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COMPARISON OF FIELD MEASUREMENTS AND LARGE EDDY SIMULATIONS OF THE SCALED WIND FARM TECHNOLOGY (SWIFT) SITE

Myra L. Blaylock[1], Brent C. Houchens
Sandia National Laboratories
Livermore, CA, USA

David C. Maniaci, Thomas Herges, Alan Hsieh, Robert C. Knaus, and Philip Sakievich
Sandia National Laboratories
Albuquerque, NM, USA

ABSTRACT

Power production of the turbines at the Department of Energy/Sandia National Laboratories Scaled Wind Farm Technology (SWiFT) facility located at the Texas Tech University's National Wind Institute Research Center was measured experimentally and simulated for neutral atmospheric boundary layer operating conditions. Two V27 wind turbines were aligned in series with the dominant wind direction, and the upwind turbine was yawed to investigate the impact of wake steering on the downwind turbine. Two conditions were investigated, including that of the leading turbine operating alone and both turbines operating in series. The field measurements include meteorological evaluation tower (MET) data and light detection and ranging (lidar) data. Computations were performed by coupling large eddy simulations (LES) in the three-dimensional, transient code Nalu-Wind with engineering actuator line models of the turbines from OpenFAST. A computationally efficient simulation, consisting of a coarse precursor without the turbines to set up an atmospheric boundary layer inflow followed by a simulation with refinement near the turbines, is demonstrated. Good agreement between simulations and field data are shown. These results demonstrate that Nalu-Wind holds the promise for the prediction of wind plant power and loads for a range of yaw conditions.

Keywords: SWiFT, Lidar, CFD, LES

NOMENCLATURE

D	turbine rotor diameter
DEM	damage equivalent momentum
Lidar	light detection and ranging
LES	large eddy simulation
MET	meteorological evaluation towers
METa1	MET tower in front of WTGa1
OOP	out of plane, used for bending moment
SWiFT	Scaled Wind Farm Technology
TI	turbulence intensity
TSR	tip speed ratio
WTGa1	Wind Turbine Generator a1, upstream
WTGa2	Wind Turbine Generator a2, downstream

INTRODUCTION

Wind turbines interact through their wakes and with the complex flow of the atmosphere. Simulating the complex flow and interactions necessitates high-fidelity computational fluid dynamics models. These models are computationally expensive and challenging but allow for innovative design concepts to be investigated that make use of these complex interactions. They also allow for the study of cases where models that do not capture these complex interactions fail to accurately predict wind turbine loads and power production. Computational codes that use wind plant Large Eddy Simulation (LES) models capture these interactions, but limits in their computational scaling on modern high-performance computing systems have restricted the amount of physical interactions they can accurately predict. The high-fidelity modeling code base Nalu-Wind is being developed to address these limitations, and is a derivative of the multiphysics, massively parallel simulation code Nalu [1]. To establish the predictive capability of Nalu-Wind for wind plant wake interactions, researchers at Sandia National Laboratories have modeled the Scaled Wind Farm Technology (SWiFT) facility [2, 3], a highly-instrumented wind turbine test site targeted at acquiring high-fidelity data required for validation of such codes.

This work includes the first simulations for comparison to experimental results from the SWiFT site using Nalu-Wind. These simulations will be used as part of a larger validation plan that includes establishing the ability of the model to capture the wake interaction between two turbines under various inflow and control settings [4-6]. While the experimental data available from the SWiFT facility wake steering experiment covers a range of conditions, the results in this paper address only experiments and simulations for the neutral atmospheric stability inflow condition. The computational model is then used to predict the effect of yaw angle on the power and loads of a downstream turbine as an example application. Future efforts will include the modeling of stable and unstable inflow conditions, and integration with models of a range of fidelities to establish the model error through multi-level, multi-fidelity uncertainty quantification [7] processes as part of a larger validation process.

[1] Contact author: myra.blaylock@sandia.gov
SAND No.:

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1 PROBLEM DESCRIPTION

The turbines of a wind farm are often aligned in rows. In this configuration, the leading row of turbines that faces the dominant wind direction will produce near optimum power. However, the production by the turbines in the trailing rows is often significantly reduced by the wake and associated velocity deficit of the leading row. To create the most economically viable and productive farms, it is critical to move away from the concept of individual turbines and instead consider the efficiency of the entire farm. The SWiFT facility was designed and built to study these wake interactions as a resource for testing and validating computational methods to characterize wake effects.

This study simulates the interaction between two of the three SWiFT turbines: the front turbine and one that is 5 diameters downwind in the prevailing wind direction. The study compares the data taken at the site during 10-minute periods of near neutral stability when the wind is from the south at an average wind speed of 8.3 m/s at hub height, measured on the meteorological tower directly in front of the first turbine using cup anemometers. The temperature in the simulation was set to 300 K (27 C), which is comparable to the actual temperature of 304.6 K. The leading turbine in the simulations was set at a yaw angle of 0°, +22.5°, and -10° with respect to the incoming wind direction. The yaw of the second turbine was kept at 0°.

