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

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ABSTRACT

Power production of two of the three turbines at Sandia's Scaled Wind Farm Technology (SWiFT) site at Texas Tech University's National Wind Institute Research Center were measured experimentally and simulated under a range of operating conditions. The 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 wind turbines from OpenFAST. A computationally efficient simulation, consisting of a coarse precursor without the turbines to set up an atmospheric boundary layer flow followed by a simulation with refinement near the turbines, is demonstrated. Good agreement between simulations and field data is shown. These results demonstrate that multilevel-multifidelity models hold promise for the optimization of the design of entire wind farms with reasonable computational resources.

Keywords: SWiFT, LiDAR, CFD, LES

NOMENCLATURE

C_p	pressure coefficient
D	turbine rotor diameter
LiDAR	light detection and ranging
LES	large eddy simulation
SWiFT	Scaled Wind Farm Technology

INTRODUCTION

Wind Turbines interact with each other through their wakes and with the complex flow of the atmosphere. Modeling this complex flow and the interaction with wind turbines necessitates high fidelity computational fluid dynamics modeling. The use of such methods is challenging and computationally expensive, but allows 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 limited 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 the high fidelity data required to validated Nalu-Wind and similar codes.

The work in this paper covers 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 these conditions, the results in this paper cover only the neutral atmospheric stability inflow condition for three yaw settings. Future efforts will build off of this work, including 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-

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fidelity uncertainty quantification [7] processes as part of the larger validation process.

1.1 Problem Description

In a typical wind farm, wind turbines are placed in multiple rows in order to maintain a compact arrangement. The result of this arrangement is that the front rows of turbines experience the highest velocity of wind but then create a wake that will propagate to the wind turbines in back rows. The velocity deficit in these wakes tends to reduce the output power from those turbines, and hence the net wind farm efficiency may be lower than predicted from the nominal efficiency of a single turbine based on the incoming wind speed with respect to the farm. The SWiFT facility was designed and built to study these wake interactions, so it is an excellent resource for testing and validating methods to characterize wake effects.

This study looks at the interaction between two of the three SWiFT turbines: the front turbine and one that is 5 diameters downwind in the prevailing wind direction. It 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. 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 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 this paper, we have begun the initial stages of a more thorough UQ study by running the three yaw cases. For the complete UQ study, variations around each of the yaw angles would be run in order to identify statistically significant trends, as well as a mesh resolution study. Currently we are showing the validation of the simulations by comparing to the experimental data.

1.2 Computational Approach

We consider the two turbines at the SWiFT site in a neutral atmospheric boundary layer and evaluate the rotor power, thrust, and root-bending moments in the x- and y-directions of both upstream and the downstream turbines. To simulate the wind turbine dynamics, we use the OpenFAST software suite [8] developed at the National Renewable Energy Laboratory (NREL). OpenFAST enables the analysis of complex physical and environment coupling, including turbine controllers, elastic dynamics, and flow-structure interactions with actuator line theory. We use the Vestas V27 in our analysis to match the rotors used at SWiFT; this is a three-bladed turbine with rotor diameter D = 27m and hub height 32.1 m from the ground.

To simulate the turbulent atmospheric boundary layer we used the multiphysics, massively parallel simulation code Nalu-Wind [1]. Nalu-Wind is used to perform large eddy simulations (LES) of the atmospheric boundary layer by solving the Navier-Stokes equations in the low-Mach number approximation with the one-equation, constant coefficient, turbulent kinetic energy model for the subgrid scale stresses [9]. Following [10], the flow-structure interaction from the turbine onto the wind is simulated by adding a body force of the form

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

where f_i is the body force in the momentum equation, l is the distance along an actuator line, F_i are forces computed from common modules of the OpenFAST code-base, and $g\left(\vec{r}(l)\right)$is a smoothing kernel of the form

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

where ϵ is a characteristic length scale that may be tuned to spread the body forces out over a larger volume. In the simulations performed in this study, ϵ was fixed at 10m. The simulation domain was taken to be 3km x 3km x1km in the *x, y*, and *z* directions, and the two wind turbine 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 take two steps: a precursor without the actuator line model to set up the flow and then a simulation with a more refined mesh and the actuator lines that use the precursor data as inputs. 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. It was then run for 20,000 seconds to establish a fully developed turbulent flow.

