed RE wind speed.

Figure 4: Estimated and expected wake center position at different lateral turbine displacements.

large lateral turbine displacement. Nevertheless, in most instances the observed and expected wake positions correlate well.

Figure 4b shows the observed RE wind speed, including the effects of errors of $\pm\Delta_{V, max}$. Here again, the observed and expected wake positions correlate well.

4. Conclusions and outlook

The paper has presented a simple algorithm to determine the lateral position of a wake impinging on a wind turbine. Experimental results obtained in a large boundary layer wind tunnel show that the estimated wake center position correlates well with the expected one even in the face of uncertainties, showing the robustness of the presented method.

Estimation errors are likely to be caused by the reference wake characteristics used for detecting the position of the wake. In fact these quantities were here based on the symmetric wake model of an isolated wind turbine, while it is clear that the real wake is not exactly symmetric and it is in general distorted by the interaction with the downstream machine. The hypothesis that reference quantities are the main culprit of estimation errors is supported by a recent simulation study [13] which, not being affected by such effects, was in fact able to achieve very accurate wake position estimates. To overcome these uncertainties, results from wind tunnel experiments with a scanning LiDAR will be used in a continuation of this work, together with an ongoing CFD simulation study.

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