

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

Contract Number: RD3-42

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MILESTONE REPORT

Executive Summary:

This project aims at developing a ‘*Virtual Wind Simulator*’ (VWS) for the prediction of 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 (quarter) activities have been carried out that address three 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.
- (c) Testing the *Virtual Wind Simulator* using wind and turbulence measurements collected at an operational wind farm.

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Technical Progress:

We have made substantial progress in Task 1, Task 2 and Task 3. The progress made in the three 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

Progress has continued on the development and testing of two of the components of the Virtual Wind Simulator: the Large-Eddy Simulation (LES) code and the RANS/LES code.

Subtask 1.1. LES of the atmospheric boundary layer and turbine models

Large-Eddy Simulation (LES) can potentially provide the kind of high-resolution spatial and temporal information needed to maximize wind energy production and minimize fatigue loads in wind farms. However, the accuracy of LES in simulations of atmospheric boundary layer flow and its interactions with wind turbines hinges on our ability to parameterize **subgrid-scale (SGS) turbulent fluxes** as well as **turbine-induced forces**. The new models can be used to simulate turbulent boundary layer flow over complex terrain and its interactions with wind turbines. Our recent efforts to develop and validate a LES framework for wind energy applications are given below.

(a) Subgrid-scale modeling and validation over complex terrain

Progress has continued on the improvement and validation of our LES code for simulations of atmospheric boundary layer flow over complex terrain. In particular, we have developed and tested state-of-the-art subgrid-scale (SGS) models recently developed by Prof. Porte-Agel's research group. These include the Lagrangian scale-dependent dynamic models (*Stoll and Porte-Agel, 2006*) and a new modulated gradient model (*Lu and Porte-Agel, 2010*). The new models allow for tuning-free simulations and are found to perform better than the existing LES models.

We have tested the new LES framework and SGS models in simulations of a turbulent boundary layer flow over simple topography, for which wind-tunnel measurements are available (Ross et al., 2004). 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. The new models are found to yield improved predictions compared with standard dynamic models (Germano et al., 1991).

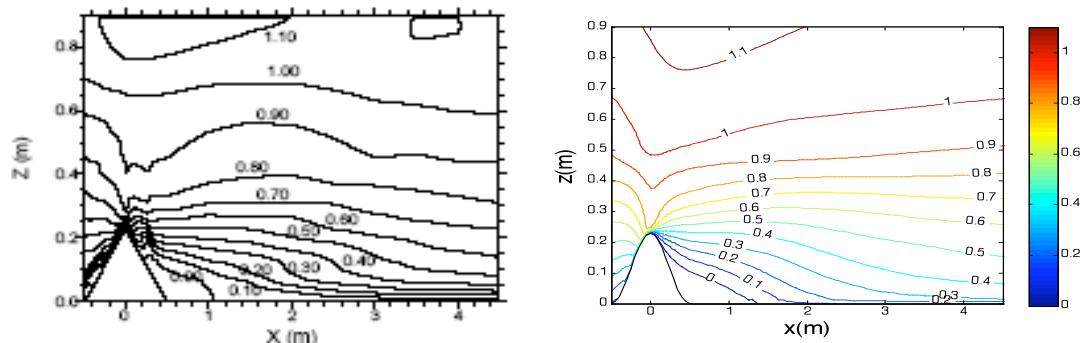


Fig. 1: Contour plot of streamwise velocity U (in m/s) in a plane perpendicular to the hill: (a) wind tunnel measurements, (b) LES simulations with the new Lagrangian scale-dependent dynamic model.

(b) Modeling turbine-induced forces in LES

We have parameterized the turbine-induced forces (e.g., thrust, lift and drag) in LES using two models: (a) the **'standard' actuator-disk model (ADM-NR)**, which calculates only the thrust force and distributes it uniformly over the rotor area; and (b) **the newly developed actuator-disk model with rotation (ADM-R)**, which uses the blade element momentum theory to calculate the lift and drag forces (which produce both thrust and rotation), and distribute them over the rotor disk based on the local blade and flow characteristics. Simulation results have been compared to high-resolution measurements collected with hot wire anemometry in the wake of a miniature wind turbine at the St. Anthony Falls Laboratory atmospheric boundary-layer wind tunnel. (see Task 2) In general, the characteristics of the wakes simulated with the proposed LES framework are in good agreement with the measurements in the far-wake region ($x/d > 10$). The ADM-R yields improved predictions compared with the ADM-NR in the near-wake region, where including turbine-induced flow rotation and accounting for the non-uniformity of the turbine-induced forces appear to be important. Our results also show that the scale-dependent Lagrangian dynamic SGS model is able to account, without any tuning, for the effects of local shear and flow anisotropy on the distribution of the SGS model coefficient. These results are now being compared with the wind tunnel and field measurements collected during Task 2 and Task 3, respectively. Emphasis is placed on the ability of LES to capture the structure of wind turbine wakes under different thermal stratification conditions.