The boundary conditions 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 used the “abltop” boundary condition from Nalu-Wind.

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 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 then the next. The coarsest level matches the precursor with a spacing of 10m in all directions. The second level has a spacing of 5m; third level has 2.5m; and the forth has 1.25m; 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.

2.1 SWiFT Experimental Data

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. 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). During the summer of 2017, a wake steering experimental campaign was undertaking through a collaboration between Sandia National Laboratories and the National Renewable Energy laboratory with funding from the Wind Energy Technologies Office Atmosphere to Electrons (A2e) program [11-13].

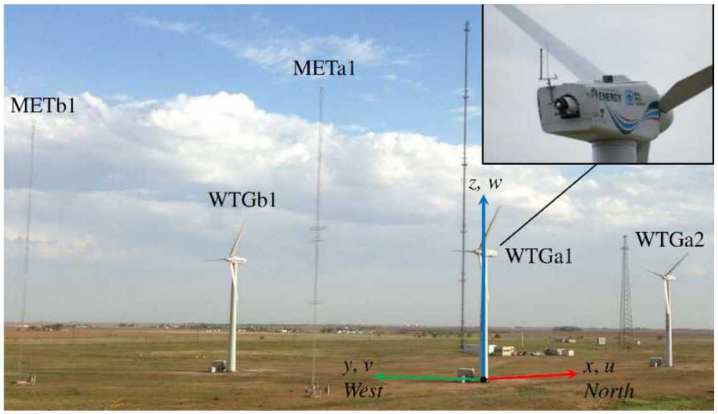

FIGURE 1: IMAGE OF THE THREE V27 ROTORS AND THE MET TOWERS AT THE SWIFT FACILITY. METEOROLOGICAL TOWER META1 AND WIND TURBINES WTGA1 AND WTGA2 WERE MODELED IN THE PRESENT WORK [11].

2.2 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. 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.

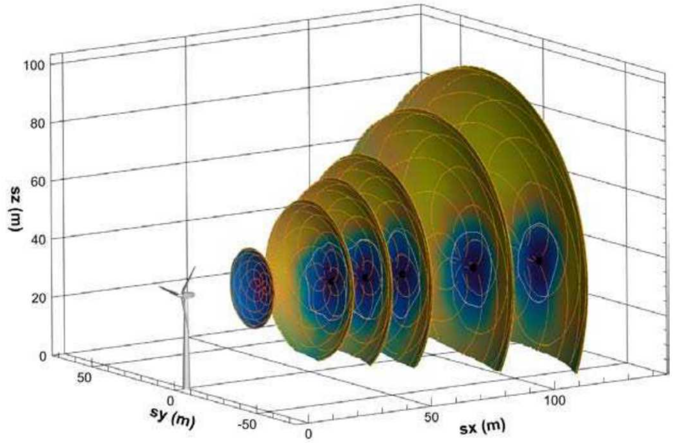

FIGURE 2: A SAMPLE OF THE WAKE DATA GATHERED AT 6 DOWNSTREAM LOCATIONS.

3.1 Inflow Results

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. The temperature was set to be 300 K throughout the domain. To insure that the conditions for the turbine match between the simulation and what was measure, comparisons of the velocity at the MET tower location are made. The MET tower is located 2.5 D in front of the first 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. It also shows the turbulence intensity, which matches quite well. In the simulation, this variable can be controlled with the roughness height parameter, which was set to 0.01.

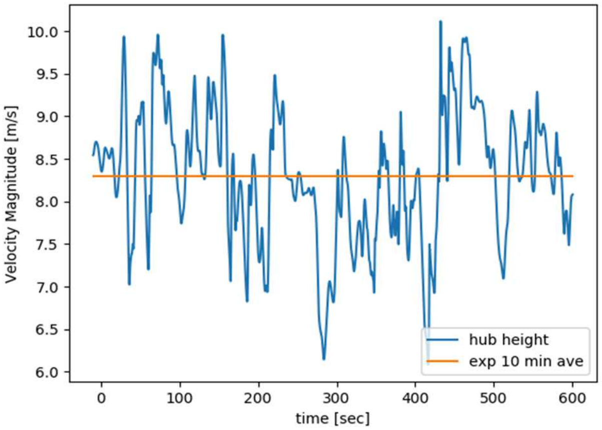

FIGURE 3: THE TIME HISTORY OF THE VELOCITY MAGNITUDE FROM THE MET TOWER LOCATION AT THE HUB HEIGHT (32.1 M) COMPARED TO THE

MEASURED 10 MIN AVERAGE MET TOWER DATA AT THE SAME HEIGHT.

