Evaluating techniques for redirecting turbine wakes using SOWFA

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1. Introduction

Wind turbine wakes are complex and difficult to model. When turbines are located together in wind power plants, wake interaction between turbines can decrease energy capture and increase turbine loads. Therefore, recent research has focused on the design of wind plant controllers to mitigate these effects. Often in the literature, the controllers are based on modifying an individual turbine’s axial induction factor by adjusting pitch and torque. Example studies that use this approach to optimize the global wind plant power capture include [1–3].

An alternative approach to wind plant power optimization is to redirect the wake using yaw misalignment rather than to optimize induction. In this method, when two turbines are aligned in the wind direction, the upstream turbine intentionally misaligns its yaw angle so as to deflect the wake such that it avoids the downstream turbine. This method has been studied experimentally in Ref. [4] and in computational fluid dynamics (CFD) simulation in Ref. [5] with encouraging results. In a similar way, vertical wake redirection obtained by changes in rotor tilt angle has been investigated in Ref. [6] using a CFD model. Note that both Refs. [5,6] use an actuator disk model of the turbine and Ref. [6] assumes laminar flow.

In this paper, we examine the potential of turbine controllers to redirect the turbine wake. This study is done through simulation experiments with the high-fidelity wind plant modeling tool the “Simulator for On/Offshore Wind Farm Applications” (SOWFA) [7]. SOWFA allows simulations to be performed that calculate performance results in terms of effects on the turbine (for example, power and loading) as well as on the flow (wake redirection).

Wake redirection methods to be examined include both the yaw- and tilt-angle based methods discussed above. We further add an additional novel, to the best of our knowledge, approach. The method attempts to employ individual pitch control (IPC) to achieve a horizontal or vertical wake skew by intentionally inducing a yaw or tilt moment. IPC is typically used to remove these moments, but we use it in reverse to apply them. The four techniques to be evaluated are illustrated in Fig. 1.

The contributions of this paper are twofold. First, we introduce a novel approach to achieving wake redirection (via IPC). Second, we use high-fidelity simulations to evaluate the methods both in terms of their capability to redirect wakes and the effect on turbine power and loads.

Note that this paper examines the ability of these approaches to predict turbine wake only in terms of measurement of wake...
relocation and effects on the turbine. In a companion paper, “High-fidelity simulation comparison of wake mitigation control strategies for a two-turbine case” [8], we use a simulation of two turbines aligned in the flow to assess the impacts of the yaw and tilt methods on a downstream turbine.

The remainder of this paper is organized as follows. Section 2 describes the high-fidelity SOWFA, which is used in this study. Section 3 provides details of the simulation setup. Section 4 provides the results and analysis of the simulations. Conclusions are given in Section 5.

2. SOWFA

SOWFA [7] is a CFD tool coupled with the National Renewable Energy Laboratory’s (NREL’s) FAST turbine simulator tool [9] for studying wind plant behavior. The CFD solver is based on the OpenFOAM CFD toolbox [10]. Specifically, a large-eddy simulation (LES) is used, which directly resolves the larger, energy-containing turbulent scales, to simulate the atmospheric boundary layer and the turbulence contained within it. Then, rotating actuator-line turbulence model that create time-dependent forces are placed in the flow to create wakes that interact with one another, and the actuator lines are coupled with FAST. Extensive details are given by Churchfield et al. [11], and are summarized here.

The flow is computed using an unstructured, collocated variable, finite-volume formulation that is second-order accurate in time and space. The filtered momentum equation is solved along with an elliptic equation for pressure that enforces continuity. Buoyancy effects are included through a Boussinesq term in the momentum equations necessitating the solution of a temperature transport equation. Coriolis forces that account for the Earth’s rotation are also included. The lower surface-boundary conditions are based on Monin–Obukhov [12] similarity theory, which is common practice in the atmospheric LES community. The upper boundary is a stress-free, rigid lid. Velocity–pressure decoupling that would normally occur with a collocated incompressible method is avoided through Rhie–Chow [13] interpolation, and the Pressure-Implicit Splitting Operation algorithm [14] is used to solve the equation set. The linear systems that arise when discretizing the implicit equations are solved using preconditioned iterative solvers.

