Presented at DEWEK 2010, 17th-18th November 2010 in Bremen, Germany (www.dewek.de)

Validation of a dynamic meandering model with near wake lidar measurements

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Summary
An important effect on the fatigue loading of wind turbines in wind farms is the dynamic change of full and partial wake inflow. A simulation approach of the so-called wind turbine wake meandering based on a Lagrangian model is proposed. This enables the generation of time series of the large scale wake movement at selected downstream stations. Simulations of the wake meandering of a 5MW wind turbine are compared with measurements of the meandering in the near wake. The measurements are performed with a lidar installed at the nacelle and are analyzed with specific techniques developed for the measurement of large scale wake dynamics.

1. Introduction

Wind turbines operating in wake are affected by an inhomogeneous wind field which is more turbulent than under free conditions. The complexity of the flow depends not only on the operating characteristics of the upstream turbine(s) but also on the constantly changing atmospheric conditions. Lately, different research activities in wind tunnel and in full field [1, 2, 3] have shown evidence that the so-called wake meandering is mainly influenced by the large-scale turbulence characteristics of the atmosphere. This phenomenon is characterized by a non-regular movement transversal to the wake mean axis. This affects downstream turbines in ways which are not reproducible by calculations based on current standards for wind turbine design [4].
In this context, there is need for better estimation of wake meandering in a steady and dynamic sense. The statistics of the wake transversal position with respect to the center of the downstream rotor can be used to study fatigue of individual components [5]. A simulation approach to capture these statistics has been proposed as the Disk Particle Model (DPM) [6]. On the other hand, the dynamic meandering can be applied in wind turbine simulation for quantification of the dynamic response of individual wind turbine components.
This paper proposes an extension of the DPM to assist in the estimation of the dynamic wake meandering. The paper shows first the description of the new approach for generating time series of large scale movements of wind turbine wakes. Next, a full field measurement technique for capturing wake dynamics with lidar is explained, and finally results of simulations and measurements are compared.

2. Dynamic meandering of wind turbine wakes

2.1. Dynamic meandering model

The approach proposed in this paper aims at generating realistic meandering time series based on the DPM. These can be eventually used for aeroelastic simulation following a similar philosophy as Risø's the dynamic wake meandering (DWM) model [7].
The DPM has been proposed to assess the statistics of the meandering amplitude at particular downstream distances. It can be applied under different stability conditions. The model is based on the assumption that atmospheric turbulent length scales affect differently the dynamics of the wake. Turbulent structures with scales smaller than the rotor act in a local way enhancing momentum exchange inside the wake. In contrast, scales in the order of magnitude of the rotor and greater make the wake meander. This separation of scales has been applied in the DPM [6]. In its formulation the interest is concentrated initially on the large scale effects. It is assumed that the wake is translated passively by large scale atmospheric turbulence. Mainly the wake is assumed to advect downstream and move transversally in planes perpendicular to the main axis passively as a plume would do.
The wake is idealized as a chain of disk volumes which are emitted downstream from the rotor with no interaction among them (see Figure 1). An analogy disk-particle is proposed and the position in time is tracked with a Lagrangian particle model. A trajectory is recorded as a function of time $\boldsymbol{X}_i\ t{:}\,t_0,X_0$ for each disk-volume. The initial wind speed components U_0 are prescribed at emission time (t_0). Finally, a proper number of disks are emitted downstream in an organized way and their deviation from the wake centre is recorded at particular downstream positions.

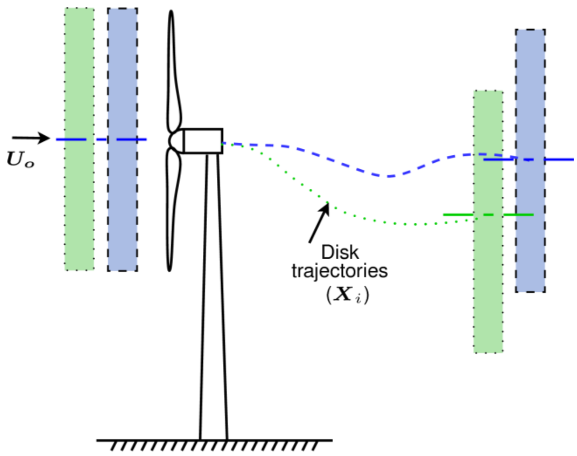

Figure 1: Idealized representation of disk volumes advecting and meandering downstream in the wake of a wind turbine.

The initial time series can be obtained from a stochastic wind field generator or directly from measurements (see Figure 2). In the case of this research the initial conditions are taken from measurements of a meteorological mast located in front of the turbine. This should enable to perform qualitative comparisons between the simulations and the lidar measurements of meandering.

