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Modeling the effect of control on the wake of a utility-scale turbine via large-eddy simulation

Xiaolei Yang\textsuperscript{a}, Jennifer Annoni\textsuperscript{b}, Pete Seiler\textsuperscript{b}, and Fotis Sotiropoulos\textsuperscript{a,∗}

\textsuperscript{a} St. Anthony Falls Laboratory, Department of Civil Engineering, University of Minnesota, 2 Third Avenue SE, Minneapolis, MN 55414, USA
\textsuperscript{b} Aerospace and Engineering Mechanics Department, University of Minnesota, 110 Union St. SE, Minneapolis, MN 55455, USA

\textsuperscript{∗} Corresponding author: fotis@umn.edu

Abstract. A model of the University of Minnesota EOLOS research turbine (Clipper Liberty C96) is developed, integrating the C96 torque control law with a high fidelity actuator line large-eddy simulation (LES) model. Good agreement with the blade element momentum theory is obtained for the power coefficient curve under uniform inflow. Three different cases, fixed rotor rotational speed \( \omega \), fixed tip-speed ratio (TSR) and generator torque control, have been simulated for turbulent inflow. With approximately the same time-averaged \( \omega \), the time-averaged power is in good agreement with measurements for all three cases. Although the time-averaged aerodynamic torque is nearly the same for the three cases, the root-mean-square (rms) of the aerodynamic torque fluctuations is significantly larger for the case with fixed \( \omega \). No significant differences have been observed for the time-averaged flow fields behind the turbine for these three cases.

1. Introduction

Individual turbines currently operate at their peak efficiency without considering the impact of wake effects on nearby turbines. This mode of operation leads to inefficient, sub-optimal power capture at the wind farm level. There is great potential to increase total power and reduce structural loads by properly coordinating the turbines in a farm. The effective design of such coordinated controllers requires an accurate model of the fluid dynamics within the wind farm.

Several studies can be found in literature reporting large-eddy simulation (LES) of wind turbines with the turbines parametrized as actuator lines/disks and including the turbine controller. In [1], the FAST \cite{2} code was coupled with an LES code and an actuator disk model. The SOWFA (Simulator for Offshore/Onshore Wind Farm Applications) \cite{3, 4, 5, 6} code developed by the National Renewable Energy Laboratory (NREL) couples OpenFOAM \cite{7} with FAST and an actuator line model. Applications of SOWFA can be found in [4] for investigation of the effects of atmospheric stability and surface roughness on turbine wake aerodynamics. In addition, [8] investigates the effects of turbine-array layout on wind farm performance. Others \cite{9} coupled SOWFA with WRF (Weather Research and Forecasting Model), in which the WRF provides the LES with initial flow fields. Lastly \cite{10, 11} used SOWFA for validation of dynamic wake meandering model. Wake mitigation control strategies, including yaw misalignment and tilt angle of an upstream turbine, repositioning of the downstream turbine and independent
pitch control (IPC) for mitigating the effects of a partial wake for a two-turbine case was also investigated in [12] using SOWFA.

As a first step to develop advanced turbine controllers on wind farm level, we implement the generator torque control along with the actuator line model in the University of Minnesota VWiS (Virtual Wind Simulator) code, a high-fidelity LES framework capable of simulating wind farms in complex terrain. We apply the resulting model to simulate the University of Minnesota 2.5MW EOLOS research wind turbine (C96) by considering cases for which the rotating speed of the turbine rotor is fixed, from a fixed tip-speed ratio and oncoming wind velocity, or governed by a control law. The objective of this paper is to examine how these different operating conditions affect the turbine performance and also the wake behaviour of a utility-scale wind turbine.

2. Numerical methods

2.1. Flow solver

The LES equations governing the incompressible turbulent flows are the 3D, unsteady, filtered continuity and Navier-Stokes equations. In the VWiS code the curvilinear immersed boundary (CURVIB) method [13] is used to solve these equations in order to facilitate future extension of the method to simulate topography effects. In this method the governing equations are first written in Cartesian coordinates \( x^i \) and then transformed fully (both the velocity vector and spatial coordinates are expressed in curvilinear coordinates) in non-orthogonal, generalized, curvilinear coordinates \( \xi^i \). The transformed equations read in compact tensor notation (repeated indices imply summation) as follows \((i, j = 1, 2, 3)\),

\[
J \frac{\partial U^j}{\partial t} = 0, \tag{1}
\]

\[
\frac{1}{J} \frac{\partial U^i}{\partial t} = \frac{\xi^i}{J} \left( - \frac{\partial}{\partial \xi^j} (U^j u_l) + \frac{\mu}{\rho} \frac{\partial}{\partial \xi^j} \left( \frac{g^{jk} \partial u_l}{J} \frac{\partial \xi^k}{J} \right) - \frac{1}{\rho} \frac{\partial}{\partial \xi^j} \left( \frac{\xi^l_p}{J} \frac{\partial \xi^l}{J} \right) - \frac{1}{\rho} \frac{\partial \tau_{ij}}{\partial \xi^j} + f_i \right), \tag{2}
\]