For validating these simulations, there are data from the first turbine with a yaw of 0° during a 10-minute period when the wind and temperature conditions are the same as described in the previous paragraph. Experimental data from the SWiFT site was also collected for the second, waked turbine during stable atmospheric conditions, which will be analyzed and simulated as part of a future paper.

This paper begins the initial stages of a more thorough UQ study by running the three yaw cases under neutral atmospheric conditions. For the complete UQ study, variations around each of the yaw angles would be run to identify statistically significant trends, and a mesh resolution study will be completed.

1.1 Computational Approach

Two turbines at the SWiFT site are considered in a neutral atmospheric boundary layer. The rotor power, thrust, and blade flap root-bending moments of both upstream and the downstream turbines are predicted. The OpenFAST software suite [8] developed at the National Renewable Energy Laboratory (NREL) is used to simulate the wind turbine dynamics. OpenFAST enables the analysis of complex physical and environment coupling, including turbine controllers, elastic dynamics, and flow-structure interactions with actuator line theory. The OpenFAST model of the Vestas V27 is used in the analyses to match the rotors used at SWiFT during the experimental campaign.

To simulate the turbulent atmospheric boundary layer the multiphysics, massively parallel large eddy simulation (LES) code Nalu-Wind is used [1]. Nalu-Wind solves the Navier-Stokes equations in the low-Mach number approximation. A one-equation, constant coefficient, turbulent kinetic energy model for the subgrid scale stresses is used [9]. Following [10], the fluid-structure interaction that the turbine imposes on the wind is simulated by adding a body force f_i in the momentum equation of the form

$$f_i = \int_0^L F_i(l)\, g(\vec{r}(l))\, dl \qquad (1)$$

where l is the distance along an actuator line and F_i are actuator line forces computed from common modules of OpenFAST. The smoothing kernel $g(\vec{r}(l))$ has the form

$$g(\vec{r}) = \frac{1}{\pi^{3/2}\epsilon^3} exp\left(-\frac{|\vec{r}|^2}{\epsilon^2}\right) \qquad (2)$$

where ϵ is a characteristic length scale that determines the volume over which the body forces are spread. Here ϵ was set to a fixed value of 10m. The simulation domain was taken to be 3km x 3km x 1km in the *x, y*, and *z* directions, and the two wind turbines were arranged in the center of the domain in the configuration that matches the SWiFT site. The *x*-direction is aligned with the dominant wind, and *z* is vertical.

Simulating a turbulent atmospheric boundary layer in Nalu-Wind takes two steps: a precursor without the actuator line model to set up the inflow and then a simulation with a more refined mesh and the actuator lines that uses the precursor data as input. The precursor mesh had a uniform grid with a spacing of 10m in all directions. The boundary layer was initialized with a small perturbation in the velocity profile near the ground in order to accelerate the development of turbulence. The simulation was then run for 20,000 seconds to establish a fully developed turbulent flow.

The boundary conditions of the precursor simulation were periodic in the directions both parallel and perpendicular to the flow. The ground was simulated as a non-slip wall with a roughness height of 0.01. The upper surface is represented by an inviscid wall with a specified temperature gradient that matches the gradient above the capping inversion.

The simulation was then run for an additional 600 seconds while saving the inflow plane to a separate mesh. These planes were used as the turbulent inflow for the subsequent runs on the refined meshes that did have the actuator-line wind turbine model running. The snapshot of the precursor for the entire domain was used as the initial condition of these runs.

The area around the two turbines was refined in a series of four smaller areas, each more refined than the next. The coarsest level matches the precursor with a spacing of 10m in all directions. The first level of refinement has a spacing of 5m; second level has 2.5m; the third has 1.25m, and the forth has 0.625m. The mesh has 22.5 million elements. A grid study with meshes with 11.7 and 40.8 million elements is underway. The smaller mesh has one fewer refinement areas, and the larger has one more.

1.2 SWiFT Experimental Facility

The SWiFT facility is located at Texas Tech University's National Wind Institute Research Center in Lubbock, Texas. The SWiFT facility includes two well instrumented meteorological towers with five measurement heights, three research turbines with root-bending strain, tower strain, rotor azimuth and yaw angles, and nacelle accelerometer measurements, all synchronized in time. These V27 upwind turbines have a hub height of 32.1m and a rotor diameter of 27m (Figure 1). Two of the research-scale turbines are spaced three rotor diameters apart (WTGa1 and WTGb1), perpendicular to the prevailing wind direction, and the third rotor is five rotor diameters downwind (WTGa2). The meteorological towers are located approximately 2.5 rotor diameters upstream of turbines WTGa1 and WTGb1 along the primary wind direction. During the summer of 2017, a wake steering experimental campaign was undertaken through a collaboration between Sandia National Laboratories and the National Renewable Energy laboratory with funding from the Department of Energy Wind Energy Technologies Office Atmosphere to Electrons (A2e) program [11-13].