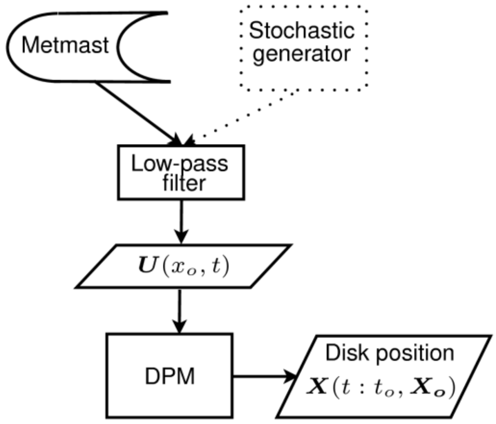

Figure 2: Sketch of process of generation of meandering time series with the DPM using synthetic or measured initial conditions

The pre-definition of initial speed from inflow measurements gives the simulation method a semi-deterministic character. Strictly speaking a comparison between simulated and measured meandering is not possible. However, the effect of the stochastic part of the model is expected to be slight in the region near the disks source. In the case of the DPM this implies that simulated and measured meandering in the near wake region can be compared directly in the time domain. Therefore, similarities could be expected from the qualitative point of view not only for the statistics but also in a unsteady sense over a period of ten minutes.

2.2. Relevant time and spatial scales

The application scope of the model is the description of wake movement over distances whcih are relevant for loading effect originating from individual wakes. The typical separation of turbines in wind farms today is around five to eight diameters in the most frequent wind direction sectors. At such distances the wind speed of a single wake is expected to have recovered in great part so that the moving wind speed deficit in front of the downstream turbine has recovered in high degree. This depends on the atmospheric stability conditions, the inflow wind speed and the operating conditions of the turbine. Mainly, stable atmospheric conditions result in more persistent wake deficits compared to unstable stratification. Moreover, the wake wind speed deficit is directly related to the thrust coefficient. Under normal operational conditions, the wake effects reduce when the turbine (pitch or stalled controlled) reaches its nominal power production. At this point the thrust coefficient of the turbine goes down as a consequence of power control. In consequence, the highest thrust coefficient, and therefore the highest wake effect occurs almost over the entire partial load range. Taking this into account a value of the maximum characteristic time can be estimated for the transport of the mean flow downstream. Mainly assuming Taylor's frozen turbulence hypothesis, a signal measured at an upstream position will be seen downstream with a time delay equal to $\Delta T = L_{1-2}\ u_0$ with u_0 being the mean longitudinal wind speed and L_{1-2} the distance between both observation points. An approximate maximum time offset of 20s per diameter separation is found considering a typical cut-in wind speed of around 5m/s and a rotor diameter of approx. 100m.

In contrast, Lagrangian models, used for dispersion studies, are applied for far distances from the source and for large time scales in the order of several minutes or hours. Hence, the computation in the DPM is comparatively faster. However, in order to speed up more the calculation, a pool of disk trajectories ($\boldsymbol{X}_i$) is precalculated. The travel time of a disk is equivalent to the time needed for the mean flow to reach a defined downstream location. The trajectories are stored in look-up tables and are sorted with respect to the horizontal and vertical initial speeds v_0 und w_0, respectively. Finally, a proper trajectory is selected from the pool for each disk-volume.

2.3. Simplified modelling in near wake

For the case of near wake, it has been observed that the disks preserve their initial path. Therefore, the calculation in this area can be simplified to straight trajectories keeping initial emission conditions. The downstream position of the wake center $\boldsymbol{X}_i = (x_i, y_i, z_i)$ at time t for a particular disk i is calculated as in Eq. (1). There, t_0 is the initial time of emission of each wake deficit disk at the rotor centre; $v_i(t_0)$ and $w_i(t_0)$ are the initial velocities of the disks in lateral and vertical direction, respectively. These speeds are filtered first with a low-pass filter as shown in Figure 2. The time series are treated with a moving average technique to filter out high frequencies. The time window for the moving average is selected as the time needed by the average inflow wind to travel a distance equal to two rotor diameters [3]. Afterwards the time signal is shifted in order to account for the mean time delay between the meteorological mast position and observation point.

$$\begin{aligned} x_i\ \ t: t_0, X_{hub} &= u_0 \cdot t \\ y_i\ \ t: t_0, X_{hub} &= v_i(t_0) \cdot t \\ z_i\ \ t: t_0, X_{hub} &= w_i(t_0) \cdot t \end{aligned} \tag{1}$$