First, a laterally periodic atmospheric boundary-layer precursor simulation with no turbines is performed to generate the turbulent atmospheric boundary layer. Once that simulation has reached quasi-equilibrium, planes of inflow data are saved every time step. These data are then used as inflow boundary conditions for the non-periodic wind turbine simulation, and the downstream boundaries are outflow.

Sørensen and Shen’s [15] actuator line method is used to model the interaction of the wind turbine blades with the wind. The basic idea is that each blade is represented as a line, and each line is discretized into segments. For each segment, the blade airfoil type, twist, and chord are known. The velocity vector experienced by that segment can be sampled from the LES flow field giving the velocity magnitude and angle of attack. Airfoil lift and drag tables are then used to compute the force vector at each actuator line segment. These time-dependent forces are then projected, using a three-dimensional Gaussian at each actuator line segment, onto the flow field as volumetric body forces that enter the momentum equation. Large-scale structures like the rotor wake and blade tip, root, and bound vortices are resolved.

FAST is two-way loosely coupled to the actuator line model. The LES model samples the velocity along the actuator line segments and returns those values to FAST. FAST, which normally computes those velocities using blade element momentum theory, operates instead in blade-element mode because the LES solver computes induction caused by the rotor. The blade forces computed with FAST are returned to the LES solver and imposed as the body forces described above.

Validation of the SOWFA tool is an ongoing process. In Ref. [16], SOWFA was used to simulate the 48-turbine Lilgrund wind plant, and the results were then compared with field data, with good agreement throughout the first five rows. Additionally Ref. [11], includes documentation of SOWFA’s capability to simulate the inertial range in the turbulent energy spectra and the log-layer mean flow. Finally, in Ref. [17], actuator line loads within CFD flow are compared to data from the NREL Phase VI experiments.

3. Simulation setup

In this study, numerous simulations were run within SOWFA of a single turbine subject to the four proposed methods shown in Fig. 1, which were applied in individual simulations with varying settings of yaw misalignment, tilt angle, or IPC moment set-point. The wind inflow was the same for all simulations. From the simulations, we extracted the turbine’s average power over the simulation, as well as the metrics of loading for several components. From the flow, we used a correlation method to identify the wake-center at all locations downstream from the turbine. The results allow for a trade-off analysis of wake redirection potential versus turbine effects.

Note that this study is limited to a single turbine and an examination of the flow behind it. However, an important consideration is the effect of changes made by an upstream turbine on a downstream turbine. Additionally, it is also important to determine if a reduction in the power output of the upstream turbine is compensated for by an increase in the power output of the downstream turbine. These issues are addressed in a related paper [18].

We simulate an NREL 5-MW baseline turbine [19] in turbulent inflow operating at its nominal Region 2 tip-speed ratio of 7.55. The inflow, which is based on the study reported in Ref. [11], is that of a neutral atmospheric boundary layer with a low aerodynamic surface roughness value of 0.001 m, typical of offshore conditions. This inflow was selected because it had previously been validated and represents a realistic scenario. The inflow is generated in a precursor atmospheric LES on a domain that is 3 km by 3 km in the horizontal and 1 km in height. The horizontally averaged wind speed is driven to 8 m/s at the turbine hub height and is controlled through a time-varying mean driving pressure gradient. The vertical change in mean wind across the rotor disk is 1.46 m/s. The turbulence intensity is 6.3%, and the shear exponent is 0.11. The wind comes from the southwest (300°) so that the elongated turbulent structures in the surface layer are not “trapped” by the periodic boundaries, continually cycling through in the same location.