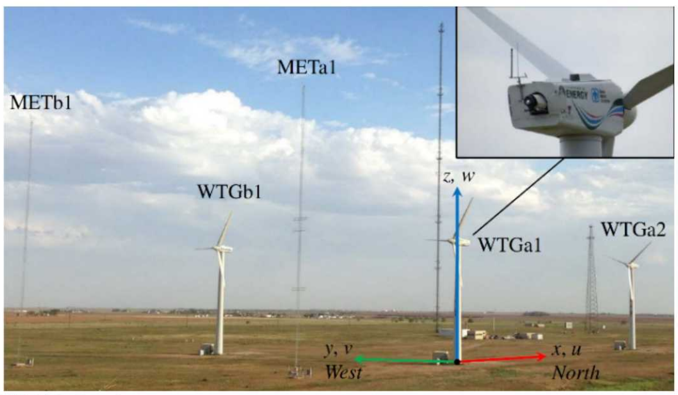

FIGURE 1: IMAGE OF THE THREE V27 ROTORS AND THE MET TOWERS AT THE SWIFT FACILITY. METEOROLOGICAL TOWER META1 AND WIND TURBINES WTGA1 AND WTGA2 WERE MODELED IN THE PRESENT WORK [11].

1.3 SWiFT Experimental Wake Data Measurements

A unique aspect of the SWiFT wake steering experiment is the use of a customized scanning lidar from the Technical University of Denmark (DTU) to measure the detailed location and strength of the wake from the upstream turbine (WTGa1) at various distances downstream (Figure 2). The wake position was tracked using the DTU SpinnerLidar and synchronized to the inflow conditions measured by the upstream MET tower and the loads on the two turbines. Some work has been performed to investigate the impact of various yaw angles and wake positions on wind turbine power and blade loads [12, 13], and more analysis will be possible as the data set will be released into the public domain through the A2e Data Archive and Portal [14]. A subset of the data from this experimental campaign is considered for comparison to the simulations, limited to conditions when the wind direction aligned directly with the orientation of the two main turbines (WTGa1 and WTGa2) and during neutral atmospheric conditions.

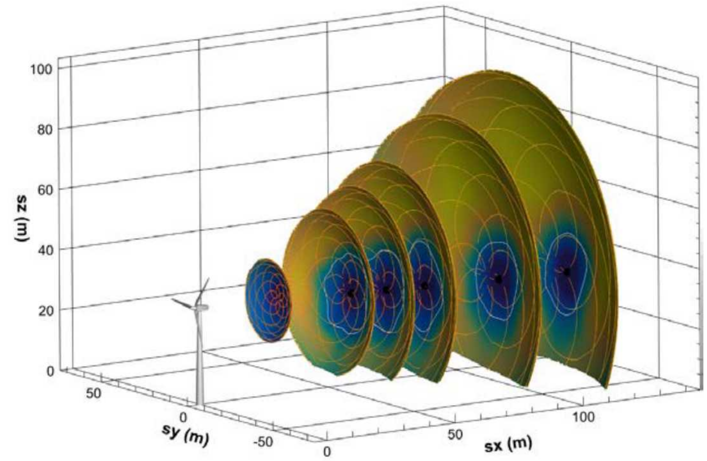

FIGURE 2: SAMPLES OF THE EXPERIMENTAL WAKE DATA GATHERED AT 6 DOWNSTREAM LOCATIONS.

2 SIMULATION RESULTS AND VALIDATION WITH SWiFT EXPERIMENTAL MEASUREMENTS

Model results are compared to experimental measurements in three ways. First, for the precursor flow, which serves as the inflow condition to the turbines, was compared to experimental measurements from the meteorological evaluation tower METa1. Second, global turbine characteristics, including the bending moment and power production, are compared to experimental measurements for the upstream turbine (WTGa1 in Figure 1). Finally, averaged wake profiles are compared between simulations and experimental measurements.

2.1 Precursor Simulation and Experimental Validation

The inflow wind characteristics were set up to be a neutral boundary layer with the velocity in the primary wind direction to be 8.3 m/s, matching the cup anemometer measurements. The temperature was set to be 300 K throughout the domain. To insure conditions for the turbine match between the LES simulation and what was measured, comparisons of the velocity at the MET tower location are made. The MET tower is located 2.5 D in front of the upstream turbine. Figure 3 shows the time history of the simulation over the 10-minute period compared to the average of what was measured. Table 1 compares the average velocities sampled at the MET tower at heights that represent the hub and the top and bottom of the rotor. The variability over the ensemble time length is expressed as the standard deviation in tables throughout, and corresponds to the turbulence intensity (TI), which matches well. In the simulations, TI is controlled with the roughness height parameter, which was set to 0.01.

