Renewable Energy xxx (2014) 1–11

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Modeling turbine wakes and power losses within a wind farm using LES: An application to the Horns Rev offshore wind farm

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A R T I C L E I N F O

Article history:
Received 30 September 2013
Accepted 5 June 2014
Available online xxx

Keywords:
Actuator-disk models
Blade element theory
Horns Rev offshore wind farm
Large-eddy simulation
Power deficit

A B S T R A C T

A modeling framework is proposed and validated to simulate turbine wakes and associated power losses in wind farms. It combines the large-eddy simulation (LES) technique with blade element theory and a turbine-model-specific relationship between shaft torque and rotational speed. In the LES, the turbulent subgrid-scale stresses are parameterized with a tuning-free Lagrangian scale-dependent dynamic model. The turbine-induced forces and turbine-generated power are modeled using a recently developed actuator-disk model with rotation (ADM-R), which adopts blade element theory to calculate the lift and drag forces (that produce thrust, rotor shaft torque and power) based on the local simulated flow and the blade characteristics. In order to predict simultaneously the turbine angular velocity and the turbine-induced forces (and thus the power output), a new iterative dynamic procedure is developed to couple the ADM-R turbine model with a relationship between shaft torque and rotational speed. This relationship, which is unique for a given turbine model and independent of the inflow condition, is derived from simulations of a stand-alone wind turbine in conditions for which the thrust coefficient can be validated. Comparison with observed power data from the Horns Rev wind farm shows that better power predictions are obtained with the dynamic ADM-R than with the standard ADM, which assumes a uniform thrust distribution and ignores the torque effect on the turbine wakes and rotor power. The results are also compared with the power predictions obtained using two commercial wind-farm design tools (WindSim and WAsP). These models are found to underestimate the power output compared with the results from the proposed LES framework.

1. Introduction

When wind turbines are clustered together in a finite area, power losses due to turbine wakes are inevitable and vary with their arrangement and the incoming wind conditions. In large offshore wind farms (e.g., Horns Rev, Lillgrund, and Nysted), average power losses have been reported in the range of 10%–25% of the total power output [3,4]. These power losses are associated with the wind velocity deficit distribution inside the wind farms, which is modulated by complex interactions between the atmospheric boundary layer (ABL) turbulence and multiple wind-turbine wakes. This ABL-wind-farm interaction is multiscale and fully coupled, and is in turn affected by several factors such as atmospheric stability, land-/sea-surface characteristics, wind-farm layout and wind direction. Accurate numerical prediction of the ABL flow and its interaction with wind turbines and wind farms, as well as of power losses due to wakes, is necessary for optimizing wind energy projects (wind-turbine siting) in order to minimize the impact of upstream wakes on the productivity of downstream turbines [45,41,27].

Several wind-farm design tools that use different analytical wake models [25,26,17] or computational fluid dynamics (CFD) flow solvers [1,12,39] have been developed and implemented in predictions of power losses in operational wind farms [44,3,11]. In general, analytical wake models are simplified and require much less computational time to estimate the wind-farm wind resources and power losses due to wakes. These models involve algebraic equations for turbine-induced wake velocities and superpositions of multiple turbine wakes. Some analytical wake models, such as the Park Model [19], have been implemented in 'industry-standard' softwares (e.g., Wind Atlas Analysis and Application Program (WAsP), WindPro and WindFarmer) for the assessment of wind

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http://dx.doi.org/10.1016/j.renene.2014.06.019

resources and the micro-siting of wind turbines and wind farms. Alternatively, CFD solvers are based on the solution of the averaged or filtered Navier–Stoke equations (e.g., EllipSys3D [18], Fuga [33], WIRE-LES [37]). The effect of the wind turbine forces is parameterized using 1D momentum theory or blade element theory.

Barthelmie et al. [3] used both types of models (analytical and CFD-based) to predict the turbine power losses at Horns Rev I wind farm for different wind directions and different wind sectors. The predicted power output results were in disagreement with the observed data for a wind sector of less than 10°. In particular, the predicted power outputs are underestimated by up to 55% in the full-wake conditions, in which the incoming wind direction is parallel to the turbine rows. This discrepancy reflects the need for improvements in both turbulence modeling and turbine parameterization in the wind-farm design tools.

In previous studies, both Reynolds-averaged Navier–Stokes (RANS) and large-eddy simulation (LES) models, coupled with actuator disk-/line-based models for turbine rotor parameterization, have been used for the modeling of the turbulence in ABL flows through wind turbines, [e.g., [14,24,22,28]]. In particular, the actuator-disk model without rotation (ADM-NR), the actuator-disk model with rotation (ADM-R), or both, have been used in wind farm simulations [6,7,48]. Recently, validation studies [38,46,48] have shown that using LES, coupled with the Lagrangian scale-dependent dynamic model for the subgrid-scale (SGS) stress and the ADM-R for turbine-induced lift and drag forces, is able to reproduce the magnitude and spatial distribution of the most relevant turbulence statistics (e.g. mean velocity, turbulence kinetic energy and turbulent stresses) of turbine wakes in turbulent boundary layer flows.

Some recent studies [18,10] examined the power losses from large wind farms using LES coupled with actuator-disk/actuator-line models. However, these studies retain uncertainties in both the turbulence modeling and the turbine parameterization, which may strongly affect the characteristics of multiple turbine wakes and the estimation of associated power losses in large wind farm simulations. Moreover, comparison of turbine power output predicted using both the ADM-NR and the ADM-R in the same flow solver has not been done so far.