2.4. Measurement of dynamic meandering

Large scale dynamics have been observed by means of nacelle lidar [2, 3]. Different techniques have been developed to analyze the wind fields of so-called line-of-sight wind speed obtained with a lidar equipped with a scanner. In particular a method for quantifying the movement of the wake centre has been shown and tested [3]. Mainly, the wake wind field is measured on planes perpendicular to the downstream mean wind. This is performed with so-

called slicing scanning trajectories. The discrete data for each full trajectory are gathered and interpolated to generate a two-dimensional wind field. This is seen as a snapshot due to the relatively fast updating rate. Then, the wind speed deficit is calculated from each snapshot and finally the "bulk" position of the deficit with respect to the wake axis is estimated. This is used as a reference point of the position of the wake; which here is called wake centre. Eventually, the large scale dynamics of the wake are obtained by measuring two-dimensional wake wind fields and finally estimating the wake centre for each snapshot. The time series of the wake centre are assumed to describe the wake meandering.
During this research the measurement is performed with a pulsed lidar, in contrast, the experiments mentioned in [2, 3] used a continuous-wave (CW) lidar. The pulsed system enables measurements at further distances due to its longer range. Additionally, it measures simultaneously different stations in the line-of-sight, while the CW system measures only at a single focused distance. However, the scope area is covered more slowly with the pulsed lidar since it requires averaging more backscattered spectra than the CW-lidar for each "focus point".

3. Experimental setup

The experiment has been performed in Bremerhaven in the north of Germany. Measurements have been performed on a prototype of the offshore wind turbine AREVA Wind M5000. The well instrumented turbine has a nominal power of 5MW, a rotor diameter of 116m and a hub height of 102m. Additionally a lidar system has been adapted and installed on the top of the wind turbine nacelle (see Figure 3).

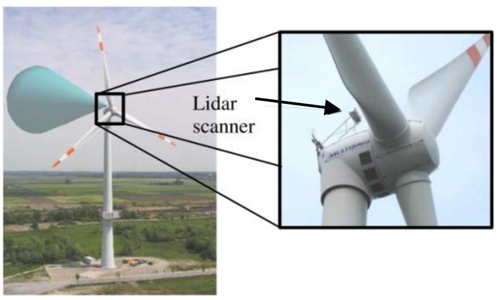

Figure 3: Close up of the wind turbine nacelle showing the installed lidar system

The lidar system is equipped with a scanner system. A mirror with two degrees of freedom enables the redirection of the laser beam. Slicing is done by following trajectories similar to Lissajous. The lidar and scanner were optimized to cover as much area as possible, in the least time suitable for a good backscatter signal. This resulted in several scanning patterns with several sampling points and update rates between 5s and 10s.
There is a meteorological mast located to the southwest of the turbine, aligned with the main wind direction. Measurement of wind speed and wind direction is performed at different heights, including hub height. The relative location of the wind turbine and the meteorological mast is shown in Figure 4. Moreover, a projection of the measurement domain of the nacelle lidar system is sketched for the main wind direction. The site is surrounded by other wind turbines and buildings which reduce the available undisturbed wind direction sectors. In effect, there is a relatively narrow wind direction sector between 197° and 229° for which the meteorological mast is undisturbed. Data are selected for this wind sector and inflow measurements are applied in meandering simulation and processing of the lidar data.

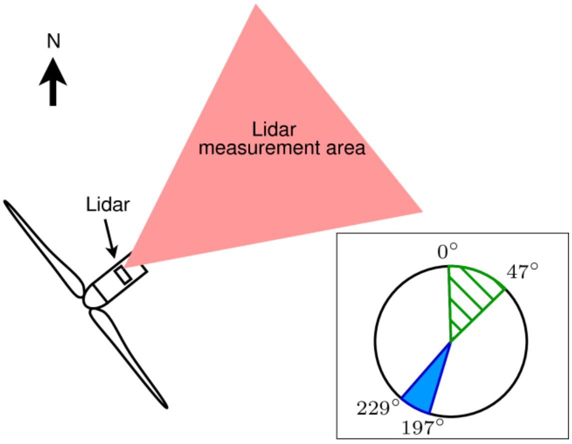

Figure 4: Sketch of wind turbine and lidar measurement domain. Free direction sector (full) and direction sector with meteorological mast in wake (hatch).

4. Results and Discussion

Measurements with the nacelle lidar system were performed during several months from 18/05/2009 until the 13/10/2009. The scanner was tested in its performance with different scanning strategies. In total there are 43 hours of data for analysis. During this time the wind turbine and scanner operated, the wind direction was from the free direction sector.
A measurement of the wind speed during a ten minute period on October 3rd between 00:10 and 00:20 at stable conditions is shown in Figure 5. This shows the result of a slicing trajectory measuring at five stations simultaneously. Slices measured every 9.2s are gathered and averaged over the span of ten minutes. The target area was selected to cover the whole rotor area at the fifth station at a distance of one and a half diameters (1.5D) downstream.

