Stochastic Velocity Perturbation Strategies for Mesoscale to Microscale Coupling and Wind Turbine Aeroelastic Simulation

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Abstract
This work investigates the feasibility of applying established engineering models of synthetic turbulence to simulations of the microscale wind plant operating environment. The study has been split into two parts. First, large-eddy simulations (LES) of the atmospheric boundary layer (ABL) have been performed given a representative mesoscale inflow. Strategies for superimposing stochastic velocity perturbations from either TurbSim or a rapid distortion theory model have been evaluated, with the objective being to minimize the non-physical fetch required to develop fully resolved turbulence in the LES domain. Second, the applicability of synthetic turbulence simulators to modern wind turbines with taller towers and larger rotors has been investigated. FAST aeroelastic simulations of the NREL 5MW reference turbine driven by a canonical LES inflow are compared with the inflows from a mesoscale-driven, perturbed LES and from a synthetic turbulence simulator alone. This work will assess the shortcomings of state-of-the-art engineering models and enable higher-fidelity mesoscale-to-microscale coupled simulation.

Keywords: *synthetic turbulence, turbulent inflow generation, mesoscale to microscale coupling, large-eddy simulation*

Introduction

Accurate wind turbine and wind plant simulation requires sufficient resolution of microscale turbulence at the wind turbine scale and smaller. This turbulence in the ABL determines the wind speed, shear, and veer seen by the wind turbine rotor, which can negatively impact performance and cause fatigue loads. Since small-scale velocity and temperature fluctuations are strongly influenced by mesoscale flow features such as frontal passages, large-scale advection, and complex terrain, a clear increment in simulation fidelity would be to perform a multi-scale analysis that includes mesoscale-to-microscale coupling (MMC). To this end, a methodology for simulating turbulence at the microscale under non-stationary conditions is essential. More specifically, a MMC strategy should be able to use generalized mesoscale data, either from measurements (with limited temporal or spatial resolution) or from a mesoscale model (which models small-scale turbulence with physical parameterizations), to drive a microscale simulation that resolves (rather than models) small-scale turbulence.

LES microscale simulations typically develop turbulence using a horizontally periodic domain to reach an equilibrium state [1]. However, the actual wind plant operating environment is never actually in such a state due to mesoscale and diurnal forcings, which limit the applicability of the current approach. Moreover, in a non-periodic domain, significant fetch is needed for a turbulent cascade to form such that turbulence is fully developed at the smallest resolved scales. These fetches may be as large as tens of kilometers depending on atmospheric conditions [2,3], and within this developing region in the LES, the flow is not necessarily representative of realistic conditions. An engineering solution to minimizing fetch is to apply synthetic perturbations to the non-stationary mesoscale input in order to promote turbulent momentum [3] and/or temperature transport [2,3].

The approach we have taken is to apply velocity perturbations using existing industry tools for turbulent inflow simulation: TurbSim and a rapid distortion theory (RDT) model (e.g., the Mann model). The motivation for using these tools is two-fold. First, they are already heavily in use by industry and can be readily adopted for future MMC applications. Second, this is an opportunity to evaluate these inflow models and their impact on wind turbine performance and loads. The assumptions built into these models, including vertical homogeneity and frozen turbulence, are not strictly valid. For example, the Kaimal spectral model used by TurbSim was developed from measurements over flat terrain using data from a 32-m tall met tower [4]; modern wind turbines have hub heights and rotor diameters on the order of 100 m. In assessing the applicability of these synthetic turbulence models to MMC, we hope to also gain insights into their applicability to simulating modern wind turbines.

Methodology

In the present work, we focus on making fundamental comparisons between a "traditional" precursor LES and an inflow-outflow LES representative of an actual wind plant simulation. The traditional precursor is described by periodic horizontal boundaries approximating a computational domain of infinite span, and momentum source terms are applied to drive the planar-averaged velocity throughout the domain to a specified mean velocity profile. In comparison, the test simulation is characterized by laterally periodic boundaries and inflow/outflow boundaries along the streamwise direction. The inlet has a time-varying velocity that on average should match mesoscale data, but other statistics are not known a priori.

We perform our LES using the Simulator fOr Wind Farm Applications (SOWFA). To accelerate the development of turbulence in the finite-length inflow-outflow LES domain, stochastic velocity perturbations are superimposed onto a mean velocity profile from a reference periodic precursor that approximates a mesoscale model output. The synthetic turbulence is either generated by TurbSim given an input spectral model (Kaimal) and coherence model, or generated by a nonlinear RDT model using the Gabor transform [5]. Since vertical homogeneity is assumed, the output turbulence from these engineering models has no height dependence; we must therefore assume a vertical profile for the variance of each velocity component. For this work, we have taken two approaches: (1) scale the variances to approximate a realistic variance profile; and (2) assume that the variance is approximately constant up to the height of the boundary layer, and then reduce the variance to zero. The latter approach is more general since the turbulent stresses in a flow are not necessarily known with sufficient resolution from the mesoscale data. Therefore, we have chosen to model the height variation using a simple hyperbolic tangent function. This presents additional modeling parameters that will be explored in this work. All inflow-outflow simulations are compared against the fully developed turbulence field from the periodic precursor simulation.

Summary

We will demonstrate the effectiveness of our stochastic velocity perturbation strategy, based on comparisons between a reference periodic LES and select inflow-outflow simulations with varying perturbation profiles from TurbSim and an RDT-based model. The ability of the inflow-outflow simulation to develop turbulence characteristics similar to those of the LES precursor will be assessed based on one- and two-point statistics. An optimal MMC strategy for a canonical neutral ABL will be established and then applied to more challenging, stably stratified conditions. Finally, the fully developed inflows that have been simulated will be applied within FAST to evaluate wind turbine aeroelastic loads and performance.

References

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