In the baseline case, the turbine rotor axis is aligned with the wind direction. The surface temperature flux is set to zero, although
a capping inversion initially at 750 m above the surface is used both to slow boundary layer growth and because it is a real feature of atmospheric boundary layers. Details on the positioning of the turbine and meshing of the domain are given in Fig. 2. Fig. 3 shows the averaged flow field in contour planes taken from the 3-dimensional simulation of the NREL 5-MW reference turbine with no yaw or pitch control applied (although this turbine’s rotor is nominally pitched up 5° to mitigate blade strikes on the tower).

The vertical slices through the wake at various downstream locations, shown in the bottom two rows of Fig. 3, show the mean wake as viewed from upstream looking downstream. It is interesting to note that the wake moves to the right with increasing downstream distance, although there is no yaw misalignment. The wake rotates counter-clockwise in these contour planes, i.e. opposite to the clockwise rotation of the turbine rotor, and the wake is like a vortex interacting with the ground. The clockwise-rotating image wake (when considering the ground plane as an image plane in potential flow) then induces motion on the actual wake, pushing it to the right. This effect is later seen in the “baseline” simulation contours shown in Fig. 5.

The yaw and tilt wake redirection strategies are tested for a range of settings. Each setting is tested in a simulation with 1000 s of simulated time. Conservatively assuming the wake convection speed to be one-half the mean hub-height wind speed, and setting a length scale equal to 7 rotor diameters, a typical turbine spacing, then the 1000 s simulation time can be expressed as 4.5 flow-through times. SOWFA requires significant computational power in order to run high-fidelity simulations: using a sample time of 0.02 s, the time steps take an average 2.5 s to calculate on the Sandia National Laboratories/NREL Red Mesa supercomputer [20],

![Fig. 2. Overview of the simulation setup in the baseline case.](image-url)
Fig. 3. Averaged velocity profiles of the wake forming behind the NREL 5-MW reference turbine with no pitch or yaw control as calculated in the SOWFA simulation. $D$ is rotor diameter. The $x$–$y$ plane is a view from above and the downstream planes are as viewed from upwind looking downwind.

Fig. 4. Illustration of the method for determining wake location from averaged slices of simulated output [23,24].
using distributed computation with 256 processors. This yields an execution time of 34.4 h for each simulation.

In each case, the turbine uses the baseline controller defined in Ref. [19] for pitch and torque control. The IPC implementation is based on the design first presented in Ref. [21] using the parameters as specified in Ref. [22]. It is adapted so that IPC can be used in below-rated conditions and to induce an asymmetric moment, rather than remove one. Details on this IPC implementation are given in the Appendix.

4. Analysis and discussion

Following completion of the simulations, slices were extracted from the simulation outputs and a method was used to determine the mean wake center based on ideas of de Maré [23,24], that have been further developed at NREL. We took a horizontal slice of the mean velocity field at the turbine hub height and a vertical slice aligned with the mean wind and passing through the turbine centerline. From the horizontal slice, we took the mean velocity along lines within the slice plane and perpendicular to the flow at successive downstream locations. When plotted, the velocity along each line is a mean velocity profile. In the near wake, the velocity profiles are double-Gaussian in shape, and in the far wake, they resemble a normal Gaussian distribution. To find the wake center, we correlate the profiles at each downstream location with a Gaussian of similar width and depth. The point of maximum correlation is taken as the wake center position at each downstream location, giving the lateral wake deflection. We followed the same process to find the vertical wake deflection using the vertical slice of mean velocity; however, we first subtract the vertical profile of mean velocity to remove the effect of vertical shear that is present in the atmospheric boundary layer. Fig. 4 illustrates the process of identifying the wake center for the horizontal case. Fig. 5 shows the output of the wake center-line identification algorithm for several cases in the horizontal and vertical planes.

The cases shown in Fig. 5 are representative of the collected results fully summarized in Table 1. Wake center tracking results in the yaw and tilt simulations demonstrate significant displacements of wake center, in agreement with the previous literature. The IPC methods produce some redirection. While it does not achieve as much redirection as yaw or tilt angle adjustments, the skew is in some cases significant. Although the IPC algorithms were intended either to approximate yaw misalignment through an IPC-induced yaw moment or tilt via a tilt moment, the results show that the largest vertical skew is obtained when a yaw moment is targeted and the largest horizontal skew is created when using a high tilt moment.