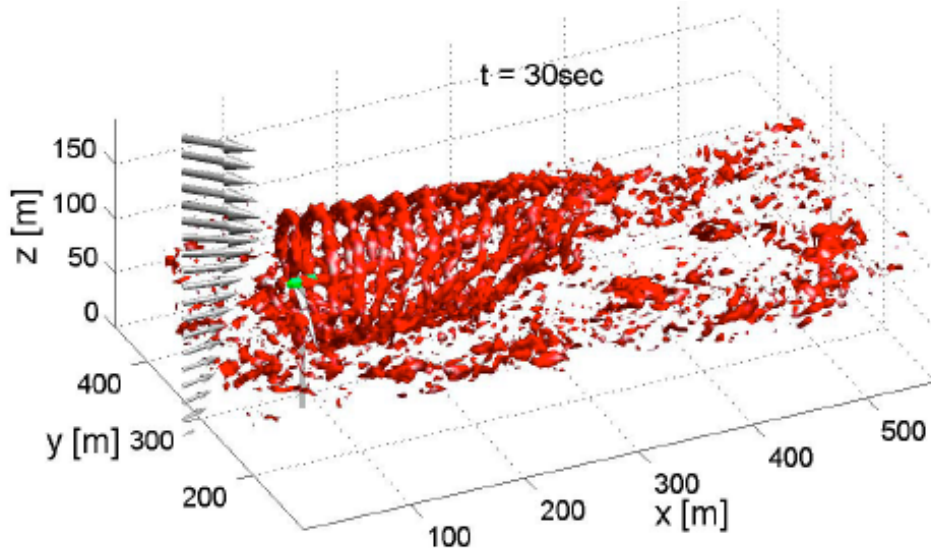


Fig. 2: Isosurface of vorticity in the wake of a 3-blade wind turbine, simulated with LES. The simulations use the recently developed Lagrangian scale-dependent dynamic models for SGS fluxes and actuator line model (ADM) for the turbine-induced forces.

Subtask 1.2. Hybrid LES/RANS model

We have made significant progress in two fronts: 1) Development of a computational framework for modeling multiple turbine rotors and topography effects; and 2) Development of a large-eddy simulation (LES) capability for simulating wind gusts and turbulence effects.

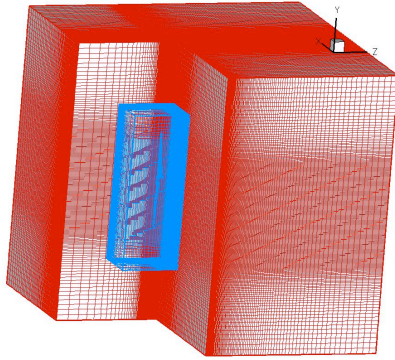


Figure 1. Background mesh with embedded fine mesh around the wind turbine blades.

Computational framework: Our objective is to develop a computational framework that enables us to perform high resolution simulations of multiple wind turbines on complex terrain. To accomplish this we have generalized our fluid/structure interaction curvilinear/immersed boundary (FSI-CURVIB) method [Borazjani et al., *J. Comp. Phys.* **227**, 7587-7620, 2008] to incorporate overset (CHIMERA) grids to increase grid resolution locally near complex immersed boundaries, such as topographic features and multiple turbine rotors. The computational domain (say a section of a wind farm) can be discretized with a Cartesian grid within which a complex topography and/or multiple turbine rotors can be treated either as sharp-interface immersed boundaries or using body fitted overset grids or a combination of the two approaches. We have developed novel interpolation

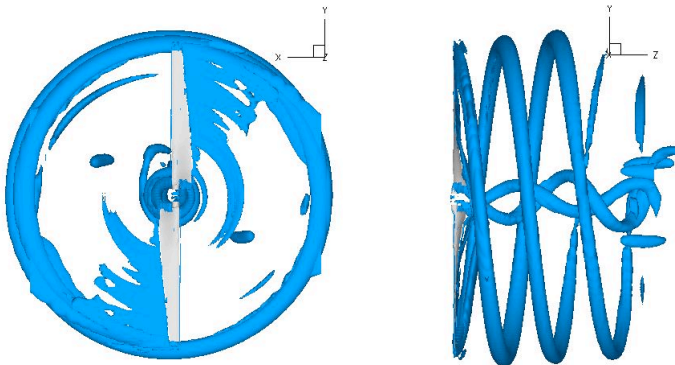


Figure 2. Simulated vortical structures in the wake of the 2-blade NREL rotor rotating at 72 rpm for approach wind speed equal to 15 m/sec