Table 1. 10 minute average velocity magnitude from the MET tower location at the heights that correspond to the hub height and the top and bottom of the rotor.

	Simulation	Experiment
Top of rotor, 45.6 m (m/s)	8.639 +/- 0.699	8.67 +/- 0.85
Hub height, 32.1m (m/s)	8.296 +/- 0.783	8.3 +/- 0.79
Bottom of rotor, 18.6 m (m/s)	7.789 +/- 0.932	7.68 +/- 0.96
Turbulent Intensity, Hub Height	0.094	0.095

3.2 Turbine Results

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

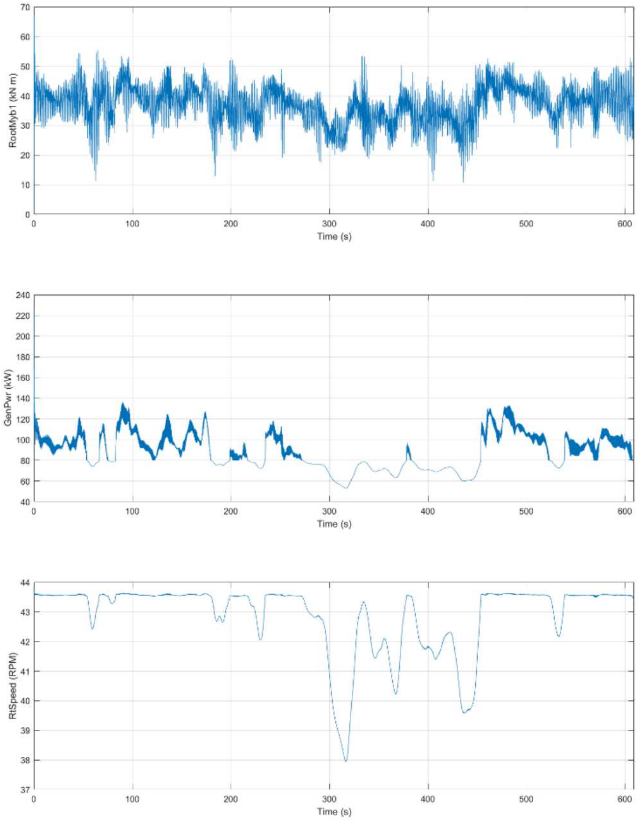

FIGURE 4: THE TIME HISTORY OF THE DATA FROM THE FAST SIMULATION CORRESPONDING TO ROOT BENDING MOMENT OF THE TOWER (kN m), THE GENERATED POWER (kW), THE ROTOR SPEED (RPM), AND THE GENERATOR TORQUE (kN m) for zero yaw angle.

<Note to Editors: Comparisons to the experimental turbine data will be added to this paper after they are released as a blind bench mark project in May.>

During the time that the SWiFT data was taken in the field, only the front turbine data collected. However, the Nalu simulations ran both the front turbine and the one that is 5D downwind. A comparison of loads and power output for both are shown in Table 2 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 2. Yaw angle of Turbine 1 comparison of the 10 minute averages of the root bending moment of the tower (kN m), generated power (kW), the change in the power compared to the yaw = 0° case, and the sum total power of both turbines.

	Turbine 1			
Yaw Turb1 (deg)	RootMyb1 (kN m)	GenPwr (kW)	ΔPwr (kW)	TotPwr (kW)
-10	30.107	69.563	-18.235	
0	36.843	87.798	-	
+22.5	31.782	68.653	-19.145	
	Turbine 2 – 5 D downwind			
-10	22.252	42.617	-5.754	112.180
0	25.794	48.371	-	136.169
+22.5	26.567	51.198	+2.827	119.851

The table shows the effect of the yaw of the first turbine on the power generated. Yawing the 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 there might be a way to tune the yaw of the first row so that sum total power of all rotors might increase, especially if a third or fourth row is considered.