Table 1. Comparison of 10-minute average velocity magnitudes and turbulent intensity at the METa1 tower location.

	Simulation	Experiment
Top of rotor, 45.6 m (m/s)	8.64 +/- 0.70	8.67 +/- 0.85
Hub height, 32.1m (m/s)	8.30 +/- 0.78	8.30 +/- 0.79
Bottom of rotor, 18.6 m (m/s)	7.79 +/- 0.93	7.68 +/- 0.96
Turbulent intensity at hub height	0.094	0.095

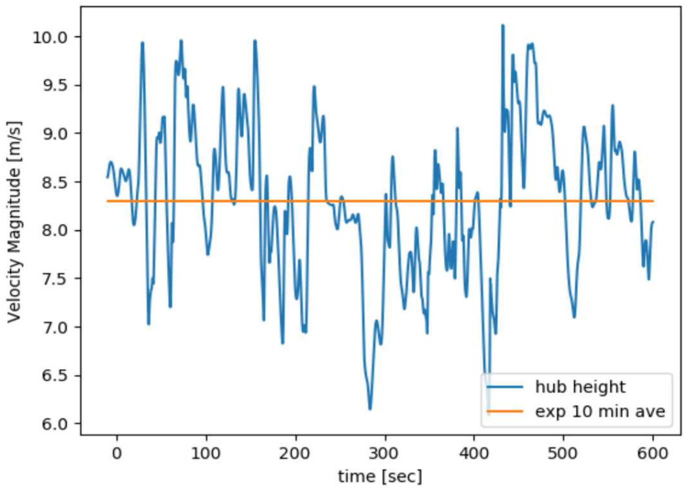

FIGURE 3: TIME HISTORY OF THE SIMULATED VELOCITY MAGNITUDE AT THE MET LOCATION AT HUB HEIGHT (32.1 M) COMPARED TO THE MEASURED 10-MIN AVERAGE MET DATA AT THE SAME HEIGHT.

2.2 Turbine Simulation and Experimental Validation

The output from OpenFAST shows the turbine variables such as blade root bending moment, generated power, rotor speed, and generator torque. Figure 4 shows a time history of these values. Comparing with Figure 3, the decrease in power and rotor speed between 300-450 seconds that corresponds to the decrease in the simulated wind speed at the METa1 tower.

The comparisons between measured experimental turbine data and the simulation are shown in Table 2. The quantities shown are the average out-of-plane (OOP) bending moment binned over a 10 minute period, the relative (simulation/experiment) flapwise damage equivalent moment (DEM) [12] binned over the 10-minute period, and the generator power. Note that, during the time that the SWiFT data was taken in the field, only the upstream turbine (WTGa1 or turbine 1) produced power while the downstream turbine 2, 5D downwind (WTGa2), was stationary. However, for all Nalu-Wind simulations presented here, both turbines were operational to allow prediction of the power and loads of the downstream turbine.

The OOP blade bending moment and relative DEM both showed excellent agreement with the experimental measurements for this case. The OPP blade bending moment correlates with rotor thrust, which is of primary importance for predicting wake momentum deficit strength and movement. The relative DEM relates to structural fatigue, which is important for the required structural material (and cost) of a wind turbine blade. The generator power is the direct quantity that is maximized in wind turbine and wind plant design, and was overpredicted by Nalu-Wind by almost 9%, a typical target is less than 5% error. One source of this error is generator and gearbox efficiency, which were not calibrated as part of this study. More recent estimation of these parameters has shown a 10% reduction in power prediction. Despite the overprediction of power, the current model is deemed useful for predicting relative changes in generator power.

