Investigation into the shape of a wake of a yawed full-scale turbine

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Abstract. In this paper, data from a lidar-based field campaign are used to examine the effect of yaw misalignment on the shape of a wind turbine wake. Prior investigation in wind tunnel research and high-fidelity computer simulation show that the shape assumes an increasingly curled shape as the wake propagates downstream, because of the presence of two counter-rotating vortices. The shape of the wake observed in the field data diverges from predictions of wake shape, and a lidar model is simulated within a large-eddy simulation of the wind turbine in the atmospheric boundary layer to understand the discrepancy.

1. Introduction
Wake steering is a form of wind farm control, in which intentional yaw misalignment of an upstream turbine is used to deflect its wake away from a downstream turbine [1]. In developing control-oriented engineering models of wake steering to design and analyze wind farm controllers, the effect on wakes from yaw misalignment is typically modeled as a change to the location of the wake and the depth of axial velocity deficit. In [2], a model is proposed in which the deflection of the wake is predicted by the coefficient of thrust and yaw angle. This approach was adopted into the FLOW Redirection and Induction in Steady State (FLORIS) model [3], which has been used in studies of wind farm control conducted at operating wind farms (c.f. [4]). More recently, [5, 6, 7], provide a new model of wind farm control and wake steering that includes turbulence intensity as an input to the prediction of wake behavior, and the latest version of the FLORIS model now includes these models [8].

In [9], a field campaign using a rear-facing lidar to assess the presence of wake deflection behind a yaw-misaligned commercial turbine, undertaken at the National Renewable Energy Laboratory (NREL), was presented. In that campaign, a lidar from the University of Stuttgart was installed on a GE 1.5-MW turbine, located at the National Wind Technology Center, in Superior, Colorado. The turbine was programmed to hold different yaw offset set points, while the lidar was oriented downstream through a moving mount underneath it. The turbine and installed lidar are shown in figure 1 and figure 2. In [8], the collected data are used to assess the FLORIS models, examining recovery and including both the deflection models of [2] and [5, 6, 7]. The results show good agreement between field data and the models.
Research in wake steering has shown that when a turbine misaligns from the flow, it generates a pair of counter-rotating vortices. An example visualization of these vortices is provided in figure 7. These vortices were measured and analyzed using a scaled turbine in a wind tunnel [10]. More recently, in [11], experiments and large-eddy simulations (LES) have been used to study the flow behind a yaw-misaligned porous disk and a wind turbine under uniform inflow. In the study, the wake is shown to “curl” as it moves downstream. The authors explain the curled shape as a result from counter-rotating vortices shed by the yawed turbine. The curled wake mechanism was also observed and explained in [6]. In [12], the curled wake is also observed when using LES of the atmospheric boundary layer with different stabilities. Lastly, in [13], the impact of these vortices on the performance of wake steering was shown to be important, especially for cases of turbines not directly aligned in the flow, and arrays of turbines greater than two.

In this paper, we examine the data set from the field campaign presented in [8] and [9] with respect to the shape of the wake. The objective of the paper is to assess if the lidar data can be used to validate the presence of these vortices and their effects on the steered wake generated in a field test campaign. Because engineering models such as FLORIS do not yet contain models of vortices (although there are models in development [14]), the data set is compared to simulations of the turbine used in the field test in the NREL large-eddy simulation tool Simulator fOr Wind Farm Applications (SOWFA) [15]. The comparison is made using a model of the lidar embedded in the LES simulation.

2. Field results and initial comparison
In the field campaign, the turbine was run continuously, while an offset was applied to the yaw alignment that was periodically changed hourly between 0, 12.5, 18, and 25°. It is important to note that when the turbine was misaligned to the flow, a turntable beneath the lidar counter rotated to maintain the lidar pointing in the nominal downwind direction. The turbine used in the campaign is a 1.5-MW GE turbine (shown in figure 1). The turbine has a 77-m rotor diameter (D) and hub height of approximately 80 m. Aside from the forced yaw misalignment, the turbine was controlled normally throughout the campaign.

The Stuttgart scanning lidar was developed by the University of Stuttgart and is composed of a Windcube V1 from Leosphere and a scanner unit designed by the university. The scanner uses a 2 degree of freedom mirror to redirect the beam. It is a pulsed lidar system and scans five ranges simultaneously. Additionally, the scan pattern is programmable. The design of the
scan pattern represents a trade-off between the number of points and time per scan. For this campaign, the scan pattern shown in figure 3 was selected. The nearest scan corresponds to a distance of approximately 1D, whereas the furthest is 2.7D.

For the remainder of this work, we focus on the second from farthest range of the five (which is located at 2.3D downstream and is shown in purple in figure 3 and has an in-plane span of 150 m by 90 m) as it was the furthest downstream plane for which sufficient good data are collected (the clear air of high-altitude Colorado makes it difficult to reliably measure the farthest range).