techniques for satisfying mass conservation in the resulting composite grids in conjunction with an efficient fractional step method. The numerical methodology has been generalized to include both inertial and non-inertial frame formulations as well as to enable simulations with hybrid formulations. For example, inertial frame can be used for the fixed background mesh while non-inertial formulations can be employed for the sub-domains containing the rotors that rotate relative to the fixed background mesh.

So far the method has been applied to carry out inviscid simulations for the two-blade NREL wind turbine rotor rotating at 72rpm and wind velocity 15 m/s. An overset grid arrangement with 12 million grid nodes has been used for these simulations and is shown in Figure 1. The computed results after 3 rotor rotations are shown in Figure 2 indicating the ability of the method to resolve the tip vortices emanating from the rotor blades.

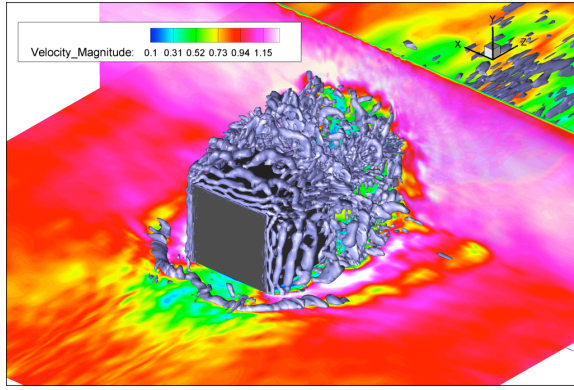


Figure 3. Instantaneous LES flowfield for a cube mounted on a flat plate ($Re = 40,000$)

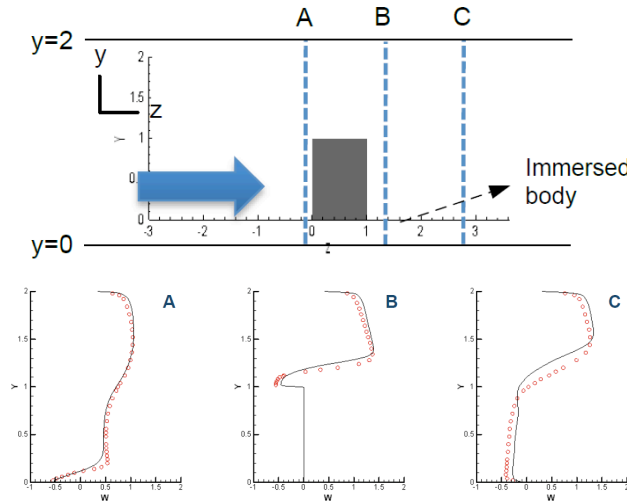


Figure 4. Measured and simulated mean velocity profiles for the cube test case ($Re = 40,000$).

LES capability: To enable turbulence resolving simulations within the aforementioned computational framework, we developed an LES methodology applicable to generalized curvilinear grids with complex immersed boundaries. A dynamic procedure proposed by Germano et al. [*Phys. Fluids A* 3, 1760, 1991] is employed to determine the sub-grid eddy viscosity and three different filtering volumes are employed for filtering the momentum equations along the three curvilinear directions. For the wall-resolving simulations, the velocity at the immersed boundary nodes is computed by linear interpolation in the wall-normal direction to satisfy the no-slip boundary condition. For high Reynolds number flows, the near-wall model of Wang and Moin [*Phys. Fluids* 14, 2043, 2002] is employed.

The LES capability of the code has been extensively validated for various test cases. Figures 3 and 4 show results for flow past a wall mounted cube at $Re = 40,000$, which was studied experimentally by Martinouzi and Tropea [*J. Fluids Eng.* 115, pp. 85–92, 1993]. The simulations were carried out on a grid with 2.7 million grid nodes and as seen the computed results are in good overall agreement with the experimental data.

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, 2010; Boundary-Layer Meteorology*) to study the effect of boundary layer flow and thermal stratification on the structure of wind turbine wakes. High-resolution spatial and temporal fields of velocity and turbulence statistics, collected at different locations (see Figs. 1 and 2) using 3-wire sensors hot-wire/cold-wire anemometers have been used to test and guide the development of parameterizations of wind turbines in computational fluid dynamic models such as LES.