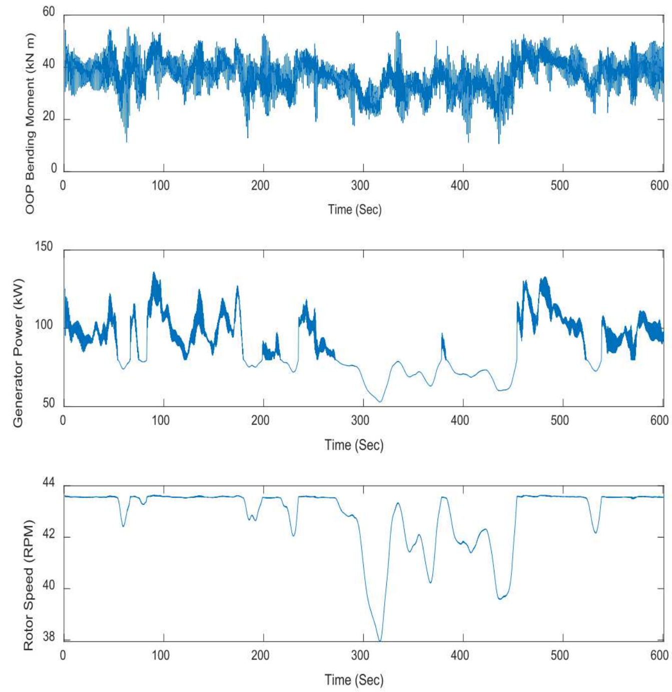

FIGURE 4: THE TIME HISTORY OF THE DATA FROM THE SIMULATION CORRESPONDING TO ROOT BENDING MOMENT OF THE BLADE (kN m), THE GENERATED POWER (kW), AND THE ROTOR SPEED (RPM) FOR ZERO YAW ANGLE OF THE UPSTREAM TURBINE (WTGA1).

Table 2. Upstream turbine (WTGa1) comparison between experimental and simulation results of the 10-minute averages of the mean out-of-plane (OOP) blade-root bending moment for the three blades (kN m), relative flapwise DEM (simulation/experiment) and generator power (kW) for yaw = 0° case.

	Simulation	Experiment
OOP Blade Bending (kN m)	37.0 ± 6.0	37.1 ± 6.2
Rel. Flapwise DEM (sim./exp.)	1.06	1.00
Generator Power (kW)	88.4 ± 17.3	81.2 ± 19.3

2.3 Wake Simulation and Experimental Validation

Instantaneous simulation and field data of wakes are shown in Figures 5 and 6. When averaged, the comparison between the simulated and measured wakes provide insight into the impact of the turbine on the CFD. Figure 5 shows an instantaneous image of the experimental SpinnerLidar data with the wake boundary highlighted in white [11]. Figure 6 shows an instantaneous image of the higher resolution Nalu-Wind data, with the wake boundary shown in white.

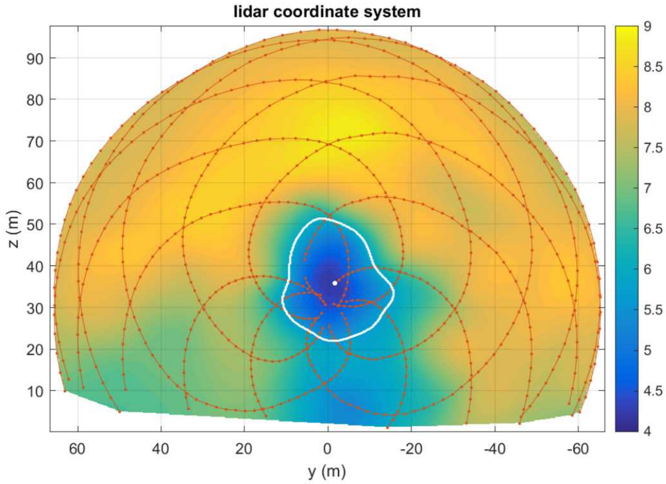

FIGURE 5: A SAMPLE OF THE EXPERIMENTAL WAKE DATA FROM THE MEASURED SPINNERLIDAR.

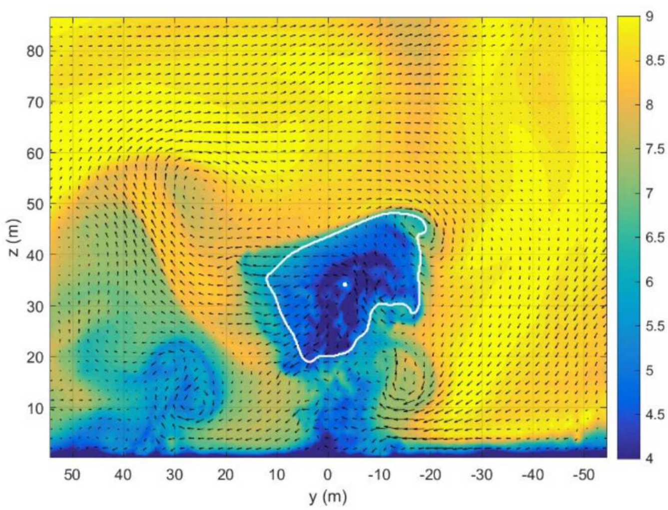

FIGURE 6: SIMULATED WAKE DATA 5 D DOWNWIND, AT ORIGNINAL RESOLUTION.

