

**Project Title:** Development of a High-Resolution *Virtual Wind Simulator* for Optimal Design of Wind Energy Projects

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**Milestone Number:** 1

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## MLESTONE REPORT

### Executive Summary:

One of the main sources of uncertainty during the design (turbine siting) and operation of wind energy projects is associated with the currently limited and imprecise prediction of wind and turbulence at spatial and temporal scales relevant to wind turbine operation. In addition, there is poor understanding of how the high spatial and temporal variability in the wind and turbulence affects the wind turbine performance (energy output) as well as the fatigue loads on the structures. For example, it has been shown that turbulence effects can lead to a reduction of turbine output as large as 10% or more. In turn, this reduction in turbine output can have large economic consequences. A 1% reduction of energy output from just one 100-megawatt wind facility reduces gross annual revenue by approximately \$165,000 per year (assuming a 32% capacity factor and \$60 per megawatt-hour in payments and tax credits).

Air flow in the atmospheric boundary layer (the lowest layer of the atmosphere, approximately 1 km deep) is highly turbulent and it is strongly modulated by complex interactions with topography and land-surface heterogeneity. This interplay between wind and the underlying terrain results in wind fields that can have large variability within short distances (a few meters) and short time scales (a few minutes). This, in turn, has an important effect on local potential for wind energy production. In spite of this, design and micro-siting of wind energy projects is commonly based on rather crude wind information, namely average wind measurements (no turbulence) collected at one location, or predictions from numerical models that are either too simple (mass-conserving models) or have spatial and temporal resolutions that are too coarse to accurately predict local wind variability at turbine scales (weather models). To date, little effort has been made to develop more accurate numerical tools that can be used to predict high-resolution local wind and turbulence fields with the purpose of guiding the design and turbine siting optimization for wind energy projects. Considering the large investments made every year on new wind energy projects, in addition to upgrades to existing sites, a predictive optimization tool like the one proposed in this project could have a significant impact on the energy production levels and, consequently, on the economic value of those projects.

This project aims at developing a ‘*Virtual Wind Simulator*’ (VWS) that can be used to predict atmospheric boundary layer flow and its interactions with wind turbines and wind farms. The use of the simulator will assist in the improved design of potential wind energy projects by providing more accurate predictions of local and wind turbulence at site and turbine levels. Additionally, the VWS will help increase the level of wind energy utilization and reduce the cost of energy production.

Computational Fluid Dynamics (CFD) methods are used in this project to develop a computational framework for conducting high-resolution simulations of wind turbulence at the meso and micro scales. In particular, the Large-Eddy Simulation (LES) technique will allow for accurate simulations of the turbulent flow at spatial resolutions as small as one to ten meters, and temporal resolutions of just a few seconds. Parameterizations for wind turbine forces will also be developed in the LES framework. In addition, three-dimensional, time-evolving flow fields obtained from LES at any location within a potential wind farm site could then be used as the inflow condition for even more detailed simulations of the turbulent flow around the blades of specific wind turbines using a hybrid Reynolds-Averaged Navier-Stokes (RANS)/LES technique. The SAFL computational models will be coupled to macro-scale regional models to develop a powerful multi-scale computational tool, the VWS. The VWS will integrate the latest advancements in computational fluid dynamics research and provide reliable, high-resolution descriptions of wind turbulence across the entire range of scales that are relevant to wind power production. This information will provide objective, scientifically based criteria that can be used by wind energy project developers for the site-specific, optimal selection and placement (micro-siting) of wind turbines.

As planned, during this reporting period (first semester) activities have been carried out that address two of the specific objectives of the project:

- (a) Development of a multi-scale computational fluid dynamics (CFD) framework for accurate simulation of high-resolution wind and turbulence fields and their effects on wind turbine operation and energy output.
- (b) Validation of the proposed *Virtual Wind Simulator* using high-resolution wind and turbulence measurements collected in an atmospheric boundary layer wind tunnel.

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## **Technical Progress:**

We have made substantial progress in both Task 1 and Task 2, and achieved the milestone set in the contract. The progress made in both tasks is discussed below.