In figure 4, the median scan across all collected data for the 2.3D scan range is shown. For most bins, this represents the median of several hundred scans collected across the 6 months of the campaign. The scans are binned by average wind speed during the scan (columns) and by yaw misalignment angle (rows). The overlaid red circles in the figure (and later figures) are the size of the turbine rotor to show that the position of the wake had advected downstream without expansion or deflection. The data are linearly interpolated based on the underlying 49-point 150-m-by-90-m scans to a smoother higher resolution grid.

As noted earlier, with regards to the predictions of engineering models, and especially to the “rotor-averaged” wind speed, both the apparent deflection and recovery match well to predictions, as was reported in earlier reported research [8]. The deflection of the wake to the right is shown in the bottom row for the 25° alignment case.

However, the shape of the wake is surprising. Beginning to be noticeable even at 12° of misalignment, but especially at 25°, the wake shows a tendency to be divided into two separate regions. In the initial qualitative discussion in [9], this appearance was thought to correspond to the expected correspondence of curl.

To test this, NREL’s LES-based wind farm simulator SOWFA was used to run a case to assess the correspondence to prior prediction. The case is run with an actuator disk model of the 1.5-MW GE turbine, operating in a flow with a mean speed of 8 m/s and turbulence intensity of 5.6%. The turbine is set to be 25° misaligned from the flow, and three-component velocity of the flow field behind the turbine is averaged over the last 1000 s of simulation. From this averaged flow, we can extract a plane representing the same point in space as the lidar scans provided in figure 4 (shown in figure 5).

Comparing figure 5 with the bottom row in figure 4, we see that while the curling process has begun in figure 5 (i.e., the wake is becoming oval-shaped as the midline of the wake contracts
Figure 4. Median scans from the lidar for various wind speeds and turbine offset positions. Note for each wind speed offset, all the scans fitting this condition are combined to produce the median value at each point in the scan (median was chosen over mean to reduce the impact of outliers). The scan is then normalized by the wind speed, and results expressed in percentage reduction (i.e., -.4 = 40% of freestream). Note the 49-point lidar scans have been interpolated up to a higher resolution for smoothness and clarity. Finally, the overlaid red circle indicates the rotor size and location assuming no cross-stream deflection for reference.

Figure 5. Slice image of the averaged axial flow at 2.3D downstream of the turbine from the SOWFA simulation. The overlaid red circle indicates the rotor size and location assuming no cross-stream deflection for reference.
from the left, the wake is not expected to be very curled at 2.3D. This is consistent with the literature cited earlier on wake curling.[10, 12, 11] Further, in a recent wind tunnel study [16], the authors show (see figure 5 of that paper for example) a similar pattern of oval-shaped curling at 3D, with the kidney-bean shape more apparent at 6D.

To resolve this discrepancy, we consider that although the slice shown in figure 5 is exactly the flow through that plane in the simulation, the images in figure 4 must be in effect reconstructed from the underlying raw measurement of the lidar. In the next section, we consider two sources of distortion that could arise from the lidar measurement process, and assess if these distortion sources can explain the differences observed by modeling the lidar measurement process within the LES simulation.

3. Lidar measurement distortion
A first source of possible distortion is that although a lidar measurement is assigned to a given point in space in the analysis, the measurement is actually a weighted volume average along the beam’s axis before and after the target location.

This volume averaging can be modeled in simulation using a discrete set of points to recreate the lidar range-weighting process. Figure 6 represents the 49-point scan of the lidar in space. The blue triangle is the location of the lidar. The red triangles represent the point’s we wish the lidar to measure in space. The gray dots represent the points we must actually measure and average if we want to recreate the underlying lidar measurement procedure. The gray dots are shown to line along the trajectory of the beam that passes through the desired measurement point. This weighted averaging can contribute distortion as the lidar measurement sample includes information from upstream and downstream of the desired measurement location.

Figure 6. Points used in lidar sampling of the SOWFA simulation. The blue triangle indicates the position of the lidar, the red triangles indicate the points of the scan, and the gray dots indicate the additional scan points to recreate the volume averaging of the lidar.

A second possible source of distortion comes from the velocity actually measured by the lidar. This is the velocity of the flow along the beam, known as the line-of-sight velocity. If
the flow contains only axial velocity, this measurement can accurately be projected to derive axial velocity. In the method used in this paper, the flow is assumed to be only axial. However, if the flow contains in-plane velocities, then they will contribute to the line-of-sight velocity and cause the calculation of axial velocity to be wrong. However, if the in-plane velocities are turbulence-driven, then perhaps they will not lead to any steady bias following averaging.

Yet, as stated, a known feature of a steered wake is the presence of the generated vortices, leading to persistent cross-flow velocities. If we visualize these velocities as they appear in the SOWFA simulation, we derive figure 7. Perhaps the presence of these cross flows explains the shape of the measured wakes.

![Figure 7](image-url)

**Figure 7.** A slice of the averaged SOWFA simulation flow at 2.3D as was done in figure 5. Overlaid on the flow is a quiver plot showing the direction and magnitude of in-plane flows.

