Computational Modeling of Wind-Plant Aerodynamics

M A Sprague,[1] P J Moriarty,[2] M J Churchfield,[2] K Gruchalla,[1] S Lee,[2] J K Lundquist,[2,3] J Michalakes,[1] and A Purkayastha[1]

[1]Computational Science Center, National Renewable Energy Laboratory, Golden, CO 80401, USA

[2]National Wind Technology Center, National Renewable Energy Laboratory, Golden, CO 80401, USA

[3]Department of Atmospheric and Oceanic Sciences, University of Colorado, Boulder, CO 80309, USA

E-mail: `michael.a.sprague@nrel.gov`

Abstract. As the US moves toward 20% wind power by 2030, computational modeling will play an increasingly important role in determining wind-plant siting, designing more efficient and reliable wind turbines, and understanding the interaction between large wind plants and regional weather. From a computing perspective, however, adequately resolving the relevant scales of wind-energy production is a petascale problem verging on exascale. In this paper we discuss the challenges associated with computational simulation of the multiscale wind-plant system, which includes turbine-scale turbulence, atmospheric-boundary-layer turbulence, and regional-weather variation. An overview of computational modeling approaches is presented, and our particular modeling strategy is described, which involves modification and coupling of three open-source codes—FAST, OpenFOAM, and WRF, for structure aeroelasticity, local fluid dynamics, and mesoscale fluid dynamics, respectively. Preliminary results are presented.

1. Introduction

With the US moving toward 20% wind energy by 2030 [1] and with the increasing accessibility of multicore desktop and supercomputers, computational modeling will play an increasingly important role in the wind-energy community. Computational modeling can be used to study complex physical interactions in wind plants, to improve siting of wind plants and individual turbines within a wind plant, to create better control systems, and to optimize structural designs for the next generation of large turbines.

In this paper, we focus on the computational simulation of a full wind-turbine power plant, along with its interaction with regional weather. This problem is a multiscale, multiphysics challenge spanning from turbine structural dynamics and blade-scale turbulence at the smallest scales to mesoscale atmospheric flow at the largest. Large wind plants are consistently found to perform below expectations. Underperformance is believed to be tied, in part, to inadequate accounting for the effects of atmospheric variability on both turbine performance and on the propagation of turbine wakes. Wakes have increased turbulence intensity and lower mean velocity. Turbine wakes may also be responsible for the structural loads that cause wind-plant turbines to suffer premature failure; downstream turbines experience extreme loading that is 33% higher than that of stand-alone turbines [8]. Moreover, little is known about the interaction between large wind plants and regional weather.

To better understand these phenomena, we are creating a modular assembly of coupled models where each model captures the most important physics of interest at sufficient fidelity and at minimum computational cost. This modular approach can be leveraged to allow for a hierarchy of interchangeable models for each system. For example, if one is interested in turbine-wake interaction within a wind plant, one might use simplified reduced-order models for blade structural dynamics but use a high-fidelity computational fluid dynamics (CFD) code to accurately simulate the turbulent flow. Alternatively, if one is interested in a prediction of localized blade failure, a high-fidelity finite-element (FE) model might be used for the blade, while a reduced-order tool or CFD with a simplified turbulence model might be used as the wake model. Below we describe modeling challenges for each subsystem, viable model choices, and model-coupling ideas. We discuss our preliminary model choices and show initial results.

2. Computational-modeling challenges and approaches

2.1. Model regimes

2.1.1. Turbine structural dynamics Models for turbine structural components (e.g., blades and towers) can be grouped into two categories: high-fidelity models, which are founded on first principles (e.g., shell FEs [12, 4]), and reduced-order models, which capture only salient features (e.g., beam FE [13] and modal [11] models). In analyses concerned with blade optimization, high-fidelity FE models are required. For turbine certification, where thousands of runs are required to characterize turbine loading, reduced-order models are appropriate. Here, we are focused on wind-plant aerodynamics and we employ the open-source aero-elastic simulation code FAST [11] (Fatigue, Aerodynamics, Structures, and Turbulence), which is an industry standard for wind-turbine characterization and certification. FAST is an assembly of reduced-order models representing an entire wind turbine. However, the tools being developed here are designed such that a high-fidelity FE blade model can be interchanged with the reduced-order blade model in FAST, which may be necessary to capture the nonlinear dynamics associated with modern blades that are long and highly flexible.

2.1.2. Turbine-proximity fluid dynamics Air flow in a wind plant is well modeled by the incompressible Navier-Stokes (NS) equations, where pressure is a "slave" quantity whose purpose is to maintain mass continuity. The incompressible-flow simplification is justified because turbines are designed such that the Mach number, which is a maximum at blade tips, does not exceed about 0.23 due to acoustic noise constraints [25]; only slightly larger Mach numbers can be found in large offshore wind turbines.