In addition to measurements of the wake, data were collected from the FAST turbine output. The data included time series of output power, blade out-of-plane (OOP) bending moment, drive-train torsion, tower fore-aft and side–side bending, and the yawing and tilting moments experienced at the yaw bearing. Using a root-sum-square combination, the separate tower and yaw moments are combined into a single moment. An average power output is computed, as well as the damage equivalent load (DEL) for each load signal. The DEL is a standard metric of fatigue damage; see Ref. [25] for an example implementation. These results are summarized in Table 1. Note that the measurement of wake displacement is taken at seven rotor diameters from the turbine, which is a typical location for a downstream turbine.

Table 1 shows promising results for yaw-based wake skew. When the turbine yaws in the positive direction, wake redirection...
and load reduction for all components are simultaneously achieved for a number of operating points. Using a yaw misalignment to reduce turbine loads has been studied in the literature and our results are consistent with those findings [26]. The intent is that the loss of power should be compensated for by a larger power gain in a downstream turbine [27].

Tilt similarly demonstrates potential for wake redirection with mostly limited impacts on loads. Blade bending increases with positive tilt angles and decreases with negative tilt angles. Conversely, drivetrain torsion tends to increase with negative tile angle and decrease with positive tilt angle. Finally, neither tower bending nor yaw bending exhibit a strong pattern of changes to load with changing tilt angle. It should be pointed out that currently there is no means of modifying tilt angle in the field. However, the effect of causing the higher-speed higher-altitude winds to be pulled downward might be rewarding enough to justify further investigation. Also, note that since positive tilt angles would cause the blades to come closer to the tower on upwind turbines, this technique would be better suited to downwind machines [28].

The results for the IPC-based methods are mixed. Significant wake skew is achieved for some cases. However, because the method is maximizing an asymmetric rotor moment, the blade loads are substantially increased. This result implies that although it may be possible to achieve wake redirection with IPC, this particular IPC algorithm is not a good method. Finding an IPC controller that achieves wake skew with reduced blade loads would be very useful because IPC is already possible to implement on many existing turbines (unlike changes to tilt), and can be adjusted more quickly than yaw angle.

In considering the results, the authors now believe the initial concept for IPC-based wake redirection followed in this paper was fundamentally flawed. Specifically, although IPC can reproduce the rotor moments generated by yaw or tilt misalignment, this moment is not what creates skew. In the left section of Fig. 6, the conceptualization of yaw-misalignment induced wake redirection from Ref. [5] is redrawn. In it, the thrust force of the turbine is shown to act along the axis of the rotor shaft. When the wind inflow is at an angle to this direction, the thrust can be divided into components $f_x$ and $f_y$. The component $f_x$ is parallel to the flow and slows the wind, while $f_y$ is perpendicular and applies the force that causes wake redirection.

IPC creates an uneven distribution of thrust forces on the rotor blades over the course of a rotation (see side view of turbine in right section of Fig. 6). This creates a tilt or yaw moment on the turbine rotor. Still, the thrust reaction forces on the flow are directed parallel to the inflow direction and so the uneven distribution of the thrust forces does not cause significant redirection of the flow behind the turbine (i.e. this does not cause wake skew). However, as shown in the turbine front view in Fig. 6, IPC also causes the blade torques to be uneven over the course of a rotor rotation (in the sense that rightward torque is not matched by leftward torque). Therefore the in-plane reaction forces of the rotor on the flow are also unbalanced resulting in the fact that the turbine applies a net force on the flow perpendicular to the thrust direction, which does cause the flow to be redirected and the wake structure to be skewed. Notice that the IPC configuration drawn in Fig. 6 will yield a tilt moment on the turbine (because the blade thrust is most different between the top and bottom azimuth positions) and a horizontal wake skew (because the reaction forces of the rotor on the flow are most different in the horizontal direction), which agrees with the results discussed earlier.