The following figures compare the measured SpinnerLidar wake data to the simulated data at a location 5 D downwind of the first turbine, directly in front of the second turbine (WTGa2). Figure 7 shows an average over 10 minutes of the SpinnerLidar data. The weighted centroid of velocity is indicated with a white dot. The white line is the velocity contour that encloses the same area as the rotor [11] and the black line is the velocity contour that encloses the area that produces the same thrust as the rotor. Figure 8 shows the Nalu-Wind simulated data that is sampled with the same scan pattern and spatial and temporal filtering as the SpinnerLidar and interpolated. The contour plot is also averaged over 10 minutes and the same wake definitions are shown in white and black. Figures 7 and 8 show that Nalu-Wind is capturing the average wake shape and position for this wind case.

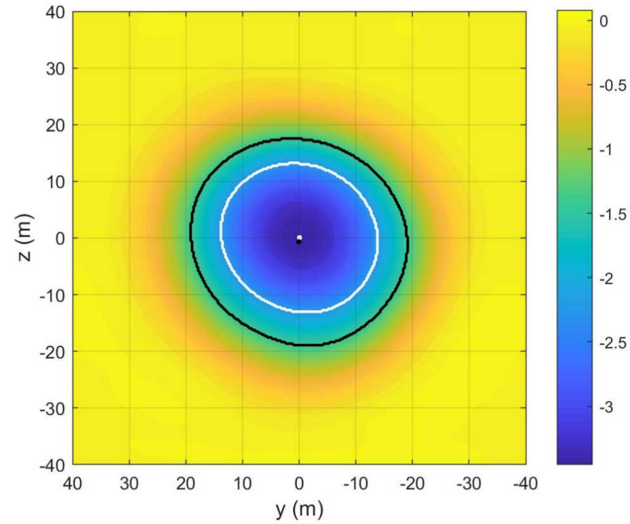

FIGURE 7: AVERAGE OVER 10 MINUTES OF THE EXPERIMENTAL WAKE DATA FROM THE MEASURED SPINNERLIDAR 5 D DOWNWIND.

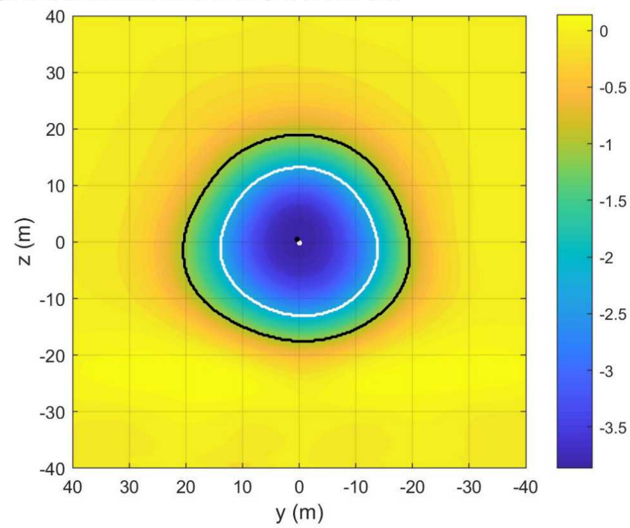

FIGURE 8: AVERAGE OVER 10 MINUTES FOR THE SIMULATED WAKE DATA 5 D DOWNWIND, SAMPLED TO MATCH THE EXPERIMENTAL LIDAR DATA.

Figure 9 shows the velocity deficit in the wake across horizontal line placed at the center of the wake. While the simulation predicts a slightly higher velocity deficit, the shapes match quite well. This indicates that Nalu-Wind is computing the correct amount of momentum extraction in the wake. It should be noted that the OpenFAST turbine model was calibrated from a large set of experimental data existing on the V27 rotor [15] for tip speed ratio (TSR) and flapwise bending moment. It is expected that calibration to the appropriate turbine is critical to achieving good agreement between simulations and experiments.

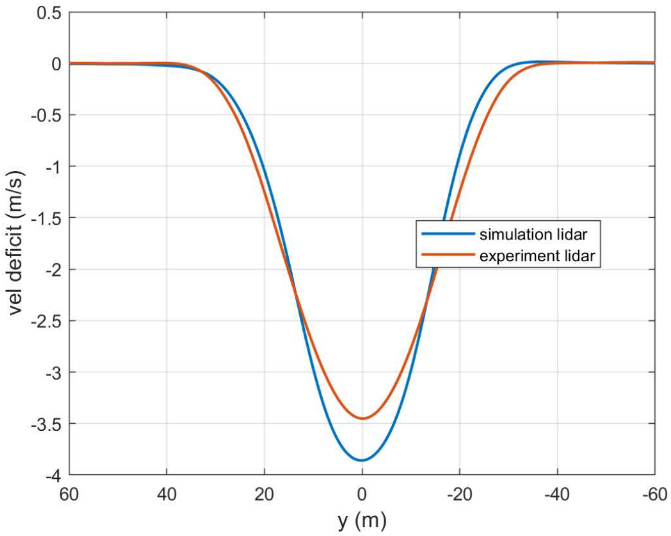

FIGURE 9: COMPARISON OF WAKE VELOCITY DEFICIT FOR THE EXPERIMENT AND THE SIMULATED LIDAR DATA 5 D DOWNWIND.