While flow is represented well by the incompressible NS equations, turbine-induced turbulence in a wake has a range of interacting scales that makes direct numerical simulation (DNS) of all relevant scales impossible. Therefore, turbulence modeling over some range of scales is required. Because of this restriction, as well as limited computational resources, CFD based on the Reynolds-averaged NS (RANS) approximation, which provides a statistical description of the flow, has dominated wind-energy simulations [23]. However, with the increased accessibility of large-scale computing, large-eddy simulation (LES), which directly resolves the largest turbulent structures and filters the smallest, is becoming increasingly feasible for wind energy [5].

Important to turbine simulation is consideration of the atmospheric boundary layer (ABL), its stability, and how it interacts with turbine wakes. While these issues are often overlooked in wind-energy simulations [23], they are important when considering large turbines and turbine plants. For example, a wind plant's efficiency can be significantly increased when operating in an unstable ABL, as opposed to a stable ABL [10], whereas the opposite is seen for a stand-alone turbine [26]. In order to capture the relevant ABL scales, simulation domains must be at least about $3 \times 3 \times 1$ km^3 and must have a grid resolution of about 10 m [16, 6]. However, localized grid refinement is appropriate if turbines are included, where resolution requirements (with suitable turbulence modeling) are on the order of 1 m.

In our code suite, local fluid dynamics are simulated with the open-source CFD tool OpenFOAM® [2], which is an unstructured finite-volume solver equipped with various LES and RANS models for incompressible flow. The finite-volume method is well suited to wind-energy simulation in that complicated geometry (e.g., topography) can be accommodated and localized grid refinement is feasible. Our OpenFOAM implementation employs the standard Smagorinsky LES model, a Monin-Obukhov wall model, and PISO [9] time integration. We have equipped it for ABL simulations [6] and have demonstrated (in DNS of turbulent channel flow [17]) linear strong scaling when there are at least about 40k grid points per core [22].

2.1.3. Mesoscale fluid dynamics At the mesoscale, moist atmospheric flow is well modeled by the fully compressible Euler equations with appropriate models for dissipation and for meteorological physics. Compressibility is important here to allow for the thermodynamic dependence of pressure [18]. We simulate the mesoscale fluid dynamics with the Weather Research and Forecasting (WRF) code [20], which is equipped with nested grids (for focused high-resolution studies) and LES capabilities and is well suited to large-scale parallel computing [15]. WRF employs finite-difference spatial discretization and explicit time integration.

2.2. Model coupling

2.2.1. Fluid-structure coupling We follow Sanderse et al. [19] and categorize approaches for coupling the fluid and turbine structural components (e.g., blades and towers) as direct methods or generalized-actuator-disk (GAD) methods. In the former, while the blade/tower may be modeled as a reduced-order or high-fidelity model, the fluid mesh accurately conforms to the true structure boundary, and no-slip or wall-model boundary conditions are employed. Such discretization necessitates complicated meshing and/or mesh-coupling methods such as overset grids (e.g., [27]), sliding interfaces that separate rotating and non-rotating domains (e.g., [24]), and/or arbitrary-Euler-Lagrangian (ALE)-type methods. Fluid forcing on the structure can be calculated directly from the fluid stress tensor. The computational cost of this rigorous approach makes such calculations impractical for multiturbine simulations. In GAD methods, fluid-structure forces are approximated from aerodynamic look-up tables based on relative fluid velocities. Fluid forcing is effected through a momentum forcing term. In our approach, we employ a GAD model in the form of an actuator line [21], which is a more realistic approximation than a porous disk, in that it is capable of inducing tip vortices. Structural forcing and response are calculated within FAST.

2.2.2. WRF-OpenFOAM coupling Coupling between WRF and OpenFOAM is challenging for the following reasons. First, the codes are solving different physics (incompressible Navier-Stokes in OpenFOAM and compressible Euler in WRF). Second, spatial and temporal grids are, in general, non-matching and the WRF grid moves in the vertical with time-dependent pressure variation. These issues can have implications for numerical stability and convergence. Third, an appropriate mechanism is not obvious for transferring turbulent energy from one code to the other. While there have been limited efforts to couple an incompressible CFD code and WRF [7, 3], there is no evidence of successful interactive coupling. Aside from some preliminary work on compressible-incompressible coupling [14], effective two-way coupling remains an important open issue that we are actively pursuing. In preliminary work described below, we use one-way WRF-to-OpenFOAM coupling.