### **Task 1. Development of the *Virtual Wind Simulator* for high-resolution simulations of wind, turbulence and their effect on energy production**

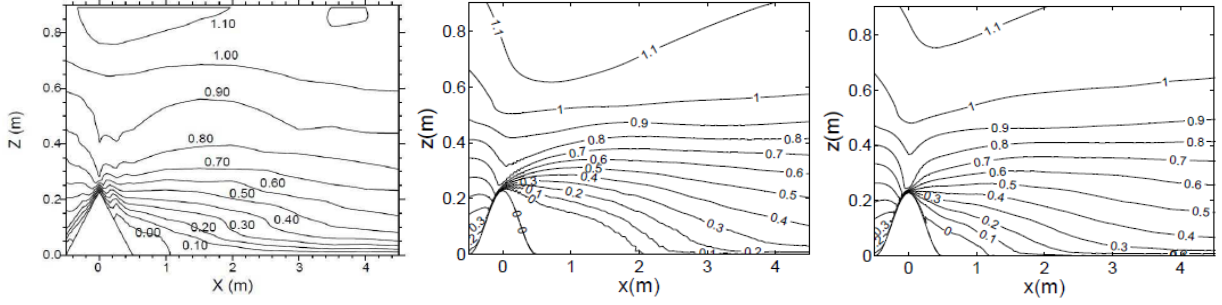
#### **Subtask 1.2. Large-Eddy Simulation (LES)**

Progress has been made on the upgrade of our LES code for simulations of atmospheric boundary layer flow over complex terrain. The following improvements have been made:

- (a) Implementation and testing of state-of-the-art subgrid-scale (SGS) models. In particular, the recently developed tuning-free Lagrangian scale-dependent models (*Stoll and Porté-Agel, 2006*) for both momentum and heat are currently being tested and their performance compared with standard models. This new modeling approach allows for tuning-free simulations, since the model coefficients are calculated dynamically at every time step and position in the flow based on the dynamics of the resolved scales.
- (b) Implementation of a terrain-following coordinate transformation to account for the effects of topography. We have successfully implemented a two-dimensional transformation and it is currently been validated. We plan to extend this approach to three dimensions in the near future.

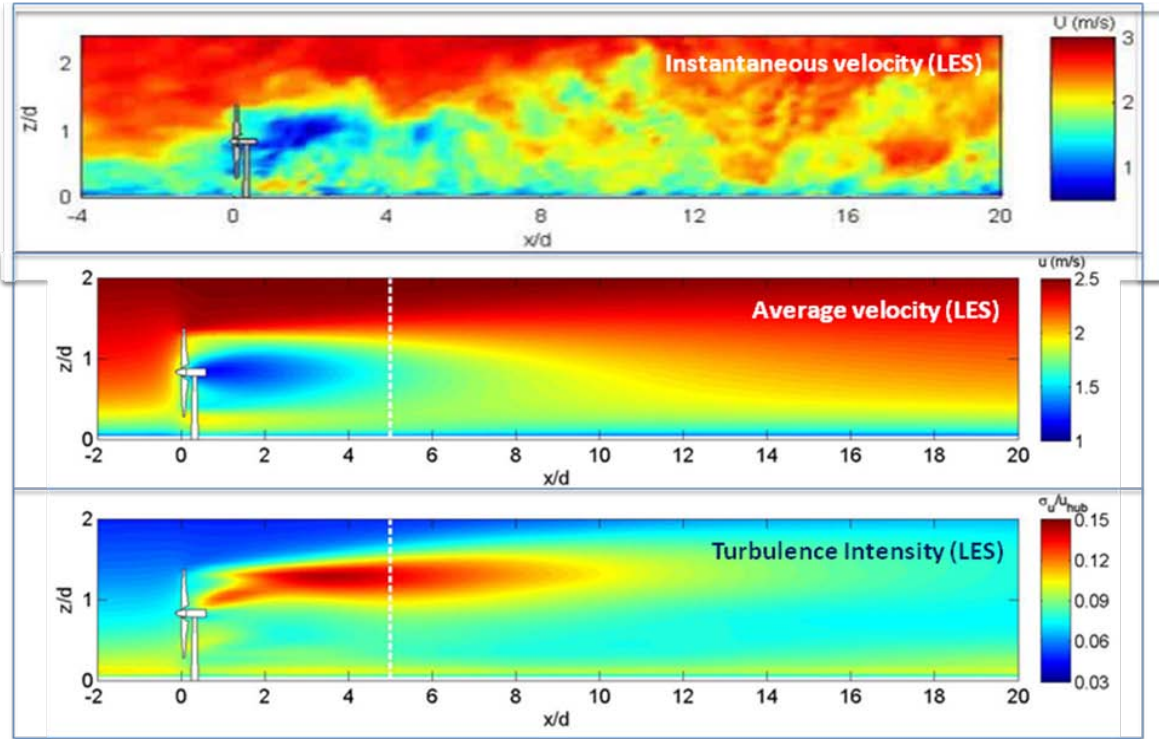
We have started testing the improved LES code in simulations of turbulent boundary layer flow over simple topography, for which wind tunnel measurements are available. **Figure 1** shows a comparison between simulated (using LES with the Lagrangian scale-dependent dynamic model) and measured