This analysis indicates that although the IPC algorithm first developed is problematic, an alternative implementation may be possible. This implementation, the subject of future work, should
attempt to maximize the wake skew through torque imbalance while limiting rotor moments.

5. Conclusions

In this paper, the U.S. Department of Energy/NREL wind plant simulation tool, SOWFA, was used to simulate and investigate several methods for wake redirection. Wake redirection is one proposed method for improving wind plant overall performance. For yaw misalignment, simulations showed significant redirection effects coupled with reductions in loading across measured components, a positive result. Tilt angle adjustment was shown to also achieve wake redirection, however with some loads increasing and some decreasing, depending on the tilt angle. Although modifying tilt angle is not currently a controllable feature of wind turbines, knowledge of the potential of this method might be useful, especially if the effect of pulling in faster wind yields greater overall power gains.

During this study, IPC-based methods also demonstrated an ability to affect wake skew, albeit with a substantial increase in blade loading. The analysis presented indicates that the IPC algorithm employed in this paper, while capable of redirecting wake, is not suitable for deployment given the substantial blade load increases. Future work is required to determine if a new implementation of IPC for wake redirection could resolve this issue.

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Appendix

Appendix A. Implementation of IPC with induced yaw or tilt moments

This section explains how individual pitch control (IPC) was implemented to allow yaw and tilt moments to be induced by the IPC. The implementation also can be used in below-rated operation with varying rotor speeds. Let $\omega$ denote the rotor speed in rad/s, let $\{ M_{j,m} \}^3_{m=1}$ denote blade root vibrations of each of the three blades, let $M_{j\text{yaw}}, M_{j\text{tilt}}$ denote setpoints for the induced yaw and tilt moments, and let $s$ denote the Laplace operator. Then the 1P and 2P IPC additive adjustments to the pitch, $\{ \delta \theta_{jip} \}^3_{i=1}$, are given by:

$$\begin{bmatrix} \delta \theta_{1,ip} \\ \delta \theta_{2,ip} \\ \delta \theta_{3,ip} \end{bmatrix} = \mathcal{L}(s) P_{jip}(\omega + \delta \omega) \begin{bmatrix} \frac{K_{p,yaw}}{s} & 0 \\ 0 & \frac{K_{p,tilt}}{s} \end{bmatrix} \begin{bmatrix} M_{j\text{yaw}} \\ M_{j\text{tilt}} \end{bmatrix},$$

for $j = 1, 2$, with Coleman transformation matrices:

$$P_{jip}(\omega) = \begin{bmatrix} \cos(j\omega) & \sin(j\omega) \\ \cos(j(\omega + 2\pi/3)) & \sin(j(\omega + 2\pi/3)) \\ \cos(j(\omega + 4\pi/3)) & \sin(j(\omega + 4\pi/3)) \end{bmatrix},$$

and with inverse notch filters $N_{jip}$ and low-pass filter $\mathcal{L}$:

$$N_{jip}(s) = \frac{K_{p,jip}s + 2\zeta_{jip}s\omega_{jip}s + \omega_{jip}^2}{s^2 + 2\zeta_{jip}\omega_{jip}s + \omega_{jip}^2},$$

$$\mathcal{L}(s) = \frac{\omega_{jip}^2}{s^2 + 2\zeta_{jip}\omega_{jip}s + \omega_{jip}^2}.$$

with $\omega_{jip} = j\omega$, and parameters $K_{jip}, \zeta_{jip}, \omega_{jip}, \delta \omega$ as specified in Ref. [22]. The filters are used in a Tustin discretized form with a sample time of 0.02 s. The pitch angles are saturated to a 5° amplitude, and the pitch rates are limited to 8 deg/s. In the IPC induced moment test cases, $M_{j\text{yaw}}$ or $M_{j\text{tilt}}$ are chosen large enough such that the pitch angles vary with maximum amplitude, in order to find the maximum effect of IPC action on the wake.

References


[23] de Maré M. Personal communication; 2012.