3 ADVANCED SIMULATION PREDICTIONS

The satisfactory agreements between simulations and experiments presented in Section 2 suggests the computations were sufficiently accurate that additional physics could be investigated purely via simulation. Simulation-only results are presented in this section covering leading-turbine yaw effects and postprocessing techniques of wake simulations.

3.1 Simulated Yaw Effects

The upstream turbine was yawed to investigate the influence on its power production and the impact of the wake on the downstream turbine. A comparison of loads and power output for both are shown in Table 3 for the cases where the front turbine is set at a yaw of 0°, +22.5°, and -10°. The yaw of the second turbine is 0° for all three cases.

Table 3. Comparison of the 5-minute simulated averages of the mean blade-root flapwise bending moment of the three blades (kN m), the normalized flapwise DEM (-), generated power (kW), the change in the power compared to the yaw = 0° case, and the sum-total power of both turbines, for various yaw angles of turbine WTGa1.

	Turbine WTGa1				
Yaw of WTGa1 (deg)	Flap Bending (kN m)	Norm. Flap DEM (-)	Generated Power (kW)	Δ Power (kW)	Total Power (kW)
-10	36.98	1.01	87.46	-4.91	-
0	38.07	1.00	92.37	-	-
+22.5	31.53	0.88	67.83	-24.54	-
	Turbine WTGa2 – 5 D downwind				
-10	25.78	1.34	47.90	+0.68	135.36
0	25.56	1.31	47.22	-	139.59
+22.5	25.87	1.46	48.80	+1.58	116.63

Table 3 shows the effect of the yaw of the upstream turbine WTGa1 on the power generated. Yawing this turbine decreases both the root bending moment and the power generated. When looking at the effect on the power generated by the second turbine, it actually increases for the case where the yaw of the first turbine is 22.5°. However, the sum of the power for both turbines is still less than the case where both turbines are at yaw = 0°. These findings hint that it might be possible to tune the yaw of the first row so that the sum-total power of all rotors might increase, especially if a third or fourth row is considered.

The DEM values in Table 3 were all normalized by the turbine WTGa1 DEM for the yaw = 0° case. The highest power generation for the downwind turbine (when turbine WTGa1 is yawed 22.5°) coincides with its highest flapwise DEM.

For the LES data, the time history of the horizonal location of the center of the wake is shown in Figure 10. The same turbulent inflow is used for all three cases. The turbine yaw can influence the position of the wake up to several meters for the neutral boundary layer case.

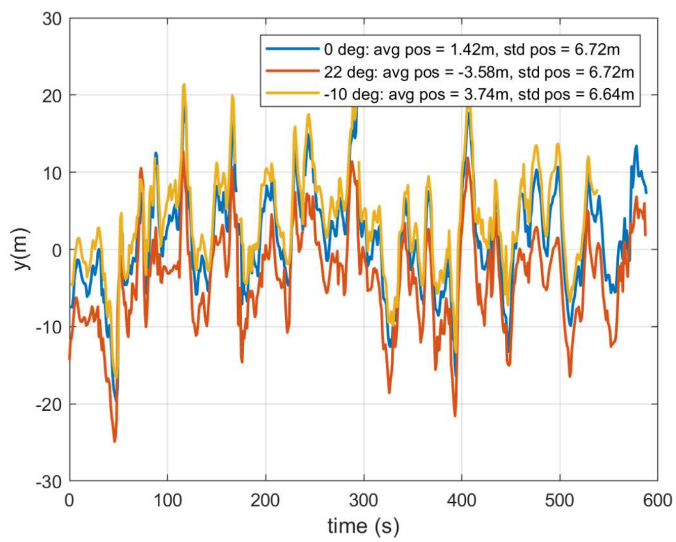

FIGURE 10: TIME HISTORY OF THE HORIZONTAL PLACEMENT OF THE CENTER OF THE WAKE 5 D DOWNWIND FOR THE THREE SIMULATED YAW ANGLES OF TURBINE WTGA1.