where \( \xi^i = \partial \xi^i / \partial x_l \) are the transformation metrics, \( J \) is the Jacobian of the geometric transformation, \( u_i \) is the \( i \)th component of the velocity vector in Cartesian coordinates, \( U^i = (\xi^i_m / J) u_m \) is the contravariant volume flux, \( g^{jk} = \xi^j l \xi^k l \) are the components of the contravariant metric tensor, \( \rho \) is the density, \( \mu \) is the dynamic viscosity, \( p \) is the pressure, \( f_i(l = 1, 2, 3) \) are the body forces introduced by the wind turbines and \( \tau_{ij} \) represents the anisotropic part of the subgrid scale stress tensor, which is modelled by the dynamic Smagorinsky subgrid scale model [14]. For details of the CURVIB method and numerical schemes, please refer to the papers [13, 15].

2.2. Actuator line model with generator torque control

The actuator line model [16] is employed for turbine parametrization. The actuator line model accounts for the blades as separate rotating lines. The forces distributed on each line (blade) are calculated based on a blade element approach, in which the blade is divided into elements in the radial direction, and tabulated as 2D airfoil data. A 4-point width discrete delta function proposed in [17] is employed for force distribution from the actuator line grid nodes to the background grid nodes. For more details about the formulation and numerical implementation of the discrete delta function in turbine parametrization models the reader is referred to [18, 19].

Utility-scale turbines have several inputs that can be controlled to increase the captured power and reduce structural loads. These inputs include generator torque, \( \tau_g \), and blade pitch, \( \beta \), at varying wind speeds, \( u \), which can control the rotor speed of the turbine, \( \omega \) (Figure 1). In general, the generator torque is varied at low wind speeds (commonly referred to as Region 2)
to maximize power captured. At high wind speed (commonly called Region 3), the blade pitch angle is used to mitigate mechanical and electrical loads.

A standard generator torque controller, which is used at low wind speeds, is considered in this paper. The power captured by a single turbine can be expressed by:

$$P = \frac{1}{2} \rho A U^3 C_P(\beta, \lambda)$$ (3)

where $\rho$ [kg/m$^3$] is the air density, $A$ [m$^2$] is the area swept by the rotor, $U$ [m/s] is the wind speed perpendicular to the rotor plane, and $C_P$ [unitless] is the power coefficient. The power coefficient is the fraction of available power in the wind captured by the wind turbine. $C_P$ is a function of blade pitch angle, $\beta$ [rad] and nondimensional tip-speed-ratio (TSR). TSR is defined as $\lambda = \omega R/U$ where $\omega$ [rad/s] is the rotor speed and $R$ [m] is the rotor radius. The peak $C_P,*$ value is achieved at some fixed blade pitch angle, $\beta_*$, and an optimal TSR, $\lambda_*$. Under realistic conditions, the blade pitch angle can be held constant at $\beta_*$, while TSR varies with varying wind speed. The optimal TSR, $\lambda_*$, can be achieved by changing the rotor speed proportionally to the wind variations. The objective of a generator torque controller is to maximize power. This is done by maintaining an optimal blade pitch angle ($\beta_*$) and TSR ($\lambda_*$). The blade pitch angle is held fixed at $\beta_*$, and the generator torque is controlled to achieve $\lambda_*$ in varying wind conditions.

The dynamics of the turbine are modelled as a single degree-of-freedom rotational system:

$$\frac{d\omega}{dt} = \frac{1}{J} (\tau_{aero} - \tau_g)$$ (4)

where $J$ is the rotational inertial of the rotor, $\tau_{aero}$ [Nm] is the aerodynamic torque given by the actuator line model, and $\tau_g$ [Nm] is the generator torque, which can be computed using the standard control law:

$$\tau_g = K_g \omega^2$$ (5)

where $K_g = \frac{1}{2} \rho A R^3 C_P N^2 N$ and $N$ is the gearbox ratio. If $K_g$ is chosen properly, the power from the turbine will converge to $C_P,*$ in steady winds. In turbulent winds, the turbine will cycle around the peak $\lambda_*$. Additional details and references on turbine control can be found in [20, 21, 22].

3. Numerical results

We apply our method to simulate a Clipper Liberty 2.5MW wind turbine, the centrepiece of the EOLOS wind energy research field station, which is installed at UMore Park in Rosemount, MN (about 20 miles southeast of the Twin Cities campus). The rotor diameter of the turbine is 96 meters at a hub height of 80 meters. A 130-meter-tall meteorological tower is located at 160 meters south of the turbine. Instruments are installed at 10 different heights on
the tower spanning the entire swept area of the turbine blades, in which four with sonic anemometers measuring wind speed and turbulence at a very rapid sampling rate, and six with temperature, barometric pressure and humidity sensors as well as cup and vane anemometers. The turbine’s Supervisory Control and Data Acquisition (SCADA) system is employed to record the operational and performance data from the turbine. A detailed description of the EOLOS turbine can be found in [23].