velocity distribution around a single hill. The simulations are found to yield turbulence statistics that are in good agreement with the experiments.



**Fig. 1:** Contour plot of streamwise velocity  $U$  (in m/s) in a plane perpendicular to the hill: wind tunnel measurements (left), (b) LES simulations with the classical dynamic model (middle), and LES with the new Lagrangian scale-dependent dynamic model (right).

We have also started deriving and implementing **parameterizations of turbine forces** to represent the interaction between turbine rotors and turbulent boundary layer flow in the context of LES. In particular, we have started using an actuator disk model and combined it with blade element momentum theory. The recently developed Lagrangian scale-dependent dynamic model is used to parameterize the subgrid-scale turbulent fluxes. **Figure 2** shows results from the new large-eddy simulation framework of boundary layer flow with a wind turbine. These results will be compared with the wind tunnel measurements performed in Task 2. Emphasis will be placed on the ability of LES to capture the structure of wind turbine wakes in both single turbine and wind farm configurations.



**Figure 2.** Two dimensional distribution of the simulated (using LES) instantaneous velocity (top), mean velocity (middle) and turbulence intensity (bottom). Vertical ( $z/d$ ) and downwind ( $x/d$ ) positions are normalized using the rotor diameter ( $d$ ).

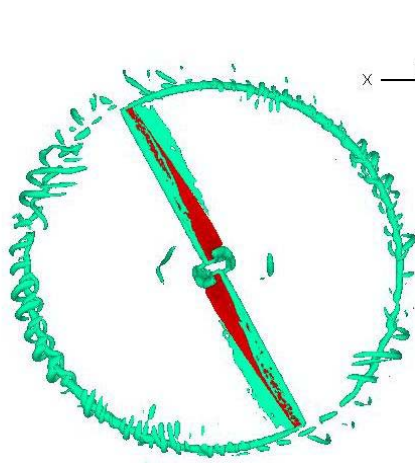
## Subtask 1.2. Hybrid LES/RANS model

### Three-dimensional simulation of flow over a wind turbine rotor

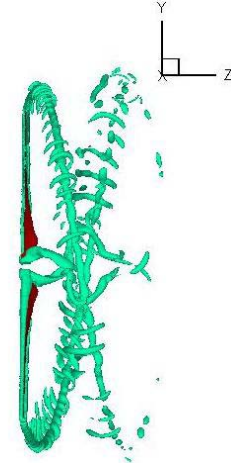
We have carried out preliminary simulations of flow over a two-blade, horizontal axis wind turbine rotor. The blades have S823 and S822 airfoils as used in the NREL experiments [1]. S823 is used for 30% of the span from the tip and the remaining 70% (upto the root) is made up of S822 airfoil. Both the blades are given linear taper and nonlinear twist along the span as specified in the NREL report [1]. The geometry of the blades has been developed using ProEngineer and the unstructured triangular surface mesh on the rotor is created in Gridgen as shown in Figure 1. The rotor is placed in a hexahedral domain with the Cartesian grid in the background. The length of the domain is two and four diameters of the rotor in the upstream and downstream, respectively. In the other four sides the domain is extended to two diameters each from the axis of the rotor. CFD simulations are performed by a finite-volume, incompressible Navier-Stokes solver with immersed boundary method [2]. The rotor is rotated about its horizontal axis at a non-dimensional angular velocity of 4. Figures 2 and 3 show the iso-surface of the  $Q$ -criterion in the wake of the rotor on  $xy$  and  $yz$  planes, respectively. The future work is focused on carrying out turbulent flow simulations using LES models for closure with coupled fluid-structure interaction so that the rotational speed of the turbine and the output power can directly be obtained. The present code is being extended to incorporate the features of overset grids in order to carry out high resolution simulations for turbine-to-turbine interaction and coupling with LES model to account for the effect of ambient turbulent wind speed fluctuations on the output power.