3.2 Postprocessing of Simulated Wakes

While the simulated lidar data is very useful for direct comparisons to the experimental data, it produces an incredibly large data set which is inconvenient to both store and post-process. For example, the simulated lidar data to create the curve shown in Figure 9 is on the order of 2.3 TB. Both issues can be somewhat mitigated if, instead of the lidar pattern of data, a flat plane placed at the same distance downstream from the turbine is sampled. Figure 11 shows the wake deficit computed using the simulated SpinnerLidar data compared to what is computed using the data from the plane. The blue line in Figure 11 is the same as the blue line in Figure 9. The wake deficit computed

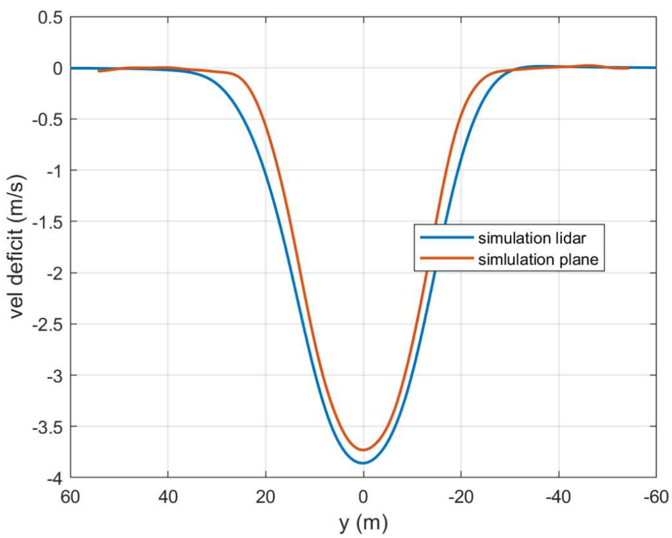

FIGURE 11: COMPARISON OF THE SIMULATED WAKE VELOCITY DEFICIT FOR THE SIMULATED LIDAR DATA AND SIMULATED DATA TAKEN FROM A PLANE 5 D DOWNWIND OF THE TURBINE WTGA1.

from the synthetic lidar matches the shape of the experimental deficit better, with the plane data being too narrow. However, the plane data is slightly closer to the maximum deficit value. The data for the flat plane is on the order of 200 GB.

There is a more significant difference when comparing the horizontal position of the center of the wake computed from the two simulated data sets, as seen in Figure 12. The plane data has wider fluctuations and a different average position in a 10-minute data set. The simulated lidar data appears to filter the wake position.

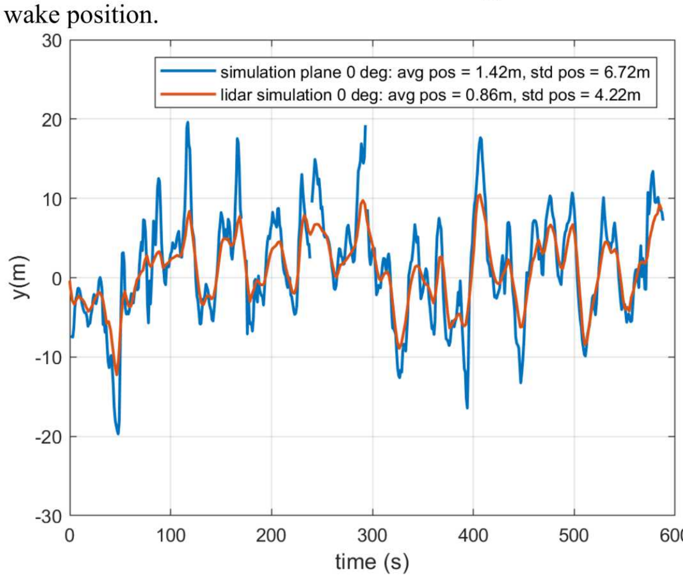

FIGURE 12: COMPARISON OF THE SIMULATED WAKE HORIZONTAL POSITION FOR THE SIMULATED LIDAR DATA AND SIMULATED DATA TAKEN FROM A PLANE AT 5 D DOWNWIND OF THE TURBINE WTGA1.

4 CONCLUSIONS

This paper has summarized the process to model and simulate the inflow, loads, and wake of two turbines at the SWiFT facility for neutral atmospheric conditions from a wake steering experiment. The simulated inflow shows reasonable agreement to the actual experimental conditions. Three yaw conditions of the upwind turbine were simulated, and results showed increased power of the second turbine under positive yaw conditions, but decreased total power for the summed upwind and downwind turbines under the specific conditions of the simulation. The predicted wake deficit qualitatively appears very similar to the wake measured from the experiment.

Future work will include quantitative statistical comparisons between the predicted and measured wake strength and deflection for a range of inflow conditions. The results of this work will be used as part of a larger effort to assess the ability of the Nalu-Wind code to predict the loads, power, and wake quantities of interest under a range of atmospheric inflow conditions. Additionally, future work will include rerunning these simulations with the downstream turbine held stationary to allow a more exact comparison with the conditions in the experimental measurements. Additional downstream locations midway between the leading and downstream turbines will be sampled to compare the wake evolution. Finally, changes in oncoming wind direction are not captured in these simulations. Quantification of this impact will be studied in future work to understand how to appropriately compare to experimental data for a range of uncertain input parameters.

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