In this study, we adopt the LES framework to investigate the effect of multiple turbine wakes on power losses in an operational large wind farm. A Lagrangian scale-dependent dynamic model is used to model the SGS stress [42]. Two actuator-disk type models for turbine parameterization are used: the traditional actuator-disk model (ADM-NR) and the actuator-disk model with rotation (ADM-R). Numerical simulations are carried out to examine the effect of different incoming wind directions on the power losses in the Horns Rev wind farm under near-neutral conditions. A short description of the LES framework is given in Section 2. The Horns Rev wind farm is described in Section 3. The numerical set-up is described in Section 4. The predicted power losses as well as the spatial distribution of the mean velocity and the turbulence intensity are shown and discussed in Section 6. Finally conclusions are given in Section 7.

2. Large-eddy simulation framework

2.1. Governing equations of the flow

We use a modified version of the LES code developed by Albertson et al. [2], Porté-Agel et al. [36], Porté-Agel [35], Stoll and Porté-Agel [42], Wu and Porté-Agel [46,48]. The code solves the continuity equation and the momentum equation written in rotation form:

$$\frac{\partial \tilde{u}_i}{\partial x_i} = 0, \tag{1}$$

and

$$\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j\left(\frac{\partial \tilde{u}_i}{\partial x_j} - \frac{\partial \tilde{u}_j}{\partial x_i}\right) = -\frac{1}{\rho}\frac{\partial \tilde{p}^*}{\partial x_i} - \frac{\partial \tau_{ij}^d}{\partial x_j} + \nu\frac{\partial^2 \tilde{u}_i}{\partial x_j^2} - \frac{f_i}{\rho} + \mathcal{F}_i, \tag{2}$$

where the tilde represents a three-dimensional spatial filtering operation at scale Δ, t is time, $\tilde{u}_i$ is the resolved velocity in the i-th direction (with $i = 1,2,3$ corresponding to the streamwise (x), spanwise (y) and vertical (z) directions in a Cartesian coordinate system), ρ is the air density, $\tilde{p}^*$ is the modified pressure, τ_{ij}^d is the deviatoric part of the SGS momentum flux, ν is the kinematic viscosity of air, f_i is an immersed force (per unit volume) for modeling the effect of wind turbines on the flow, and $\mathcal{F}_i$ is a forcing term (e.g., a mean pressure gradient). The SGS momentum flux is modeled using a Lagrangian scale-dependent dynamic model [42]. An immersed force (per unit volume) f_i is parameterized using actuator disk models. Periodic boundary conditions are used along the horizontal directions and a stress-free boundary condition is employed at the top of the domain. Monin–Obukhov similarity theory is applied to compute the instantaneous (filtered) surface shear stress as a function of the velocity field at the lowest vertical grid point. More details on the numerical method of the LES code can be found in Porté-Agel et al. [36], Porté-Agel [35], Stoll and Porté-Agel [42,43].

2.2. Actuator-disk model without rotation (ADM-NR)

The actuator-disk model without rotation (ADM-NR), also called the traditional/Rankine–Froude actuator-disk model, is a popular numerical wind turbine model implemented in both in-house LES codes [20,21] and commercial software (e.g., WindSim) [11]. The ADM-NR only considers a uniform thrust load over the circular rotor disk and neglects the effect of wake rotation. The axial normal (thrust) force acting on the actuator disk can be modeled as

$$F_x^{\mathrm{ADM-NR}} = \frac{\rho}{2}\langle \tilde{u}_0\rangle^2 C_T\cdot A_e = \frac{\rho}{2}\frac{\langle V_x\rangle^2}{(1-a)^2}C_T\cdot A_e, \tag{3}$$

where the angle bracket denotes a spatial average within the rotor disk, $\tilde{u}_0$ is the unperturbed streamwise velocity of the incident flow, V_x is the velocity at the rotor, C_T is the thrust coefficient, and A_e is the frontal area of each element on a cylindrical mesh system (see Fig. 1a). For simplicity, we compute the power output of a wind turbine based on its power curve and the unperturbed velocity corrected with the disk-averaged velocity and axial induction factor (i.e., $\langle \tilde{u}_0\rangle = \langle V_x\rangle/(1-a)$). The axial induction factor a is calculated using $a = 0.5(1-\sqrt{1-C_T})$ derived from 1D momentum theory.

2.3. Actuator-disk model with rotation (ADM-R)

A common parameterization strategy in turbine models consists of computing the turbine-induced lift and drag forces with the blade element approach. In this approach, both lift and drag forces acting on each blade element (see Fig. 1b) are parameterized based on the relative wind velocity, the geometry of a blade airfoil, and tabulated airfoil data. The decomposition of the resultant force $\boldsymbol{F}$ is shown in Fig. 1b, and its components can be formulated as follows:

$$\text{Lift force}: L = 0.5\rho V_{\mathrm{rel}}^2 c\Delta r C_L \tag{4}$$

Please cite this article in press as: Wu Y-T, Porté-Agel F, Modeling turbine wakes and power losses within a wind farm using LES: An application to the Horns Rev offshore wind farm, Renewable Energy (2014), http://dx.doi.org/10.1016/j.renene.2014.06.019