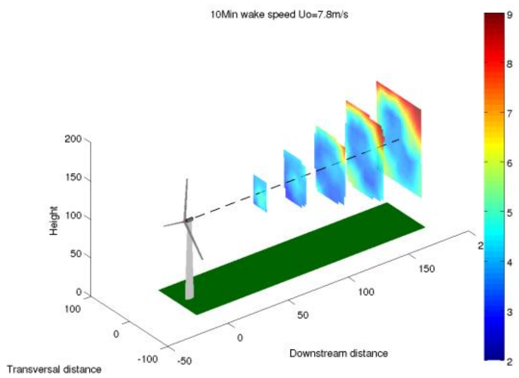

Figure 5: Wind speed in wake [m/s] at five stations downstream of the M5000. Ten minutes average of lidar line-of-sight measurement.

This shows the effect of measuring from the nacelle where the covered area is relatively small at nearer stations. The advantage of simultaneous measurements at different stations is more evident when observing the dynamics by reproducing the snapshots in sequence. In those cases not only the meandering can be observed but also, downstream advection of gusts, if the flow is highly turbulent.
The estimated transversal meandering for the ten minutes measurement mentioned above can be seen in Figure 6 for the station at 1.5D downstream. The meandering time series (red with dots) is compared to the time series estimated by the simplified model in near wake (blue). Data from wind direction at hub height have been used as input for the model. The time is presented relative to the time at the downstream station. A volume of air measured at the meteorological mast should arrive later to the downstream position. A time delay of ~60s is calculated with a mean wind speed of 7.8m/s.

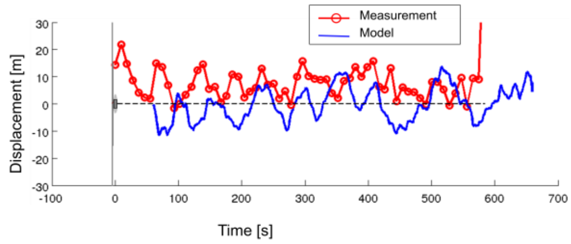

Figure 6: Time series of transversal meandering as obtained with the model (blue) and the measurement (red with dots) at a downstream distance of 1.5D. Measurement performed on 03/10/2009 00:10-00:20.

The two time series show a similar cyclic behaviour with comparable amplitudes. However, there seems to be a time shift for some of the peaks. This behaviour is seen in several of our measurements and is a task of further research. In the vertical direction, the model predicts based on the vertical wind speed from an ultra sonic anemometer at the meteorological mast. It can be seen that a slowly cyclic behaviour can also be predicted and measured (see Figure 7). However, the simulated amplitude is underestimated.

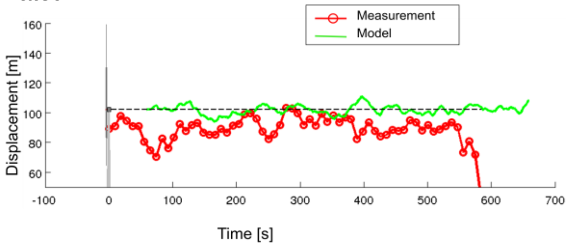

Figure 7 Time series of vertical meandering as obtained with the model (green) and the measurement (red with dots) at a downstream distance of 1.5D. Measurement performed on 03/10/2009 00:10-00:20.

5. Conclusions

The results shown, demonstrate that it is possible to also perform measurements with high spatial resolution in the wake of wind turbines using a pulsed lidar from the nacelle. The sampling rate and flexibility of the instrument allows measurements which are not possible with conventional met mast anemometry. The wind field at several downstream positions can be resolved in a quasi-instantaneous time frame. The large scale dynamics of the wake can be obtained with wake tracking procedures applied over consecutive wind field snapshots. The methods have been tested before with continuous wave lidar measurements and here they have been further tested with relatively slower pulsed systems.
The performance seems to be less robust for the pulsed measurements. However, one important factor for the tracking procedure is that the wake should be fully “visible”. In the case of the near wake measurements the wake was not fully covered. Moreover, during turbulent situations the wake gets out of scope very often, or the wake deficit is relatively “flat” or asymmetric. This reduces the reliability of the wake centre tracking method.
The model shows similar qualitative behaviour as the measurements in stable atmosphere. This suggests that the underlying assumption of passive advection is a realistic first order approach to the description of meandering. However, under turbulent and unstable atmosphere there seems to be rather difference between the model and the measurements. These observations are similar to other studies that the authors have done before in far-wake with continuous wave lidars [3]. These issues are going to be further evaluated with similar but improved measurements at the offshore test site alpha ventus.

Acknowledgements

We thank Francisco Castellote for his work on the deterministic analysis of lidar wake measurements, and AREVA Wind, especially Björn Sigmeier, for the access to the wind turbine and the support during the measurement campaigns. This research was funded by The German Federal Ministry for the Environment in the framework of the German joint project RAVE-LIDAR (0327642).

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