HIGH-FIDELITY BLADE-RESOLVED WIND FARM SIMULATIONS

Andrew Kirby, University of Wyoming
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EXECUTIVE SUMMARY

Wind energy is an emergent renewable energy source throughout the world. Costs have dropped dramatically over the past two decades, making it a desirable alternative to fossil fuels. Improvement in wind energy application simulation technologies may have a profound economic impact through improved wind plant efficiency. Complete wind farm simulations will elucidate the flow physics that govern overall wind plant performance, including complex blade aerodynamics, turbine–turbine wake interference, and complex terrain effects. High-fidelity simulations of complete wind farm installations using blade-resolved models for wind turbines in complex terrain and atmospheric conditions will set unprecedented milestones in wind farm modeling capabilities. The goal of this work is to develop state-of-the-art aerodynamics modeling techniques using high-fidelity blade-resolved turbine models to simulate complete wind farms. The numerical methods in this research utilize multiple mesh and multiple computational fluid dynamics flow solvers coupled in an overset framework.

RESEARCH CHALLENGE

Predicting wind farm performance represents a complex problem that spans spatial and temporal scales over 10 orders of magnitude from the continental scales that govern wind patterns to the thin boundary layers over the wind turbine blades. Improved prediction of wind farm productivity requires good resolution of flow structures and reliable modeling of turbulent eddies in this entire length-scale range. The temporal scales are also quite disparate: wind turbine rotation periods are of the order of seconds, while atmospheric inflow modes have time periods ranging from a few minutes to hours. Structural mechanics further compound this problem by introducing yet another set of temporal scales such as those due to significant elastic vibrations of the rotor blade and masts, which can be one to two orders of magnitude smaller than the wind turbine rotor period.

The aim of this work is to demonstrate the feasibility of simulating entire wind farm installations, including atmospheric turbulence effects in complex terrain with high-fidelity methods with the goal of impacting wind farm siting decisions and wind turbine design practices. A major objective is to advance the state of the art of computational methods for achieving realistic and affordable petaflop simulations of time-dependent flows over complex configurations with moving bodies and overlapping mesh systems. Unsteady flows in nature are dictated by vortex structures and turbulent eddies that span relatively large scales of atmospheric dynamics to relatively small scales near moving wall boundaries (ocean surface, wind turbines, aircraft, etc.).

METHODS & CODES

At the University of Wyoming, we have developed a high-fidelity multiscale modeling methodology that can accurately predict the performance of wind turbines by reliably modeling the entire range of these spatial and temporal scales. The software framework uses the Large-Eddy Simulation (LES) approach for prediction of the turbulent flow fields in the off-body region. We used a multimesh framework to provide accurate and efficient prediction capabilities for vortex-dominated wind turbine flow fields.

We realized the multimesh paradigm by using multiple flow solvers, with each code optimized for the corresponding mesh type. In regions near wind turbine blades and towers, an unstructured mesh was used to handle the complex geometry and thin boundary layer regions. These mesh systems rotate with the blades and are overset on a background dynamically adaptive Cartesian mesh that is responsible for simulating the wakes propagating downstream of the turbines. A fully parallelized and load balanced adaptive mesh refinement capability was incorporated in the Cartesian mesh system to enable propagation of highly resolved wake features over long distances. Flow field values were interpolated in the regions of overlap between these two mesh systems at each timestep, and these overlapping patterns were computed dynamically in parallel using efficient search algorithms.

Nearly all software used on our framework was developed in-house at the University of Wyoming with the exception of the p4est adaptive mesh refinement framework. The two flow solvers we developed are NSU3D, an unstructured 3D finite-volume solver, and dg4est, a high-order discontinuous Galerkin finite-element solver. The overset solver we used was TIOGA, developed by Jay Sitaraman of Parallel Geometric Algorithms, LLC. The complete framework is known as the Wyoming Wind and Aerodynamics Applications Komputation Environment (WwAaKE3D).

Figure 1: Wind turbine wake slice visualizing instantaneous normalized absolute tangential flow velocity demonstrating the wake propagation downstream of a small-scale rotor design with a two-meter diameter.

