High-Fidelity Blade-Resolved Wind Plant Modeling

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1 INTRODUCTION

Wind energy today is becoming an emergent renewable energy source throughout the United States and the world. Wind energy costs have dropped dramatically over the past two decades making wind energy a desirable alternative to fossil fuels. Improvement in wind energy application simulation technologies may have a profound impact economically through improved wind plant efficiency. The goal of this work is to develop state-of-the-art modeling techniques from an aerodynamics perspective using high-fidelity blade-resolved turbine models to simulate complete wind farms. The numerical methods in this research utilize multiple mesh and multiple computational flue dynamics flow solvers coupled in an overset framework.

High-fidelity numerical simulation of wind energy applications is becoming a precedent for future technologies not only for the wind energy sector but also for lower-fidelity modeling as well. The need for high-fidelity simulation using a complete geometric description of wind turbines with tower and nacelle is essential for capturing the true aerodynamic nature of the flow that is highly turbulent and chaotic. This is especially important in the study of downstream wake effects on wind turbines which cause the primary decrease in wind plant power production efficiency. Wind farm simulation is a truly multi-scale problem; the smallest turbulent structures are on the order of microns and the largest scales present from atmospheric turbulent inflow are on the order of tens of kilometers. To simulate ten orders of spatial magnitude, tens to hundreds of thousands of computing cores are required to simulate this grand challenge problem.

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2 METHODS

The computational framework deployed in this work is known as the **W**yoming **W**ind and **A**erospace **A**pplications **K**omputation **E**nvironment (W^2A^2KE3D). W^2A^2KE3D has been previously demonstrated on various aerodynamics problems such as flow over the NACA0015 wing and flow over a sphere[2]. Additionally, wind energy application results were presented using the NREL Unsteady Aerodynamics Experiment Phase VI, NREL 5MW, and Siemens SWT-2.3-93[8, 9]. The framework is derived to have a flexible solver and mesh system paradigm in order to perform simulations for a large class of problems in aerospace and wind energy.

W^2A^2KE3D is designed to support a dynamic overset system using multiple flow solvers and multiple computational meshes. The mesh system generally consists of a collection of *near-body* and *off-body* meshes. The near-body meshes are inherently unstructured to model the complex geometry and resolve boundary layers of wind turbine bodies. The off-body mesh is a dynamically adaptive Cartesian grid system. The use of Cartesian meshes in the off-body region allows for efficient flow solvers, efficient storage, and ease of dynamic solution-based mesh adaption. This multiple mesh paradigm allows for effective use of solver and mesh technologies in variable flow conditions. This hypothesis holds strongly for wind energy applications that require capturing boundary layer phenomenon as well as wake dynamics. Figure 1 demonstrates an overset mesh system of a traditional three bladed wind turbine with a tower and nacelle. Each blade is represented by a single mesh that is replicated, transitioned, and rotated to the correct starting position. The tower geometry is fitted with an independent unstructured near-body mesh component.

The W^2A^2KE3D framework allows for multiple CFD solvers individually optimized for their respective mesh system in the multiple-mesh paradigm. The use of multiple meshes and multiple flow solvers introduces the requirement of coordination. A C-programming-language based driver choreographs all flow solvers and all mesh systems. This driver allows for solvers to run on disjoint groups of CPU cores, allowing for variable amounts of computational resources to be allocated appropriately where needed. This is particularly important for the off-body solver which uses a dynamically adaptive mesh. During the evolution of a wind turbine simulation, the flow features of interest such as the wake require additional mesh resolution. As the propagation of the wake grows over time, more computational resources are required in the off-body

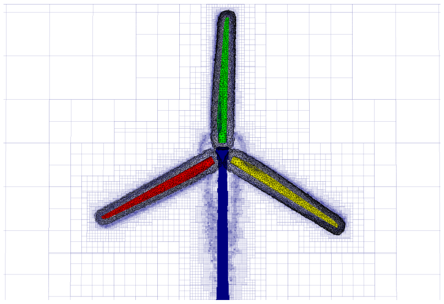

Figure 1: NREL 5MW wind turbine overset mesh system. One turbine blade unstructured mesh is replicated three times, rotated and translated to the initial positions. A fourth unstructured mesh is used to represent the tower and nacelle. The off-body adaptive mesh is visualized in the background.

regions. The flow solvers present in the framework can be redistributed to different amounts of cores at the beginning of restarted simulations. This allows for long run-time simulations to be moderately load balanced. Additionally, once a solver is implemented into the framework, flow visualization and analysis is provided to the solver through the use of in-situ visualization. Pointers to the flow solver's data and mesh are held by the driver which is fed to the in-situ flow visualization software implemented the driver.