*Figure 1: Unstructured surface mesh on a two-blade rotor.*



*Figure 2: Iso-surface of  $Q$ -criterion on  $xy$ -plane. Free stream flow is along  $z$ -axis*



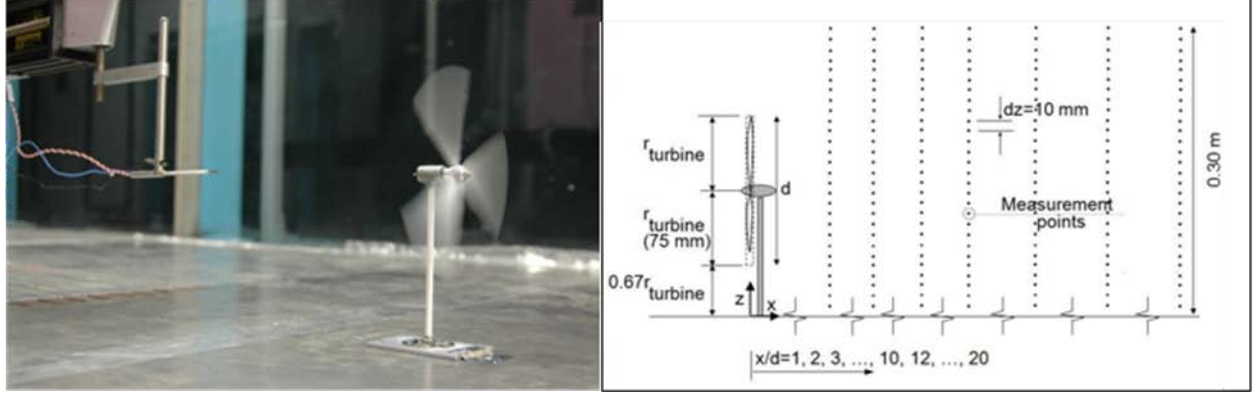
*Figure 3: Iso-surface of  $Q$ -criterion on  $yz$ -plane.*

#### References:

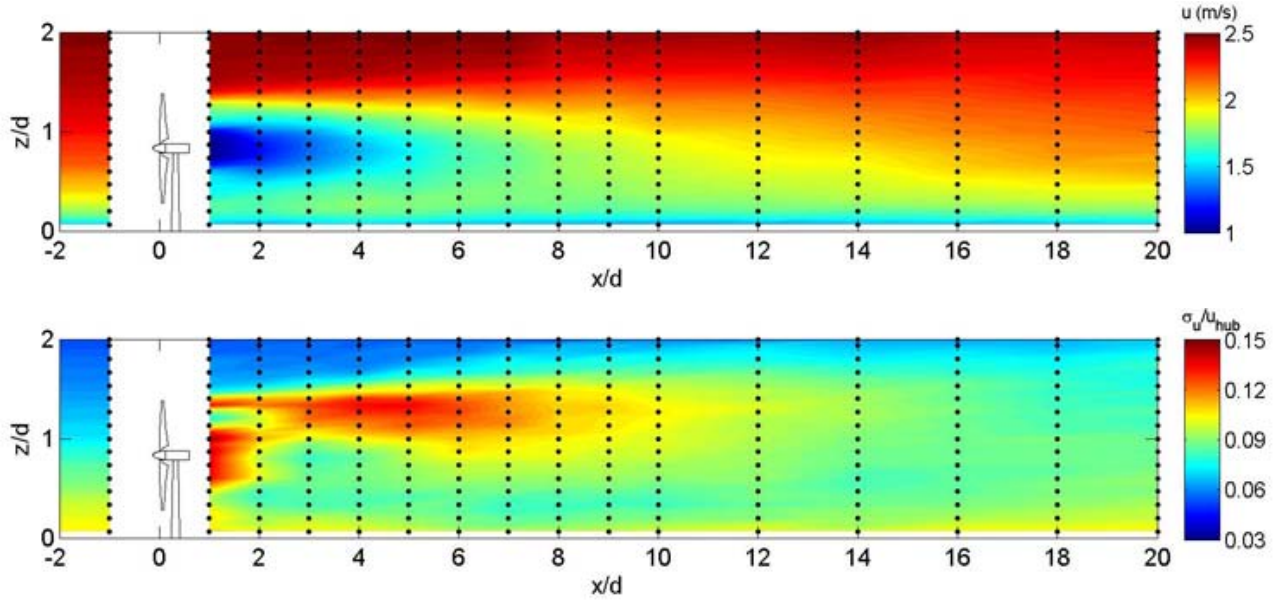
1. Giguere, P. and Selig, M.S., Design of a Tapered and Twisted Blade for the NREL Combined Experiment Rotor. April, 1999, NREL/SR-500-26193.
2. Borazjani, I., Ge, L., Sotiropoulos, F., Curvilinear immersed boundary method for simulating fluid structure interaction with complex 3D rigid bodies. *J. Comp. Physics*, **227**, 2008, 7587-7620.