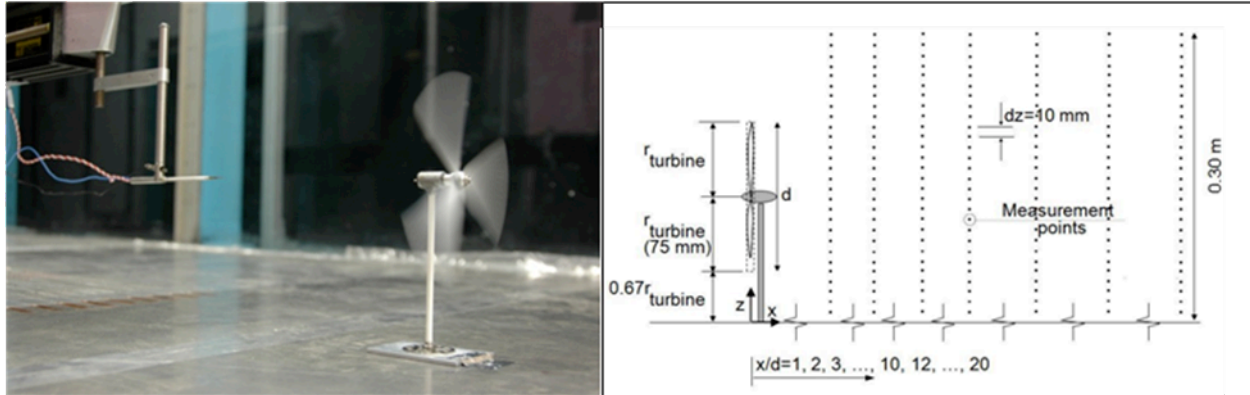


Figure 1. Left: Miniature wind turbine placed in a turbulent boundary layer developed at the St. Anthony Falls Laboratory. Right: Schematic of wind turbine dimensions and measurement locations.

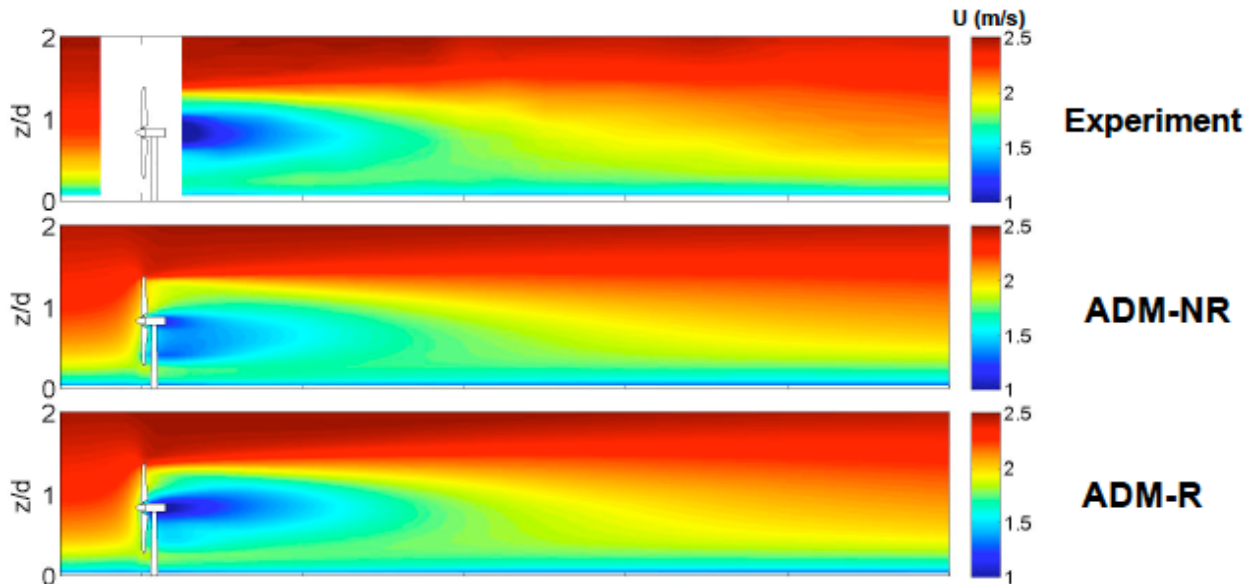


Figure 2. Wind tunnel measurements of average velocity in the wake of the miniature wind turbine (a), and comparison with simulated (from LES) velocity fields obtained with a traditional actuator disk model (b) as well as a modified version developed in this project (b). Note the improvement achieved with the new approach. More details are given by Wu and Porté-Agel (2010).