2.2.3. Computational/software issues From a software and computing perspective, adequately resolving the relevant scales of the wind-energy problem is a petascale problem verging on exascale. Model coupling for multiscale wind-energy simulation requires efficient transfer and interpolation of forcing and feedback data between component models scaled to thousands of processors. As with the individual components, the coupling and synchronization mechanism of the overall system must scale efficiently to avoid becoming a bottleneck. Issues for performance and scaling at the coupled-system level include the transfer and interpolation of data between components and load imbalance.

3. Preliminary results and future work

We discuss here some preliminary work and future directions. Figure 1 shows preliminary LES simulations with OpenFOAM in an ABL where horizontal periodic boundary conditions are employed. Here, the rotating single and multiple turbines force the fluid through blade actuator lines. Figure 2 shows preliminary coupled OpenFOAM-WRF LES simulations of the ABL. This figure illustrates that care must be taken to effectively translate turbulent structures from WRF into OpenFOAM. Future work includes (1) improving the one- and two-way coupling between OpenFOAM and WRF, with attention on compressible/incompressible effects and transfer of turbulent energy, (2) improving two-way OpenFOAM-FAST coupling, (3) adding high-fidelity finite-element structural modeling capability, and (4) validation with wind-plant observation data.

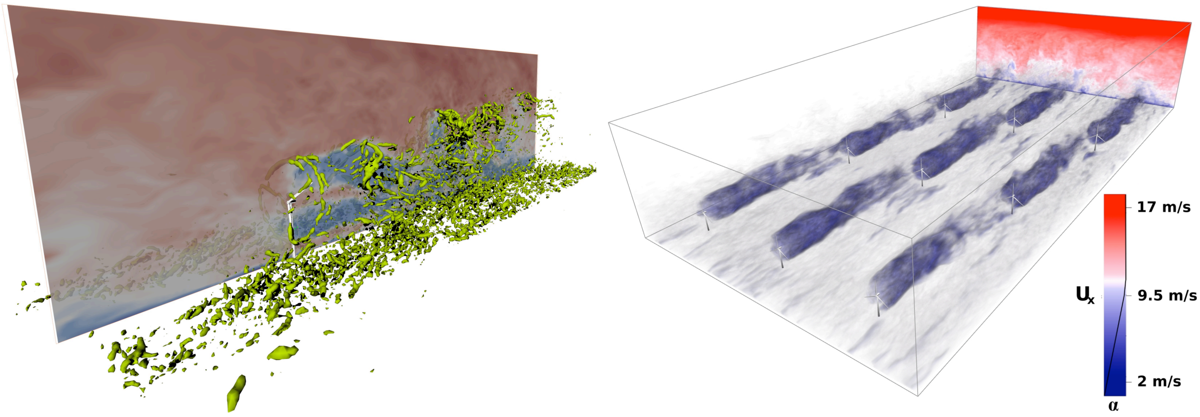

Figure 1. Preliminary OpenFOAM (LES) simulations in a neutrally stable ABL with turbines represented as actuator lines. (a) Locally refined grid with a single turbine; vertical-plane data are streamwise velocity magnitude, and green isosurfaces are of the Q-criterion. (b) Volume rendering of streamwise velocity in a wind-turbine plant.

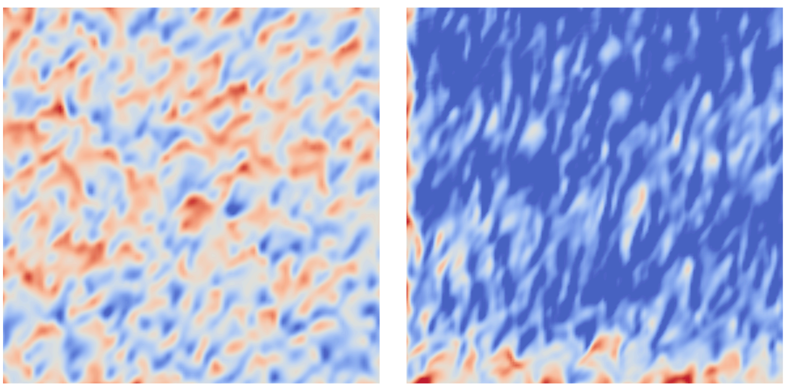

Figure 2. Horizontal slices at 10 m elevation showing northward velocity calculated using OpenFOAM in a $3 \times 3 \times 1$ km^3 domain: (a) WRF (LES) initialization and (b) 8 minutes later. WRF inflow was specified on South and West faces with outflow conditions for the others. Results illustrate how turbulence structure significantly changes when passed from WRF to OpenFOAM.

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