The lengths of the computational domain are 1500 meters, 800 meters and 1000 meters in the streamwise (x), spanwise (y) and vertical (z) directions, respectively. The mesh near the turbine and in turbine near-wake is uniform with a grid spacing of 5 meters. The numbers of grid nodes are 201, 121 and 121 in x, y and z directions, respectively. The time step is 0.044s. For the actuator line grid, 51 points are employed along each line (blade). For the turbulent inflow cases, a fully developed turbulent boundary layer flow, which is from a precursor simulation, is fed at the inlet. Wall model is employed at the ground. Free slip boundary condition is used for the top boundary. Periodic boundary condition is employed in the spanwise direction. The VWiS code is used to carry out simulations for three cases: fixed $\lambda$, fixed TSR, and generator torque control. For the fixed TSR case, the inflow velocity for calculating $\lambda$ is taken at hub height 1.67D upstream of the turbine. The distance 1.67D is chosen as this is the upstream distance of the met tower from the turbine at the EOLOS field station. The computations were first carried out until the total kinetic energy of the computational domain reached a quasi-steady state, and subsequently the flow fields were averaged for approximately 20 minutes.

Simulations with uniform inflow were carried out first at different fixed TSR and with different values of $K_g$ in the generator torque control. In Figure 2, we compare the computed $C_P$ of these simulations with those predicted from blade element momentum theory, which should work well for uniform inflow. Good agreement is obtained between the theory and the results of the simulations with fixed TSR and generator torque control.

For the turbulent inflow cases, the selected time period for comparison is from 11:20 am to 12:20 pm on May 19, 2012, in which the wind is from the south (where the meteorological tower is installed) and the atmospheric stability is neutral. The time-averaged wind speed from the upstream meteorological tower is 8.4 m/s at the turbine hub height. The comparison of the vertical profiles is shown in Figure 3. Good agreement with the measurements is obtained.

Figure 2: Power coefficients calculated for uniform flow. Solid black line: Blade element momentum theory; Red circles: Simulated with VWiS for different fixed TSR; Blue squares: Simulated with VWiS with generator torque control with different $K_g$. 
Figure 3: Vertical profiles of the streamwise velocity (a) and turbulence intensity $\sigma_u$ (b) at the inlet for the turbulent inflow cases. Solid lines: Simulated with VWiS; Symbols: Measurements from the meteorological tower.

|                | $\omega$ (rad/s) | TSR | P (MW) | $P_{rms}$ | $\tau_{aero}$ ($Nm \times 10^6$) | $\tau_{rms}^{aero}$ ($Nm \times 10^6$) |
|----------------|------------------|-----|--------|-----------|-------------------------------|----------------------------------------|
| Fixed $\omega$ | 1.43             | 8.43| 1.21   | 0.45      | 0.81                          | 0.31                                   |
| Fixed TSR      | 1.50             | 8.65| 1.20   | 0.43      | 0.76                          | 0.19                                   |
| Torque control | 1.46             | 8.49| 1.22   | 0.41      | 0.79                         | 0.20                                   |
| Measurements   | 1.51             | 8.37| 1.21   | 0.19      | 0.79*                         | 0.09*                                  |

*The aerodynamic torque is calculated by $P/\omega$, where $P$ and $\omega$ are the measured values.

Table 1: Summary of the computed results from the three cases: fixed $\omega$, fixed TSR and generator torque control.

As seen, the time-averaged power and aerodynamic torque from the VWiS simulations agree well with the measurements for all the three cases. However the turbulence intensity $\sigma_u$ is over predicted. The computed results from the three cases with turbulent inflow are summarized in Table 1, in which the power is calculated by the following equation

$$P = \tau_{aero}\omega \quad (6)$$

4. Summary

Generator torque control for the University of Minnesota EOLOS wind turbine has been implemented in an actuator line model of the VWiS LES code. The computed power coefficients agree well with the ones calculated from the blade element momentum theory for uniform inflow.
The model has also been applied to three cases with turbulent inflow: fixed turbine rotating speed, fixed TSR and generator torque control. The time-averaged flow fields from the three cases are nearly the same. Good agreement is obtained for the time-averaged power for all three cases. Significantly larger root-mean-square (rms) of the aerodynamic torque fluctuations is observed for the case with fixed $\omega$. The reason for this will be investigated in the future work.

In addition to a generator torque controller, turbines typically have a blade pitch controller at or above rated wind speeds. This controller holds generator torque constant and pitches the blades to minimize structural loads. A blade pitch controller was not considered in this paper, but will be incorporated in future work.

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