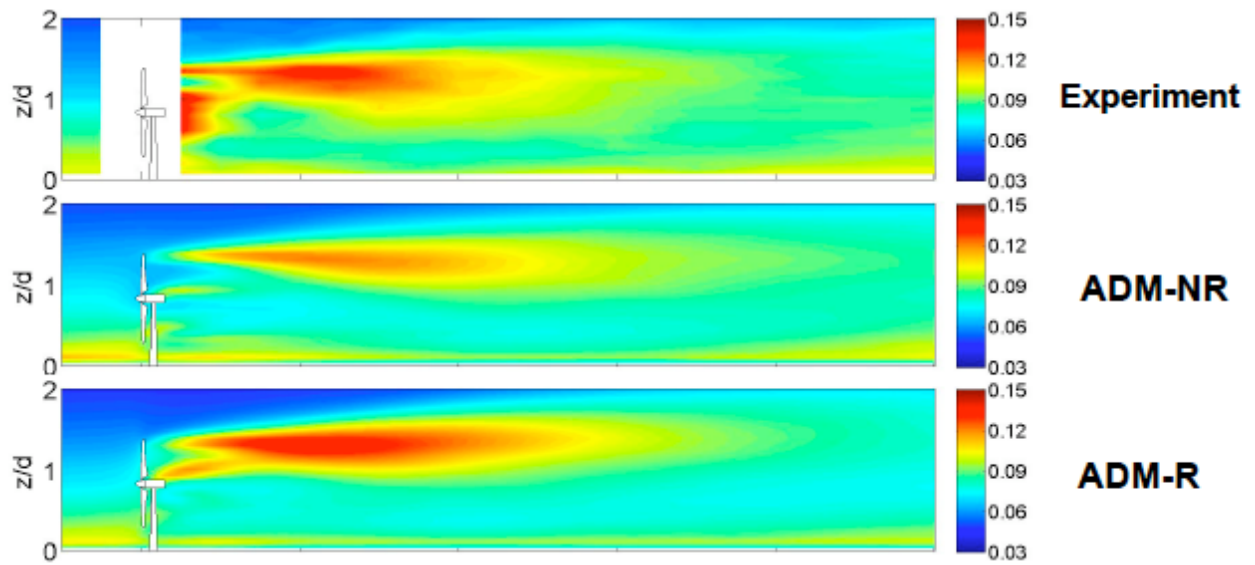


Figure 3. Wind tunnel measurements of average velocity in the wake of the miniature wind turbine (a), and comparison with simulated (from LES) velocity fields obtained with a traditional actuator disk model (b) as well as a modified version developed in this project (b). Note the improvement achieved with the new approach. More details are given by Wu and Porte-Agel (2010).

Task 3. Testing the *Virtual Wind Simulator* using wind and turbulence measurements collected at an operational wind farm

Field measurements have started at the selected field site located at the SW corner of Mower County Wind Farm. Two SODARs (yellow dots in Figure 3) and one LiDAR have been deployed to measure wind velocity profiles. Figure 3 shows a satellite image showing the group of five turbines as well as the location of the SODARS, and a picture of SODAR 169 deployed on the access road. Velocity measurements obtained with the SODARs are currently being used to test the computational models such as LES.



Figure 3. Left: Satellite image of the South-West corner of the Mower County Wind Farm, where the field campaign is under way. Coordinates indicate location of the turbines and SODARS (represented by yellow dots). Right: Picture of SODAR-169 and wind turbines 41 and 42 in the background.

Additional Milestones:

Work is in progress towards Milestone 3.

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, 2010. 'A modulated subgrid-scale model for large-eddy simulation: Application to a neutral atmospheric boundary layer'. *Physics of Fluids*, in press.
3. Chamorro, L.P., and F. Porté-Agel, 2010. 'Thermal stability and boundary-layer effects on wind turbine wakes. A wind tunnel study'. *Boundary-Layer Meteorology*, in press.

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. 'Large-eddy simulation of wind-turbine wakes'. 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.
6. Porté-Agel, F., F. Sotiropoulos, R. Conzemius, L. Chamorro, Y.-T. Wu, S. Behara, H. Lu, 2009. '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.
7. Chamorro, L.P., and F. Porté-Agel, 2009. 'A wind tunnel investigation of wind turbine wakes'. American Physical Society Meeting. Minneapolis, MN, 2009.
8. Porté-Agel, F., Y.-T. Wu, and H. Lu, 2009. 'Large-eddy simulation of wind-turbine wakes'. American Physical Society Meeting. Minneapolis, MN, 2009.