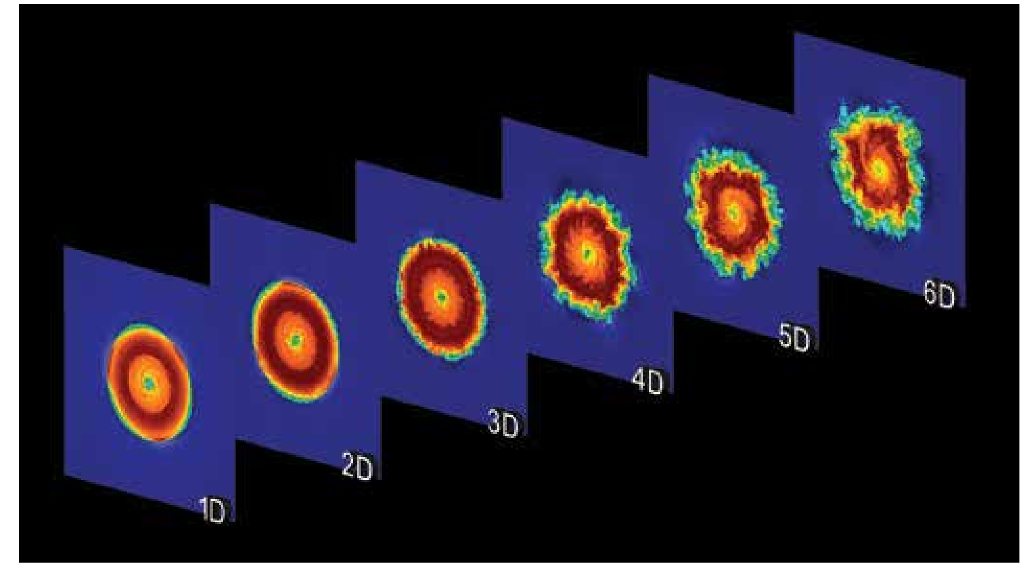

Figure 2: Instantaneous axial momentum at multiple downstream positions of the National Renewable Energy Laboratory WindPACT–1.5MW wind turbine.

RESULTS & IMPACT

Understanding the aerodynamics of the wind turbine is an essential aspect for energy production optimization, not only for the individual turbine but also for the complete wind farm. Exploration of wind turbine yawing for wind farm optimization introduces complex aerodynamics and possible structural effects. These complex aerodynamics, such as flow separation, cannot be captured accurately using lower-fidelity methods, such as actuator disk and actuator line methods. High-fidelity blade-resolved simulations are required for accurate prediction.

As a result of this research, state-of-the-art simulation analysis is now feasible through this computational framework. New pioneering analysis is now accessible, enabling the fundamental understanding of these complex wind turbine wake physics and their interactions. In particular, blade-resolved simulations allow for the study of the impact of complex aerodynamics on wake characteristics through a first-principles viewpoint.

At present, coupled experimental and computational studies are underway at the University of Wyoming (see Figs. 1 and 2) with the overarching goal of providing the first validation wake data and first validated wind energy computational framework. By generating validated wake simulated data, lower-fidelity models can be more accurately derived with the possibility of improving full wind farm simulations at low cost thereby improving wind farm layout and wind farm efficiency. This can have a far-reaching impact on the renewable energy sector around the globe.

WHY BLUE WATERS

Blue Waters offers a unique environment not only as a computational resource but also for its expert project staff. The design of Blue Waters makes it an excellent machine geared toward scientific output rather than just its flop rate. Blue Waters allowed us to perform large-scale wind farm simulations using tens of thousands of compute cores. In addition, the project staff provided excellent insight for optimizing throughput.

PUBLICATIONS & DATA SETS:

Kirby, A., et al., Wind Turbine Wake Dynamics Analysis Using a High-Fidelity Simulation Framework with Blade-Resolved Turbine Models. *Proceedings of the 2018 Wind Energy Symposium* (AIAA SciTech Forum, Kissimmee, Florida), DOI:10.2514/6.2018-0256.

Kirby, A., et al., Visualization and Data Analytics Challenges of Large-Scale High-Fidelity Numerical Simulations of Wind Energy Applications. *Proceedings of the 2018 AIAA Aerospace Sciences Meeting* (AIAA SciTech Forum, Kissimmee, Florida), DOI:10.2514/6.2018-1171.

Andrew Kirby completed a PhD in mechanical engineering in May 2018. He worked under the supervision of Dimitri Mavriplis at the University of Wyoming.