## Task 2. Validation of the *Virtual Wind Simulator* using wind tunnel measurements

A series of wind tunnel experiments have been designed and are being carried out using miniature wind turbines (Chamorro and Porté-Agel, 2009; *Boundary-Layer Meteorology*) to study the effect of different surface conditions (different roughness) on the structure of wind turbine wakes. High-resolution spatial and temporal fields of velocity and turbulence statistics, collected at different locations (see Figs. 3 and 4) using 3-wire sensors hot-wire/cold-wire anemometers will be used to test and guide the development of parameterizations of wind turbines in computational fluid dynamic models such as LES.



**Figure 3.** Left: Miniature wind turbine placed in a turbulent boundary layer developed at the St. Anthony Falls Laboratory. Right: Schematic of wind turbine dimensions and measurement locations.



**Figure 4.** Wind tunnel measurements in the wake of the miniature wind turbine: Two dimensional distribution of the measured mean velocity (top) and turbulence intensity (bottom). Vertical ( $z/d$ ) and downwind ( $x/d$ ) positions are normalized using the rotor diameter ( $d$ ).



### **Additional Milestones:**

Work is in progress towards Milestone 2.

### **Project Status:**

The project is ahead of schedule due to the fact that work on the project started before the contract was finalized.

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### **Appendix:**

#### **List of publications that have resulted from this research:**

##### **Papers in Refereed Journals**

1. Chamorro, L.P., and F. Porté-Agel, 2009. 'A wind tunnel investigation of wind turbines wakes: Boundary-layer turbulence and surface roughness effects'. *Boundary-Layer Meteorology*, 132: 129-149.
2. Lu, H., and F. Porté-Agel, 2009. 'A modulated subgrid-scale model for large-eddy simulation: Application to a neutral atmospheric boundary layer'. *Physics of Fluids*, under review.

##### **Conference Presentations**

1. Porté-Agel, F., F. Sotiropoulos, R. Conzemius, L. Chamorro, Y.-T. Wu, S. Behara, H. Lu, 2008. 'Development of a high-resolution Virtual Wind Simulator for optimal design of wind energy projects'. E3 -Energy, Economic and Environmental- Conference. Minneapolis, MN, November 2008.
2. Chamorro, L.P., and F. Porté-Agel, 2008. 'A wind tunnel investigation of wind turbine wakes: Boundary-layer turbulence and surface roughness effects'. American Geophysical Union. San Francisco CA, December 2008.
3. Wu, Y.-T., H. Lu, and F. Porté-Agel, 2008. 'A wind tunnel investigation of wind turbine wakes: Boundary-layer turbulence and surface roughness effects'. American Geophysical Union. San

Francisco CA, December 2008.

4. Chamorro, L.P., and F. Porté-Agel, 2009. 'A wind tunnel investigation of wind turbine wakes: Boundary-layer turbulence and surface roughness effects'. European Geophysical Union. Vienna, April, 2009.
5. Porté-Agel, F., Y.-T. Wu, Y.-T., H. Lu, 2009. 'Parameterization of turbulent fluxes and wind-turbine forces in large-eddy simulation'. European Geophysical Union. Vienna, April, 2009.