It is also worth noting that root bending moment of the downwind turbine for the yaw = +22.5 ° is also higher than the baseline case.

3.3 Wake Results

The following figures compare the measured LiDAR wake data to the simulated data at a plane 5 D downwind of the first turbine, directly in front of the second turbine. Figure 5 shows the SpinnerLiDAR data with the wake boundary highlighted in white [11]. Figure 6 shows the Nalu-Wind simulated data that is sampled with the same algorithm that is used for the SpinnerLiDAR and interpolated. The black line indicates the wake boundary using this data collection method, while the white line is the boundary that corresponds to the unsampled, more refined data. Figure 7 shows the higher resolution Nalu-Wind data, with the wake boundary shown in white. (This same boundary is shown in Figure 6 for comparison.)

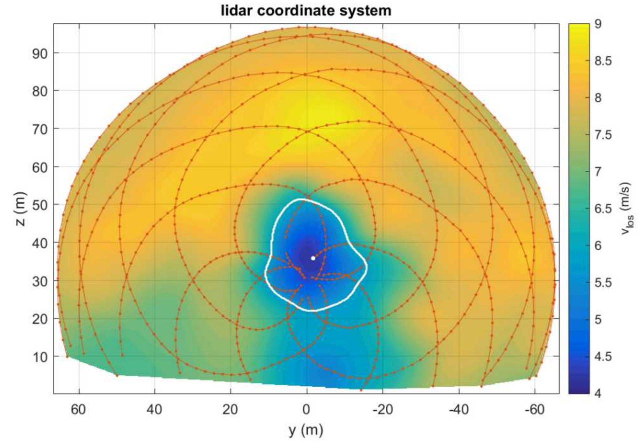

FIGURE 5: A SAMPLE OF THE WAKE DATA FROM THE MEASURED SPINNERLIDAR.

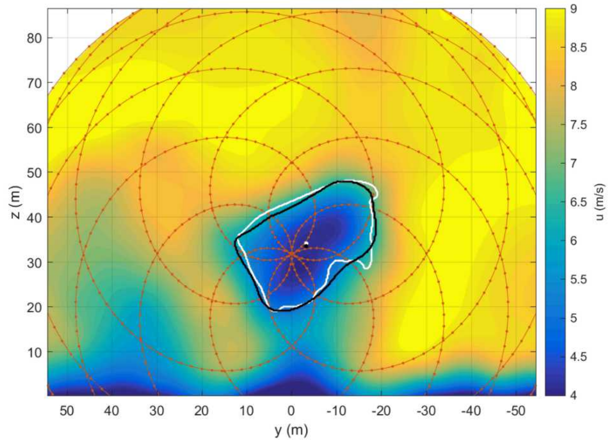

FIGURE 6: SIMULATED WAKE DATA 5 D DOWNWIND, SAMPLED TO MATCH THE EXPERIMENTAL LIDAR DATA.

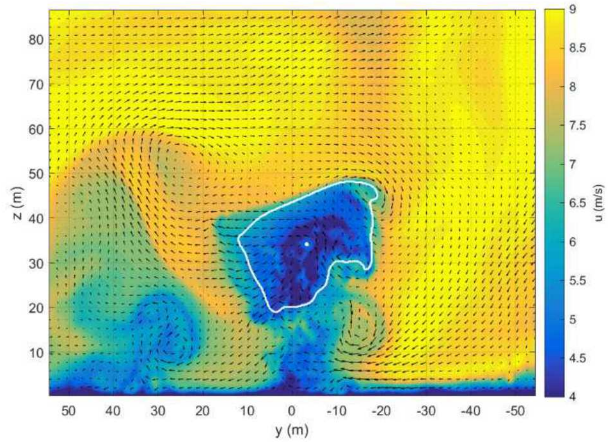

FIGURE 7: SIMULATED WAKE DATA 5 D DOWNWIND, AT ORIGNINAL RESOLUTION.

4.1 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 upwind and downwind turbines. The predicted wake deficit qualitatively appears similar to the wake measured from the experiment, and future work will include quantitative statistical comparison 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.

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