To test these two hypothesis, a model of the lidar was implemented within SOWFA. The lidar model then returns measurements based on the averaged SOWFA flow. In a first iteration, the lidar scans the exact points of the plane and directly measures the axial flow component. In a second iteration, the lidar again scans the precise plane, but this time first computes the line-of-sight velocity from all three flow components \((u, v, w)\), and then calculates the axial velocity by assuming no in-plane velocity \((v = w = 0)\). In a third step, volume averaging, or range weighting, is included, and the lidar measurement, although based on measuring axial velocity directly, is a weighted average of the points as shown in Figure 6. Finally, the two effects are combined to give the total distortion. Each of these steps is visualized in figure 8.

One quick note: an extra source of distortion is derived from the fact that the underlying mesh resolution of the LES simulation is 10 m, and the difficulties of three-dimensional interpolation lead to further distortion of the flow. To remove this unwanted effect, the lidar points were moved onto the LES grid (leading to a 135-point scan). However, this was done for clarity and removing an unrelated source of error. Repeating with the actual 49-point scan leads to the same conclusions.

4. Discussion
Although it is clear from figure 8 that the two lidar effects modeled distort the apparent axial measurement, they do not explain the bimodal appearance of the scans of the steered wakes.
Figure 8. Evaluation of possible distortion in wake appearance from the impact of including in-plane flows (vw components) and of volume averaging. While the considered effects do distort the shape somewhat, they do not explain the bimodal appearance of the scans.

from the field experiment.

One point is that on the whole, both effects are small. This can be observed again by checking the rotor-averaged wind speed at each cross-wise location in the scan, computing the average wind speed (technically the cube root of the average of the cubed velocity) of a circle the size of the rotor, scanned laterally across the plane. This is the approach described in [12] and used to compare field data and engineering models in [8] (shown in figure 9). The very close values returned from all four cases indicate a good result for the analysis in [8], suggesting that the lidar should be able to measure this quantity of interest well. Predicting available power at a given location, under different atmospheric and control conditions, is the main objective of control-oriented wind farm engineering models, such as FLORIS.

The minimal impact of including the in-plane velocities $v$ and $w$ components can be understood by considering that figure 7 shows the maximum magnitude of the inflows, which appears to be around 0.5 m/s. This can be combined with the insight that the angles of the laser beams with respect to axial velocity are relatively small for most beam angles, as shown in figure 6. These two factors imply the impact must be small as is shown in the top row in figure 8.

The minimal impact of range weighting can be explained by first considering the progression of curling as illustrated in figure 10. The figure shows (as is consistent with literature) that extensive curling is not expected until well downstream of the 2.3D location. Figure 6 shows that that range weighting includes measurements $+/- 20$ m along the beam; this only corresponds to approximately 1/3 D axial displacement, and the main source of distortion is that the beams are angled to mix measurements from the wake “center” and outside of the wake.

If these two sources of distortion can be ruled out as explaining the divided-region wake shapes in figure 4, are there other lidar-based explanations? One could be the coarse grid of the 49-point scan—when interpolated up to the smooth images, it can exaggerate the impact of one measurement point. Figure 11 shows the same data as Figure 4 but at the actual resolution of...
Figure 9. Normalized “rotor-averaged” wind speed computing by averaging the axial flow at different cross-wind locations over a circle the size of the turbine rotor.

Figure 10. Slices of axial flow extracted from the averaged SOWFA simulation at different positions downstream to show the evolution of wake shape predicted from LES.

It is more challenging to interpret the coarse mesh of figure 11 (again, each subplot represents the median scan of every scan that matches the set conditions); however, it is still possible to observe that the wake of the unyawed turbine shows the largest reduction in axial velocity toward the “center” of the wake; whereas, especially for 25°, the increased speed of the center relative to the regions above and below is noticeable. For comparison, figure 12 shows the simulated lidar measurement from the averaged SOWFA simulation reproduced at this coarse resolution.

A second potential explanation could derive from the assembly of the median scans in figure 4 and figure 11 from all collected data, and not by binning by atmospheric conditions. The size of
Figure 11. Reproduction of figure 4 at the resolution of the lidar scan pattern.

Figure 12. Simulated lidar measurement from the averaged SOWFA flow reproduced at a lower resolution of the underlying scan pattern.

the available data set from this present campaign means that subdividing the bins further leads to much noisier and less stable results; however, this is the subject of future work.

5. Conclusion
This paper reviews the results of a lidar-based field measurement of wake steering. While previous studies have compared the predictions of engineering models of wake deflection, this study focused on the predictions of wake shape coming from LES simulation studies and wind tunnel studies in the literature.

The lidar data showed that the more misaligned the turbine yaw was to the flow, the more
likely the resulting wake 2.3D behind the rotor was to appear divided into two regions of deficit. LES simulations with an embedded lidar were performed to determine if the appearance could be explained through modeling of the lidar measurement process, but unfortunately, this experiment showed only small distortion as a result of these processes.

The paper reveals that neither this apparent feature of wake shape, nor the lidar distortion investigated, negatively impact the comparison of wake deficit and location in an overall rotor-averaged sense to engineering models. However, it is not known at this point if the bimodal appearance of the wake in the data represents a physical reality or a yet-unexplained artifact of the experiment. Future campaigns using other lidar systems, perhaps with finer scan resolutions, will be required to answer this question.

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