Nearly all software used on our framework is developed in-house at the University of Wyoming with the exception of the *p4est* adaptive mesh refinement framework developed Carsten Burstedde et. al[4, 5]. The two flow solvers developed at the University of Wyoming are NSU3D[10, 11], an unstructured 3D finite-volume solver, and dg4est[1], a high-order discontinuous Galerkin finite-element solver. The overset solver used is TIOGA[3, 6, 13] developed by Jay Sitaraman of Parallel Geometric Algorithms, LLC.

3 RESULTS

Figure 2 shows the power and thrust predictions for inflow velocities 6-11.4 m/s using a mesh containing nearly one million grid points per blade compared to the NREL FAST[7] reference solution. The reference solution uses blade element momentum theory with a fluid-structure interface to model structural wake effects[7]. The power predicted from W^2A^2KE3D agrees well with FAST and the thrust is slightly under predicted for inflow velocities less than the nominal inflow velocity of 11.4 m/s. We note that the W^2A^2KE3D framework results do not contain blade elastic structural deflection responses compared to the NREL FAST results.

A generic Siemens SWT-2.3.93 turbine model using specifications from the IAE Wind Task 31-Wakebench[12] is simulated. The geometry of the turbine blade is constructed from multiple cylinder and airfoil sections. The wind turbine contains three blades and a tower with a nacelle for a total of four near-body meshes per wind turbine. The nominal rotor rotation speed is 16 RPM. The rated power inflow velocity is 10.9 m/s generating a rated electrical power of 2.3 MW. The Siemens blade has a radius of 46.5 m and a low-speed shaft title angle of 6°, pre-cone angle of 2.5°, and nominal blade pitch of -1°. The tower has a height of 65 m. To accurately

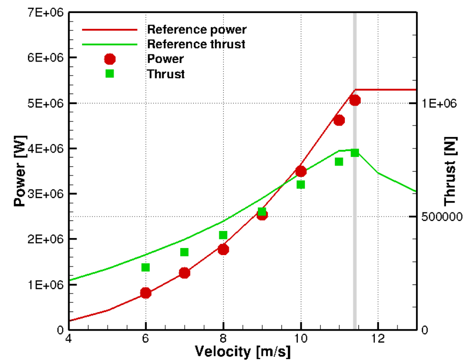

Figure 2: NREL 5MW power and thrust simulation results using a time step corresponding to a 1/4° rotation. Each time was solved with BDF-2 using 50 sub-iterations for the near-body flow solver. Reference solution data provided by the NREL FAST[7] software.

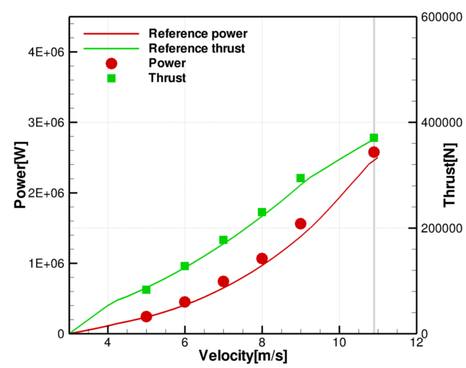

Figure 3: Siemens SWT-2.3-93 power and thrust simulation results using a time step corresponding to a 1/4° rotation. Each time was solved with BDF-2 using 25 sub-iterations for the near-body flow solver. Reference solution data provided by the NREL FAST[7] software.

predict the power and thrust forces, as indicated by a mesh refinement study of the NREL 5MW wind turbine, a near-body blade mesh containing 2,219,940 nodes and a tower with nacelle mesh containing 504,960 nodes are used. The global time step is set to a corresponding rotation of 1/4° and 25 non-linear sub-iterations are used to converge the BDF-2 time step for the near-body solver.

Our predicted power from the simulation framework at the nominal uniform inflow velocity of 10.9 m/s is 2.5 mega-watts and the torque is predicted at 373,000 Newtons which agrees well with the NREL FAST software (2.5 mega-watts is the aerodynamic power force before losses due to the generator which yields 2.3 mega-watts). The power and thrust convergence results are shown in Figure 3.

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